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WHIZARD¹

Wolfgang Kilian,² Thorsten Ohl,³ Jürgen Reuter⁴

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¹The original meaning of the acronym is *W, Higgs, Z, And Respective Decays*. The current program is more than that, however.

²e-mail: kilian@hep.physik.uni-siegen.de

³e-mail: ohl@physik.uni-wuerzburg.de

⁴e-mail: juergen.reuter@physik.uni-freiburg.de

Abstract

WHIZARD is an application of the VAMP algorithm: Adaptive multi-channel integration and event generation. The bare VAMP library is augmented by modules for Lorentz algebra, particles, phase space, etc., such that physical processes with arbitrary complex final states [well, in principle. . .] can be integrated and *unweighted* events be generated.

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Chapter 1

Changes

- 2.0.0
 - Most of the WHIZARD 1 code has either been revised or rewritten
 - Completely new user interface (script language)
 - New implementation of density matrix evaluation (which is the very core)

Chapter 2

Tools

This part contains modules needed for auxiliary purposes:

limits Compile-time (integer) constants: fixed array sizes, input field lengths, and such. Any module that uses such constants has to access them via **limits**.

mpi90 Parallel execution (currently disabled!). This module contains dummy replacements for the message passing interface subroutines.

clock Store and handle dates and times

diagnostics Error and diagnostic message handling. Any messages and errors issued by WHIZARD functions are handled by the subroutines in this module, if possible.

files Files and auxiliary routines that do not belong anywhere else.

permutations Handle permutations of integers.

unix_args Parse the command-line arguments and options. This part is system-dependent, and we provide a replacement if the functions are not available.

2.1 Preliminaries

The WHIZARD file header:

```
<File header>≡
! WHIZARD <Version> <Date>
!
! (C) 1999-2010 by
!   Wolfgang Kilian <kilian@hep.physik.uni-siegen.de>
!   Thorsten Ohl <ohl@physik.uni-wuerzburg.de>
!   Juergen Reuter <juergen.reuter@physik.uni-freiburg.de>
!   with contributions by Sebastian Schmidt
!
! WHIZARD is free software; you can redistribute it and/or modify it
! under the terms of the GNU General Public License as published by
! the Free Software Foundation; either version 2, or (at your option)
! any later version.
```

```

!
! WHIZARD is distributed in the hope that it will be useful, but
! WITHOUT ANY WARRANTY; without even the implied warranty of
! MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the
! GNU General Public License for more details.
!
! You should have received a copy of the GNU General Public License
! along with this program; if not, write to the Free Software
! Foundation, Inc., 675 Mass Ave, Cambridge, MA 02139, USA.
!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! This file has been stripped of most comments. For documentation, refer
! to the source 'whizard.nw'

```

We are strict with our names:

```

<Standard module head>≡
    implicit none
    private

```

This is the way to invoke the kinds module (not contained in this source)

```

<Use kinds>≡
    use kinds, only: default !NODEP!

```

And we make heavy use of variable-length strings

```

<Use strings>≡
    use iso_varying_string, string_t => varying_string !NODEP!

```

Some parameters (buffer sizes etc.) are hardcoded. They are collected in this module:

```

<limits.f90>≡
    <File header>

    module limits

    <Standard module head>

    <Limits: public parameters>

    end module limits

```

The version string is used for checking files. Note that the string length MUST NOT be changed, because reading binary files relies on it.

```

<Limits: public parameters>≡
    integer, parameter, public :: VERSION_STRLEN = 255
    character(len=VERSION_STRLEN), parameter, public :: &
        & VERSION_STRING = "WHIZARD version <Version> (<Date>)"

```

2.2 Parallelization

This section has been removed, it was never used even in WHIZARD1. Parallelization should be reimplemented from scratch.

2.3 File utilities

This module provides tools for finding a free unit, filename handling: directory prefixes and extensions, default filenames. Furthermore, the `upper_case` and `lower_case` functions and a tool for formatting numbers in TeX style.

```
<file_utils.f90>≡  
  <File header>  
  
  module file_utils  
  
    use iso_fortran_env, only: stdout => output_unit !NODEP!  
    <Use kinds>  
    <Use strings>  
    use limits, only: MIN_UNIT, MAX_UNIT !NODEP!  
    use limits, only: DEFAULT_FILENAME, FILENAME_LEN !NODEP!  
  
    <Standard module head>  
  
    <File utils: public>  
  
    <File utils: interfaces>  
  
    contains  
  
    <File utils: procedures>  
  
  end module file_utils
```

2.3.1 Finding an I/O unit

Fortran 95 (even Fortran 2003) has no notion of implicit I/O units. Therefore, we have to find a free unit by trial and error.

```
<Limits: public parameters>+≡  
  integer, parameter, public :: MIN_UNIT = 11, MAX_UNIT = 99  
  
<File utils: public>≡  
  public :: free_unit  
  
<File utils: procedures>≡  
  function free_unit () result (unit)  
    integer :: unit  
    logical :: exists, is_open  
    integer :: i, status  
    do i = MIN_UNIT, MAX_UNIT  
      inquire (unit=i, exist=exists, opened=is_open, iostat=status)  
      if (status == 0) then  
        if (exists .and. .not. is_open) then  
          unit = i; return  
        end if  
      end if  
    end do  
    unit = -1  
  end function free_unit
```

Return the given unit, if present, otherwise the default STDOUT unit.

```

<File utils: public>+≡
    public :: output_unit

<File utils: procedures>+≡
    function output_unit (unit) result (u)
        integer, intent(in), optional :: unit
        integer :: u
        if (present (unit)) then
            u = unit
        else
            u = stdout
        end if
    end function output_unit

```

This activates the ubiquitous functions `free_unit` and `output_unit`:

```

<Use file utils>≡
    use file_utils !NODEP!

Flush all units possibly activated by free_unit

<File utils: public>+≡
    public :: flush_all

<File utils: procedures>+≡
    subroutine flush_all ()
        integer :: u
        do u = MIN_UNIT, MAX_UNIT
            flush (u)
        end do
    end subroutine flush_all

```

2.3.2 Filename handling

Choose a filename. If the first one is empty, take the second one. (Of course, this function works for any string.)

```

<Limits: public parameters>+≡
    integer, parameter, public :: FILENAME_LEN = 256

<File utils: public>+≡
    public :: choose_filename

<File utils: procedures>+≡
    function choose_filename (file, default_file) result (chosen_file)
        character(len=*), intent(in) :: file, default_file
        character(len=FILENAME_LEN) :: chosen_file
        if (len_trim (file) == 0) then
            chosen_file = default_file
        else
            chosen_file = file
        end if
    end function choose_filename

```

Concat filename with dot(s) and extension(s). The directory prefix is prepended only if the filename is relative

```

<File utils: public routines>≡
    public :: concat

<File utils: interfaces>≡
    interface concat
        module procedure concat_two, concat_three
    end interface

<File utils: procedures>+≡
    function concat_two (prefix, filename, extension) result (file)
        character(len=*) :: prefix, filename, extension
        character(len=FILENAME_LEN) :: file
        file = trim(filename)//"."//trim(extension)
        if (prefix /= "" .and. filename(1:1) /= "/" .and. filename(1:2) /= "./") &
            & file = trim(prefix) // "/" // file
    end function concat_two

    function concat_three (prefix, filename, process_id, extension) result (file)
        character(len=*) :: prefix, filename, process_id, extension
        character(len=FILENAME_LEN) :: file
        file = trim(filename)//"."//trim(process_id)//"."//trim(extension)
        if (prefix /= "" .and. filename(1:1) /= "/" .and. filename(1:2) /= "./") &
            & file = trim(prefix) // "/" // file
    end function concat_three

```

Select a file (to open later for reading). If the first one does not exist, try the default filename. Return the filename with extension appended. If the default file does not exist either, return the empty string.

```

<Limits: public parameters>+≡
    character(len=*), parameter, public :: DEFAULT_FILENAME = "whizard"

<File utils: public>+≡
    public :: file_exists_else_default

<File utils: procedures>+≡
    function file_exists_else_default (prefix, filename, extension) result (file)
        character(len=*) :: prefix, filename, extension
        character(len=FILENAME_LEN) :: file
        logical :: exist
        file = concat (prefix, filename, extension)
        inquire (file=trim(file), exist=exist)
        if (.not.exist) then
            file = concat (prefix, DEFAULT_FILENAME, extension)
            inquire (file=trim(file), exist=exist)
            if (.not.exist) then
                file = ""
            end if
        end if
    end function file_exists_else_default

```

2.3.3 String auxiliary functions

These are, unfortunately, not part of Fortran.

```
<File utils: public>+≡
    public :: upper_case
    public :: lower_case

<File utils: interfaces>+≡
    interface upper_case
        module procedure upper_case_char, upper_case_string
    end interface
    interface lower_case
        module procedure lower_case_char, lower_case_string
    end interface

<File utils: procedures>+≡
    function upper_case_char (string) result (new_string)
        character(*), intent(in) :: string
        character(len(string)) :: new_string
        integer :: pos, code
        integer, parameter :: offset = ichar('A')-ichar('a')
        do pos = 1, len (string)
            code = ichar (string(pos:pos))
            select case (code)
                case (ichar('a'):ichar('z'))
                    new_string(pos:pos) = char (code + offset)
                case default
                    new_string(pos:pos) = string(pos:pos)
            end select
        end do
    end function upper_case_char

    function lower_case_char (string) result (new_string)
        character(*), intent(in) :: string
        character(len(string)) :: new_string
        integer :: pos, code
        integer, parameter :: offset = ichar('a')-ichar('A')
        do pos = 1, len (string)
            code = ichar (string(pos:pos))
            select case (code)
                case (ichar('A'):ichar('Z'))
                    new_string(pos:pos) = char (code + offset)
                case default
                    new_string(pos:pos) = string(pos:pos)
            end select
        end do
    end function lower_case_char

    function upper_case_string (string) result (new_string)
        type(string_t), intent(in) :: string
        type(string_t) :: new_string
        new_string = upper_case_char (char (string))
    end function upper_case_string

    function lower_case_string (string) result (new_string)
```

```

type(string_t), intent(in) :: string
type(string_t) :: new_string
new_string = lower_case_char (char (string))
end function lower_case_string

```

2.3.4 Formatting numbers

Format a number with n significant digits.

```

<File utils: public>+≡
public :: tex_format

<File utils: procedures>+≡
function tex_format (rval, n_digits) result (string)
  type(string_t) :: string
  real(default), intent(in) :: rval
  integer, intent(in) :: n_digits
  integer :: e, n, w, d
  real(default) :: absval
  real(default) :: mantissa
  character :: sign
  character(20) :: format
  character(80) :: cstr
  n = min (abs (n_digits), 16)
  if (rval == 0) then
    string = "0"
  else
    absval = abs (rval)
    e = log10 (absval)
    if (rval < 0) then
      sign = "-"
    else
      sign = ""
    end if
    select case (e)
    case (:-3)
      d = max (n - 1, 0)
      w = max (d + 2, 2)
      write (format, "('(F',IO,'.',IO,'A,IO,A)')") w, d
      mantissa = absval * 10._default ** (1 - e)
      write (cstr, fmt=format) mantissa, "\times 10^{", e - 1, "}"
    case (-2:0)
      d = max (n - e, 1 - e)
      w = max (d + e + 2, d + 2)
      write (format, "('(F',IO,'.',IO,')')") w, d
      write (cstr, fmt=format) absval
    case (1:2)
      d = max (n - e - 1, -e, 0)
      w = max (d + e + 2, d + 2, e + 2)
      write (format, "('(F',IO,'.',IO,')')") w, d
      write (cstr, fmt=format) absval
    case default
      d = max (n - 1, 0)
      w = max (d + 2, 2)

```

```

        write (format, "(('F',IO,'.',IO,',A,IO,A)')") w, d
        mantissa = absval * 10._default ** (- e)
        write (cstr, fmt=format) mantissa, "\times 10^{", e, "}"
    end select
    string = sign // trim (cstr)
end if
end function tex_format

```

2.4 Operating-system interface

For specific purposes, we need direct access to the OS (system calls). This is, of course, system dependent. The current version is valid for GNU/Linux; we expect to use a preprocessor for this module if different OSs are to be supported.

The current implementation lacks error handling.

```

<os_interface.f90>≡
  <File header>

  module os_interface

    use iso_c_binding !NODEP!
    <Use strings>
    <Use file utils>
    use system_dependencies !NODEP!
    use limits, only: DLERROR_LEN !NODEP!
    use diagnostics !NODEP!

    <Standard module head>

    <OS interface: public>

    <OS interface: types>

    <OS interface: interfaces>

    contains

    <OS interface: procedures>

  end module os_interface

```

2.4.1 System dependencies

We store all potentially system- and user/run-dependent data in a transparent container. This includes compiler/linker names and flags, file extensions, etc.

```

<OS interface: public>≡
  public :: os_data_t

<OS interface: types>≡
  type :: os_data_t
    logical :: use_libtool
    logical :: use_testfiles

```

```

type(string_t) :: fc
type(string_t) :: fcflags
type(string_t) :: fcflags_pic
type(string_t) :: fc_src_ext
type(string_t) :: obj_ext
type(string_t) :: ld
type(string_t) :: ldflags
type(string_t) :: ldflags_so
type(string_t) :: ldflags_static
type(string_t) :: shlib_ext
type(string_t) :: whizard_omega_binpath
type(string_t) :: whizard_includes
type(string_t) :: whizard_ldflags
type(string_t) :: whizard_libtool
type(string_t) :: whizard_modelpath
type(string_t) :: whizard_models_libpath
type(string_t) :: whizard_susypath
type(string_t) :: whizard_gmlpath
type(string_t) :: whizard_cutspath
type(string_t) :: whizard_texpath
type(string_t) :: whizard_testdatapath
logical :: event_analysis_ps = .false.
logical :: event_analysis_pdf = .false.
type(string_t) :: latex
type(string_t) :: gml
type(string_t) :: dvips
type(string_t) :: ps2pdf
end type os_data_t

```

Since all are allocatable strings, explicit initialization is necessary.

```

<OS interface: public>+≡
public :: os_data_init

<OS interface: procedures>≡
subroutine os_data_init (os_data)
  type(os_data_t), intent(out) :: os_data
  os_data%use_libtool = .true.
  inquire (file = "TESTFLAG", exist = os_data%use_testfiles)
  os_data%fc           = DEFAULT_FC
  os_data%fcflags      = DEFAULT_FCFLAGS
  os_data%fcflags_pic  = DEFAULT_FCFLAGS_PIC
  os_data%fc_src_ext   = DEFAULT_FC_SRC_EXT
  os_data%obj_ext      = DEFAULT_OBJ_EXT
  os_data%ld           = DEFAULT_LD
  os_data%ldflags      = DEFAULT_LDFLAGS
  os_data%ldflags_so   = DEFAULT_LDFLAGS_SO
  os_data%ldflags_static = DEFAULT_LDFLAGS_STATIC
  os_data%shlib_ext    = DEFAULT_SHLIB_EXT
  if (os_data%use_testfiles) then
    os_data%whizard_omega_binpath = WHIZARD_TEST_OMEGA_BINPATH
    os_data%whizard_includes      = WHIZARD_TEST_INCLUDES
    os_data%whizard_ldflags       = WHIZARD_TEST_LDFLAGS
    os_data%whizard_libtool       = WHIZARD_LIBTOOL_TEST
    os_data%whizard_modelpath     = WHIZARD_TEST_MODELPATH
  end if
end subroutine os_data_init

```

```

os_data%whizard_models_libpath = WHIZARD_TEST_MODELS_LIBPATH
os_data%whizard_susypath       = WHIZARD_TEST_SUSYPATH
os_data%whizard_gmlpath       = WHIZARD_TEST_GMLPATH
os_data%whizard_cutspath      = WHIZARD_TEST_CUTSPATH
os_data%whizard_texpath       = WHIZARD_TEST_TEXPATH
os_data%whizard_testdatapath  = WHIZARD_TEST_TESTDATAPATH
else
os_data%whizard_omega_binpath = WHIZARD_OMEGA_BINPATH
os_data%whizard_includes      = WHIZARD_INCLUDES
os_data%whizard_ldflags      = WHIZARD_LDFLAGS
os_data%whizard_libtool      = WHIZARD_LIBTOOL
os_data%whizard_modelpath     = WHIZARD_MODELPATH
os_data%whizard_models_libpath = WHIZARD_MODELS_LIBPATH
os_data%whizard_susypath      = WHIZARD_SUSYPATH
os_data%whizard_gmlpath      = WHIZARD_GMLPATH
os_data%whizard_cutspath      = WHIZARD_CUTSPATH
os_data%whizard_texpath       = WHIZARD_TEXPATH
os_data%whizard_testdatapath  = WHIZARD_TESTDATAPATH
end if
os_data%event_analysis_ps = EVENT_ANALYSIS_PS == "yes"
os_data%event_analysis_pdf = EVENT_ANALYSIS_PDF == "yes"
os_data%latex = PRG_LATEX
os_data%gml = os_data%whizard_gmlpath // "/"gml"
os_data%dvips = PRG_DVIPS
os_data%ps2pdf = PRG_PS2PDF
end subroutine os_data_init

```

Write contents

<OS interface: public>+≡

public :: os_data_write

<OS interface: procedures>+≡

```

subroutine os_data_write (os_data, unit)
  type(os_data_t), intent(in) :: os_data
  integer, intent(in), optional :: unit
  integer :: u
  u = output_unit (unit); if (u < 0) return
  write (u, "(A)") "OS data:"
  write (u, *) "use_libtool = ", os_data%use_libtool
  write (u, *) "use_testfiles = ", os_data%use_testfiles
  write (u, *) "fc = ", char (os_data%fc)
  write (u, *) "fcflags = ", char (os_data%fcflags)
  write (u, *) "fcflags_pic = ", char (os_data%fcflags_pic)
  write (u, *) "fc_src_ext = ", char (os_data%fc_src_ext)
  write (u, *) "obj_ext = ", char (os_data%obj_ext)
  write (u, *) "ld = ", char (os_data%ld)
  write (u, *) "ldflags = ", char (os_data%ldflags)
  write (u, *) "ldflags_so = ", char (os_data%ldflags_so)
  write (u, *) "ldflags_static = ", char (os_data%ldflags_static)
  write (u, *) "shlib_ext = ", char (os_data%shlib_ext)
  write (u, *) "whizard_omega_binpath = ", &
    char (os_data%whizard_omega_binpath)
  write (u, *) "whizard_includes = ", char (os_data%whizard_includes)
  write (u, *) "whizard_ldflags = ", char (os_data%whizard_ldflags)

```

```

write (u, *) "whizard_libtool      = ", char (os_data%whizard_libtool)
write (u, *) "whizard_modelpath    = ", &
char (os_data%whizard_modelpath)
write (u, *) "whizard_testdatapath = ", &
char (os_data%whizard_testdatapath)
end subroutine os_data_write

```

2.4.2 Dynamic linking

We define a type that holds the filehandle for a dynamically linked library (shared object), together with functions to open and close the library, and to access functions in this library.

```

<OS interface: public>+≡
public :: dlaccess_t

<OS interface: types>+≡
type :: dlaccess_t
private
type(string_t) :: filename
type(c_ptr) :: handle = c_null_ptr
logical :: is_open = .false.
logical :: has_error = .false.
type(string_t) :: error
end type dlaccess_t

```

The interface to the library functions:

```

<OS interface: interfaces>≡
interface
function dlopen (filename, flag) result (handle) bind(C)
import
character(c_char), dimension(*) :: filename
integer(c_int), value :: flag
type(c_ptr) :: handle
end function dlopen
end interface

interface
function dlclose (handle) result (status) bind(C)
import
type(c_ptr), value :: handle
integer(c_int) :: status
end function dlclose
end interface

interface
function dlderror () result (str) bind(C)
import
type(c_ptr) :: str
end function dlderror
end interface

interface

```

```

function dlsym (handle, symbol) result (fptr) bind(C)
  import
  type(c_ptr), value :: handle
  character(c_char), dimension(*) :: symbol
  type(c_funptr) :: fptr
end function dlsym
end interface

```

This reads an error string and transforms it into a `string_t` object, if an error has occurred. If not, set the error flag to false and return an empty string.

```

<Limits: public parameters>+≡
  integer, parameter, public :: DLERROR_LEN = 160

<OS interface: procedures>+≡
  subroutine read_dlerror (has_error, error)
    logical, intent(out) :: has_error
    type(string_t), intent(out) :: error
    type(c_ptr) :: err_cptr
    character(len=DLERROR_LEN, kind=c_char), pointer :: err_fptr
    integer :: str_end
    err_cptr = dlerror ()
    if (c_associated (err_cptr)) then
      call c_f_pointer (err_cptr, err_fptr)
      has_error = .true.
      str_end = scan (err_fptr, c_null_char)
      if (str_end > 0) then
        error = err_fptr(1:str_end-1)
      else
        error = err_fptr
      end if
    else
      has_error = .false.
      error = ""
    end if
  end subroutine read_dlerror

```

This is the Fortran API. Init/final open and close the file, i.e., load and unload the library.

The flag with value 1 is defined as `RTLD_LAZY`, which means to resolve symbols only when they are used. The opposite would be `RTLD_NOW=2` (resolve everything immediately).

Note that a library can be opened more than once, and that for an ultimate close as many `dlclose` calls as `dlopen` calls are necessary. However, we assume that it is opened and closed only once.

```

<OS interface: public>+≡
  public :: dlaccess_init
  public :: dlaccess_final

<OS interface: procedures>+≡
  subroutine dlaccess_init (dlaccess, prefix, libname, os_data)
    type(dlaccess_t), intent(out) :: dlaccess
    type(string_t), intent(in) :: prefix, libname
    type(os_data_t), intent(in) :: os_data

```

```

type(string_t) :: filename
logical :: exist
dlaccess%filename = libname
filename = prefix // "/" // libname
inquire (file=char(filename), exist=exist)
if (.not. exist) then
    filename = prefix // "/.libs/" // libname
    inquire (file=char(filename), exist=exist)
    if (.not. exist) then
        dlaccess%has_error = .true.
        dlaccess%error = "Library '" // filename // "' not found"
        return
    end if
end if
dlaccess%handle = dlopen (char (filename) // c_null_char, 1_c_int)
dlaccess%is_open = c_associated (dlaccess%handle)
call read_dlerror (dlaccess%has_error, dlaccess%error)
end subroutine dlaccess_init

subroutine dlaccess_final (dlaccess)
type(dlaccess_t), intent(inout) :: dlaccess
integer(c_int) :: status
if (dlaccess%is_open) then
    status = dlclose (dlaccess%handle)
    dlaccess%is_open = .false.
    call read_dlerror (dlaccess%has_error, dlaccess%error)
end if
end subroutine dlaccess_final

```

Return true if an error has occurred.

```

<OS interface: public>+≡
public :: dlaccess_has_error

<OS interface: procedures>+≡
function dlaccess_has_error (dlaccess) result (flag)
    logical :: flag
    type(dlaccess_t), intent(in) :: dlaccess
    flag = dlaccess%has_error
end function dlaccess_has_error

```

Return the error string currently stored in the dlaccess object.

```

<OS interface: public>+≡
public :: dlaccess_get_error

<OS interface: procedures>+≡
function dlaccess_get_error (dlaccess) result (error)
    type(string_t) :: error
    type(dlaccess_t), intent(in) :: dlaccess
    error = dlaccess%error
end function dlaccess_get_error

```

The symbol handler returns the C address of the function with the given string name. (It is a good idea to use `bind(C)` for all functions accessed by this, such

that the name string is well-defined.) Call `c_f_procpointer` to cast this into a Fortran procedure pointer with an appropriate interface.

```

<OS interface: public>+≡
    public :: dlaccess_get_c_funptr

<OS interface: procedures>+≡
    function dlaccess_get_c_funptr (dlaccess, fname) result (fptr)
        type(c_funptr) :: fptr
        type(dlaccess_t), intent(inout) :: dlaccess
        type(string_t), intent(in) :: fname
        fptr = dlsym (dlaccess%handle, char (fname) // c_null_char)
        call read_dLError (dlaccess%has_error, dlaccess%error)
    end function dlaccess_get_c_funptr

```

2.4.3 Predicates

Return true if the library is loaded. In particular, this is false if loading was unsuccessful.

```

<OS interface: public>+≡
    public :: dlaccess_is_open

<OS interface: procedures>+≡
    function dlaccess_is_open (dlaccess) result (flag)
        logical :: flag
        type(dlaccess_t), intent(in) :: dlaccess
        flag = dlaccess%is_open
    end function dlaccess_is_open

```

2.4.4 Shell access

This is the standard system call for executing a shell command, such as invoking a compiler.

In F2008 there will be the equivalent built-in command `execute_command_line`.

```

<OS interface: public>+≡
    public :: os_system_call

<OS interface: procedures>+≡
    subroutine os_system_call (command_string, status, verbose)
        type(string_t), intent(in) :: command_string
        integer, intent(out), optional :: status
        logical, intent(in), optional :: verbose
        logical :: verb
        integer :: stat
        verb = .false.; if (present (verbose)) verb = verbose
        if (verb) &
            call msg_message ("command: " // char (command_string))
        stat = system (char (command_string) // c_null_char)
        if (present (status)) then
            status = stat
        else if (stat /= 0) then
            if (.not. verb) &

```

```

        call msg_message ("command: " // char (command_string))
        write (msg_buffer, "(A,I0)") "Return code = ", stat
        call msg_message ()
        call msg_fatal ("System command returned with nonzero status code")
    end if
end subroutine os_system_call

```

```

<OS interface: interfaces>+≡
interface
    function system (command) result (status) bind(C)
        import
        integer(c_int) :: status
        character(c_char), dimension(*) :: command
    end function system
end interface

```

2.4.5 Fortran compiler and linker

Compile a single module for use in a shared library, but without linking.

```

<OS interface: public>+≡
public :: os_compile_shared

<OS interface: procedures>+≡
subroutine os_compile_shared (src, os_data, status)
    type(string_t), intent(in) :: src
    type(os_data_t), intent(in) :: os_data
    integer, intent(out), optional :: status
    type(string_t) :: command_string
    if (os_data%use_libtool) then
        command_string = &
            os_data%whizard_libtool // " --mode=compile " // &
            os_data%fc // " " // &
            "-c " // &
            os_data%whizard_includes // " " // &
            os_data%fcflags // " " // &
            "" // src // os_data%fc_src_ext // ""
    else
        command_string = &
            os_data%fc // " " // &
            "-c " // &
            os_data%fcflags_pic // " " // &
            os_data%whizard_includes // " " // &
            os_data%fcflags // " " // &
            "" // src // os_data%fc_src_ext // ""
    end if
    call os_system_call (command_string, status)
end subroutine os_compile_shared

```

Link an array of object files to build a shared object library. In the libtool case, we have to specify a `-rpath`, otherwise only a static library can be built. However, since the library is never installed, this `rpath` is irrelevant.

```

<OS interface: public>+≡

```

```

public :: os_link_shared
<OS interface: procedures>+≡
subroutine os_link_shared (objlist, lib, os_data, status)
  type(string_t), intent(in) :: objlist, lib
  type(os_data_t), intent(in) :: os_data
  integer, intent(out), optional :: status
  type(string_t) :: command_string
  if (os_data%use_libtool) then
    command_string = &
      os_data%whizard_libtool // " --mode=link " // &
      os_data%fc // " " // &
      "-module " // &
      "-rpath /usr/local/lib" // " " // &
      os_data%fcflags // " " // &
      os_data%whizard_ldflags // " " // &
      os_data%ldflags // " " // &
      "-o '" // lib // ".la' " // &
      objlist
  else
    command_string = &
      os_data%ld // " " // &
      os_data%ldflags_so // " " // &
      os_data%fcflags // " " // &
      os_data%whizard_ldflags // " " // &
      os_data%ldflags // " " // &
      "-o '" // lib // os_data%shlib_ext // "' " // &
      objlist
  end if
  call os_system_call (command_string, status)
end subroutine os_link_shared

```

Link an array of object files / libraries to build a static executable.

```

<OS interface: public>+≡
public :: os_link_static
<OS interface: procedures>+≡
subroutine os_link_static (objlist, exec_name, os_data, status)
  type(string_t), intent(in) :: objlist, exec_name
  type(os_data_t), intent(in) :: os_data
  integer, intent(out), optional :: status
  type(string_t) :: command_string
  if (os_data%use_libtool) then
    command_string = &
      os_data%whizard_libtool // " --mode=link " // &
      os_data%fc // " " // &
      "-static " // &
      os_data%whizard_ldflags // " " // &
      os_data%ldflags // " " // &
      os_data%ldflags_static // " " // &
      "-o '" // exec_name // "' " // &
      objlist
  else
    command_string = &
      os_data%ld // " " // &

```

```

        os_data%ldflags_so // " " // &
        os_data%whizard_ldflags // " " // &
        os_data%ldflags // " " // &
        os_data%ldflags_static // " " // &
        "-o '" // exec_name // "' " // &
        objlist
    end if
    call os_system_call (command_string, status)
end subroutine os_link_static

```

Determine the name of the shared library to link. If libtool is used, this is encoded in the .la file which resides in place of the library itself.

```

<OS interface: public>+≡
    public :: os_get_dlname
<OS interface: procedures>+≡
    function os_get_dlname (lib, os_data, ignore) result (dlname)
        type(string_t) :: dlname
        type(string_t), intent(in) :: lib
        type(os_data_t), intent(in) :: os_data
        logical, intent(in), optional :: ignore
        type(string_t) :: filename
        type(string_t) :: buffer
        logical :: exist, required
        integer :: u
        u = free_unit ()
        if (present (ignore)) then
            required = .not. ignore
        else
            required = .true.
        end if
        if (os_data%use_libtool) then
            filename = lib // ".la"
            inquire (file=char(filename), exist=exist)
            if (exist) then
                open (unit=u, file=char(filename), action="read", status="old")
                SCAN_LTFEILE: do
                    call get (u, buffer)
                    if (extract (buffer, 1, 7) == "dlname=") then
                        dlname = extract (buffer, 9)
                        dlname = remove (dlname, len (dlname))
                        exit SCAN_LTFEILE
                    end if
                end do SCAN_LTFEILE
                close (u)
            else if (required) then
                call msg_fatal (" Library '" // char (lib) &
                    // "': libtool archive not found")
                dlname = ""
            else
                call msg_message ("[No compiled library '" &
                    // char (lib) // "']")
            end if
        else

```

```

    dlname = lib // os_data%shlib_ext
    inquire (file=char(dlname), exist=exist)
    if (.not. exist) then
        if (required) then
            call msg_fatal (" Library '" // char (lib) &
                // "' not found")
        else
            call msg_message ("[No compiled process library '" &
                // char (lib) // "']")
        end if
    end if
end if
end function os_get_dlname

```

2.4.6 Test

```

<OS interface: public>+≡
    public :: os_interface_test
<OS interface: procedures>+≡
    subroutine os_interface_test ()
        call os_interface_test1 ()
    end subroutine os_interface_test

```

Write a Fortran source file, compile it to a shared library, load it, and execute the contained function.

```

<OS interface: procedures>+≡
    subroutine os_interface_test1 ()
        type(dlaccess_t) :: dlaccess
        type(string_t) :: fname, libname
        type(os_data_t) :: os_data
        type(string_t) :: filename_src, filename_obj
        interface
            function so_test_proc (i) result (j) bind(C)
                import c_int
                integer(c_int), intent(in) :: i
                integer(c_int) :: j
            end function so_test_proc
        end interface
        procedure(so_test_proc), pointer :: so_test => null ()
        type(c_funptr) :: c_fptr
        integer :: u
        integer(c_int) :: i
        call os_data_init (os_data)
        fname = "so_test"
        filename_src = fname // os_data%fc_src_ext
        filename_obj = fname // os_data%obj_ext
        libname = fname // os_data%shlib_ext
        print *, "* write source file 'so_test.f90'"
        u = free_unit ()
        open (unit=u, file=char(filename_src), action="write")
        write (u, "(A)") "function so_test (i) result (j) bind(C)"
    end subroutine os_interface_test1

```

```

write (u, "(A)") " integer(c_int), intent(in) :: i"
write (u, "(A)") " integer(c_int) :: j"
write (u, "(A)") " j = 2 * i"
write (u, "(A)") "end function so_test"
close (u)
print *, "* compile and link as 'so_test.so'"
call os_compile_shared (fname, os_data)
call os_link_shared (filename_obj, fname, os_data)
print *, "* load library 'so_test.so'"
call dlaccess_init (dlaccess, var_str("."), libname, os_data)
if (dlaccess_is_open (dlaccess)) then
  print *, " success"
else
  print *, " failure"
end if
print *, "* load symbol 'so_test'"
c_fptr = dlaccess_get_c_funptr (dlaccess, fname)
if (c_associated (c_fptr)) then
  print *, " success"
else
  print *, " failure"
end if
call c_f_procpointer (c_fptr, so_test)
print *, "* Execute function from 'so_test.so'"
i = 7
print *, " input = ", i
print *, " result =", so_test(i)
print *, "* Cleanup"
call dlaccess_final (dlaccess)
end subroutine os_interface_test1

```

2.5 Accessing the system clock

Fortran 90 provides a standard interface for the system clock. Here, we define a record for storing the information, and higher-level functions for accessing it.

<clock.f90>≡
<File header>

module clock

<Use kinds>

<Use file utils>

<Standard module head>

<Clock: public types>

<Clock: public parameters>

<Clock: public routines>

<Clock: interfaces>

contains

<Clock: subroutines>

end module clock

The format for storing the current date. We want to be able to store time differences, therefore everything is converted to the time difference between now and Jan 01 2000, 0:00. The timezone is ignored.

<Clock: public types>≡

```
type, public :: time
    integer :: day, hour, minute, second, millisecond
end type time
```

The time 0

<Clock: public parameters>≡

```
type(time), public, parameter :: time_null = time (0, 0, 0, 0, 0)
```

Write the time in readable form

<Clock: public routines>≡

```
public :: write
```

<Clock: interfaces>≡

```
interface write
    module procedure time_write_unit
    module procedure time_write_string
end interface
```

The maximal time that can be written is 999 days. No way to write negative times.

<Clock: subroutines>≡

```
subroutine time_write_unit (unit, t, advance, days, milliseconds)
    integer, intent(in) :: unit
    type(time), intent(in) :: t
    character(len=*), intent(in), optional :: advance
    logical, intent(in), optional :: days, milliseconds
    logical :: dd, ms
    character(len=3) :: adv
    if (present (advance)) then
        adv = advance
    else
        adv = "yes"
    end if
    dd = .false.; if (present (days)) dd = days
    ms = .false.; if (present (milliseconds)) ms = milliseconds
    if (dd) then
        write (unit, "(I3,A,I2.2,A,I2.2,A,I2.2)", advance="no") &
            t%day, "d ", t%hour, "h ", t%minute, "m ", t%second
    else
        write (unit, "(I5,A,I2.2,A,I2.2)", advance="no") &
            t%day*24+t%hour, "h ", t%minute, "m ", t%second
    end if
    if (ms) then
        write (unit, "(A,I3.3,A)", advance=trim(adv)) " ", t%millisecond, "s"
    else

```

```

        write (unit, "(A)", advance=trim(adv)) "s"
    end if
end subroutine time_write_unit

```

Write the time to a string. This uses a scratch file for simplicity. Non-advancing output is not possible.

```

<Clock: subroutines>+=
subroutine time_write_string (string, t, days, milliseconds)
character(len=*), intent(out) :: string
type(time), intent(in) :: t
logical, intent(in), optional :: days, milliseconds
integer :: unit
unit = free_unit ()
open (unit, status="scratch", action="readwrite")
call time_write_unit (unit, t, days=days, milliseconds=milliseconds)
rewind (unit)
read (unit, "(A)") string
close (unit)
end subroutine time_write_string

```

Set the current time to number of days, minutes, seconds, milliseconds elapsed since Jan 1 2000. Works for dates after Jan 1 2001 until Dec 31 2099.

```

<Clock: public routines>+=
public :: time_current

<Clock: subroutines>+=
function time_current () result (t)
type(time) :: t
integer, dimension(8) :: values
integer :: year
call date_and_time (values = values)
t%millisecond = values(8)
t%second = values(7)
t%minute = values(6)
t%hour = values(5)
! values(4) is the difference local time - GMT in minutes
t%day = values(3) - 1
select case (values(2))
case ( 1)
case ( 2); t%day = t%day + 31
case ( 3); t%day = t%day + 31 + 28
case ( 4); t%day = t%day + 31 + 28 + 31
case ( 5); t%day = t%day + 31 + 28 + 31 + 30
case ( 6); t%day = t%day + 31 + 28 + 31 + 30 + 31
case ( 7); t%day = t%day + 31 + 28 + 31 + 30 + 31 + 30
case ( 8); t%day = t%day + 31 + 28 + 31 + 30 + 31 + 30 + 31
case ( 9); t%day = t%day + 31 + 28 + 31 + 30 + 31 + 30 + 31 + 31
case (10); t%day = t%day + 31 + 28 + 31 + 30 + 31 + 30 + 31 + 31 + 30
case (11); t%day = t%day + 31 + 28 + 31 + 30 + 31 + 30 + 31 + 31 + 30 + 31
case (12); t%day = t%day + 31 + 28 + 31 + 30 + 31 + 30 + 31 + 31 + 30 + 31 + 30
end select
year = values(1) - 2000
if (year < 1) return

```

```

t%day = t%day + 365 * year + ((year-1) / 4 + 1)
if (mod (year, 4) == 0 .and. values(2) > 2) t%day = t%day + 1
end function time_current

```

Convert from and to seconds

```

<Clock: public routines>+≡
public :: time_to_seconds, time_from_seconds

```

```

<Clock: subroutines>+≡
function time_to_seconds (t) result (s)
  type(time), intent(in) :: t
  real(kind=default) :: s
  s = t%millisecond / 1000._default &
    & + t%second &
    & + 60._default * ( t%minute &
    & + 60._default * ( t%hour &
    & + 24._default * t%day ))
end function time_to_seconds

```

```

<Clock: subroutines>+≡
function time_from_seconds (s) result (t)
  real(kind=default), intent(in) :: s
  type(time) :: t
  t%millisecond = 1000 * mod (s, 1._default)
  t%second = s
  t%minute = t%second / 60
  t%second = mod (t%second, 60)
  t%hour = t%minute / 60
  t%minute = mod (t%minute, 60)
  t%day = t%hour / 24
  t%hour = mod (t%hour, 24)
end function time_from_seconds

```

Add and subtract times

```

<Clock: public routines>+≡
public :: operator(+), operator(-)

```

```

<Clock: interfaces>+≡
interface operator(+)
  module procedure time_add
end interface
interface operator(-)
  module procedure time_subtract
end interface

```

```

<Clock: subroutines>+≡
function time_add (t1, t2) result (t)
  type(time), intent(in) :: t1, t2
  type(time) :: t
  t%millisecond = t1%millisecond + t2%millisecond
  t%second = t1%second + t2%second
  t%minute = t1%minute + t2%minute
  t%hour = t1%hour + t2%hour
  t%day = t1%day + t2%day

```

```

if (t%millisecond > 999) then
    t%second = t%second + t%millisecond / 1000
    t%millisecond = modulo (t%millisecond, 1000)
end if
if (t%second > 59) then
    t%minute = t%minute + t%second / 60
    t%second = modulo (t%second, 60)
end if
if (t%minute > 59) then
    t%hour = t%hour + t%minute / 60
    t%minute = modulo (t%minute, 60)
end if
if (t%hour > 23) then
    t%day = t%day + t%hour / 24
    t%hour = modulo (t%hour, 24)
end if
end function time_add

```

This works for positive difference only, the first time must be later than the second. Otherwise, the number of days is set to zero.

```

⟨Clock: subroutines⟩+≡
function time_subtract (t1, t2) result (t)
    type(time), intent(in) :: t1, t2
    type(time) :: t
    t%millisecond = t1%millisecond - t2%millisecond
    t%second = t1%second - t2%second
    t%minute = t1%minute - t2%minute
    t%hour = t1%hour - t2%hour
    t%day = t1%day - t2%day
    if (t%millisecond < 0) then
        t%second = t%second - 1 + t%millisecond / 1000
        t%millisecond = modulo (t%millisecond, 1000)
    end if
    if (t%second < 0) then
        t%minute = t%minute - 1 + t%second / 60
        t%second = modulo (t%second, 60)
    end if
    if (t%minute < 0) then
        t%hour = t%hour - 1 + t%minute / 60
        t%minute = modulo (t%minute, 60)
    end if
    if (t%hour < 0) then
        t%day = t%day - 1 + t%hour / 24
        t%hour = modulo (t%hour, 24)
    end if
    if (t%day < 0) then
        t%day = 0
    end if
end function time_subtract

```

Compare times

```

⟨Clock: public routines⟩+≡
public :: operator(==)

```

```

public :: operator(<), operator(>)
public :: operator(<=), operator(>=)

<Clock: interfaces>+≡
interface operator(==)
  module procedure time_equal
end interface
interface operator(<)
  module procedure time_less_than
end interface
interface operator(>)
  module procedure time_greater_than
end interface
interface operator(<=)
  module procedure time_less_equal
end interface
interface operator(>=)
  module procedure time_greater_equal
end interface

<Clock: subroutines>+≡
function time_equal (t1, t2) result (equal)
  type(time), intent(in) :: t1, t2
  logical :: equal
  equal = (t1%day==t2%day) .and. (t1%hour==t2%hour) .and. &
    (t1%minute==t2%minute) .and. (t1%second==t2%second) .and. &
    (t1%millisecond==t2%millisecond)
end function time_equal

<Clock: subroutines>+≡
function time_less_than (t1, t2) result (less)
  type(time), intent(in) :: t1, t2
  logical :: less
  if (t1%day < t2%day) then
    less = .true.
  else if (t1%day == t2%day) then
    if (t1%hour < t2%hour) then
      less = .true.
    else if (t1%hour == t2%hour) then
      if (t1%minute < t2%minute) then
        less = .true.
      else if (t1%minute == t2%minute) then
        if (t1%second < t2%second) then
          less = .true.
        else if (t1%second == t2%second) then
          if (t1%millisecond < t2%millisecond) then
            less = .true.
          else
            less = .false.
          end if
        else
          less = .false.
        end if
      else
        less = .false.
      end if
    else
      less = .false.
    end if
  else
    less = .false.
  end if
end function time_less_than

```

```

        end if
    else
        less = .false.
    end if
else
    less = .false.
end if
end function time_less_than

```

```

⟨Clock: subroutines⟩+≡
function time_greater_than (t1, t2) result (greater)
    type(time), intent(in) :: t1, t2
    logical :: greater
    greater = time_less_than (t2, t1)
end function time_greater_than

```

```

⟨Clock: subroutines⟩+≡
function time_less_equal (t1, t2) result (less_equal)
    type(time), intent(in) :: t1, t2
    logical :: less_equal
    less_equal = time_equal (t1, t2) .or. time_less_than (t1, t2)
end function time_less_equal

```

```

⟨Clock: subroutines⟩+≡
function time_greater_equal (t1, t2) result (greater_equal)
    type(time), intent(in) :: t1, t2
    logical :: greater_equal
    greater_equal = time_equal (t1, t2) .or. time_greater_than (t1, t2)
end function time_greater_equal

```

2.6 Hashtables

Hash tables, like lists, are not part of Fortran and must be defined on a per-case basis. In this section we define a module that contains a hash function.

Furthermore, for reference there is a complete framework of hashtable type definitions and access functions. This code is to be replicated where hash tables are used, mutatis mutandis.

```

⟨hashes.f90⟩≡
    ⟨File header⟩

    module hashes

        use kinds, only: i8, i32 !NODEP!

        ⟨Standard module head⟩

        ⟨Hashes: public⟩

        contains

```

```

    <Hashes: procedures>

```

```

end module hashes

```

2.6.1 The hash function

This is the one-at-a-time hash function by Bob Jenkins (from Wikipedia), re-implemented in Fortran. The function works on an array of bytes (8-bit integers), as could be produced by, e.g., the `transfer` function, and returns a single 32-bit integer. For determining the position in a hashtable, one can pick the lower bits of the result as appropriate to the hashtable size (which should be a power of 2). Note that we are working on signed integers, so the interpretation of values differs from the C version. This should not matter in practice, however.

```

    <Hashes: public>≡

```

```

        public :: hash

```

```

    <Hashes: procedures>≡

```

```

        function hash (key)
            integer(i8), dimension(:), intent(in) :: key
            integer(i32) :: hash
            integer :: i
            hash = 0
            do i = 1, size (key)
                hash = hash + key(i)
                hash = hash + ishft (hash, 10)
                hash = ieor (hash, ishft (hash, -6))
            end do
            hash = hash + ishft (hash, 3)
            hash = ieor (hash, ishft (hash, -11))
            hash = hash + ishft (hash, 15)
        end function hash

```

2.6.2 The hash table

We define a generic hashtable type (that depends on the `hash_data_t` type) together with associated methods.

This is a template:

```

    <Hashtables: types>≡

```

```

        type :: hash_data_t
            integer :: i
        end type hash_data_t

```

Associated methods:

```

    <Hashtables: procedures>≡

```

```

        subroutine hash_data_final (data)
            type(hash_data_t), intent(inout) :: data
        end subroutine hash_data_final

        subroutine hash_data_write (data, unit)
            type(hash_data_t), intent(in) :: data

```

```

integer, intent(in), optional :: unit
integer :: u
u = output_unit (unit); if (u < 0) return
write (u, *) data%i
end subroutine hash_data_write

```

Each hash entry stores the unmasked hash value, the key, and points to actual data if present. Note that this could be an allocatable scalar in principle, but making it a pointer avoids deep copy when expanding the hashtable.

```

<Hashtables: types>+≡
type :: hash_entry_t
integer(i32) :: hashval = 0
integer(i8), dimension(:), allocatable :: key
type(hash_data_t), pointer :: data => null ()
end type hash_entry_t

```

The hashtable object holds the actual table, the number of filled entries and the number of entries after which the size should be doubled. The mask is equal to the table size minus one and thus coincides with the upper bound of the table index, which starts at zero.

```

<Hashtables: types>+≡
type :: hashtable_t
integer :: n_entries = 0
real :: fill_ratio = 0
integer :: n_entries_max = 0
integer(i32) :: mask = 0
type(hash_entry_t), dimension(:), allocatable :: entry
end type hashtable_t

```

Initializer: The size has to be a power of two, the fill ratio is a real (machine-default!) number between 0 and 1.

```

<Hashtables: procedures>+≡
subroutine hashtable_init (hashtable, size, fill_ratio)
type(hashtable_t), intent(out) :: hashtable
integer, intent(in) :: size
real, intent(in) :: fill_ratio
hashtable%fill_ratio = fill_ratio
hashtable%n_entries_max = size * fill_ratio
hashtable%mask = size - 1
allocate (hashtable%entry (0:hashtable%mask))
end subroutine hashtable_init

```

Finalizer: This calls a `hash_data_final` subroutine which must exist.

```

<Hashtables: procedures>+≡
subroutine hashtable_final (hashtable)
type(hashtable_t), intent(inout) :: hashtable
integer :: i
do i = 0, hashtable%mask
if (associated (hashtable%entry(i)%data)) then
call hash_data_final (hashtable%entry(i)%data)
deallocate (hashtable%entry(i)%data)
end if
end do

```

```

        end if
    end do
    deallocate (hashtable%entry)
end subroutine hashtable_final

```

Output. Here, we refer to a `hash_data_write` subroutine.

```

<Hashtables: procedures>+=
subroutine hashtable_write (hashtable, unit)
    type(hashtable_t), intent(in) :: hashtable
    integer, intent(in), optional :: unit
    integer :: u, i
    u = output_unit (unit); if (u < 0) return
    do i = 0, hashtable%mask
        if (associated (hashtable%entry(i)%data)) then
            write (u, *) i, "(hash =", hashtable%entry(i)%hashval, ")", &
                hashtable%entry(i)%key
            call hash_data_write (hashtable%entry(i)%data, unit)
        end if
    end do
end subroutine hashtable_write

```

2.6.3 Hashtable insertion

Insert a single entry with the hash value as trial place. If the table is filled, first expand it.

```

<Hashtables: procedures>+=
subroutine hashtable_insert (hashtable, key, data)
    type(hashtable_t), intent(inout) :: hashtable
    integer(i8), dimension(:), intent(in) :: key
    type(hash_data_t), intent(in), target :: data
    integer(i32) :: h
    if (hashtable%n_entries >= hashtable%n_entries_max) &
        call hashtable_expand (hashtable)
    h = hash (key)
    call hashtable_insert_rec (hashtable, h, h, key, data)
end subroutine hashtable_insert

```

We need this auxiliary routine for doubling the size of the hashtable. We rely on the fact that default assignment copies the data pointer, not the data themselves. The temporary array must not be finalized; it is deallocated automatically together with its allocatable components.

```

<Hashtables: procedures>+=
subroutine hashtable_expand (hashtable)
    type(hashtable_t), intent(inout) :: hashtable
    type(hash_entry_t), dimension(:), allocatable :: table_tmp
    integer :: i, s
    allocate (table_tmp (0:hashtable%mask))
    table_tmp = hashtable%entry
    deallocate (hashtable%entry)
    s = 2 * size (table_tmp)
    hashtable%n_entries = 0

```

```

hashtable%n_entries_max = s * hashtable%fill_ratio
hashtable%mask = s - 1
allocate (hashtable%entry (0:hashtable%mask))
do i = 0, ubound (table_tmp, 1)
  if (associated (table_tmp(i)%data)) then
    call hashtable_insert_rec (hashtable, table_tmp(i)%hashval, &
      table_tmp(i)%hashval, table_tmp(i)%key, table_tmp(i)%data)
  end if
end do
end subroutine hashtable_expand

```

Insert a single entry at a trial place h , reduced to the table size. Collision resolution is done simply by choosing the next element, recursively until the place is empty. For bookkeeping, we preserve the original hash value. For a good hash function, there should be no clustering.

Note that if the new key exactly matches an existing key, nothing is done.

```

<Hashtables: procedures> +=
recursive subroutine hashtable_insert_rec (hashtable, h, hashval, key, data)
  type(hashtable_t), intent(inout) :: hashtable
  integer(i32), intent(in) :: h, hashval
  integer(i8), dimension(:), intent(in) :: key
  type(hash_data_t), intent(in), target :: data
  integer(i32) :: i
  i = iand (h, hashtable%mask)
  if (associated (hashtable%entry(i)%data)) then
    if (size (hashtable%entry(i)%key) /= size (key)) then
      call hashtable_insert_rec (hashtable, h + 1, hashval, key, data)
    else if (any (hashtable%entry(i)%key /= key)) then
      call hashtable_insert_rec (hashtable, h + 1, hashval, key, data)
    end if
  else
    hashtable%entry(i)%hashval = hashval
    allocate (hashtable%entry(i)%key (size (key)))
    hashtable%entry(i)%key = key
    hashtable%entry(i)%data => data
    hashtable%n_entries = hashtable%n_entries + 1
  end if
end subroutine hashtable_insert_rec

```

2.6.4 Hashtable lookup

The lookup function has to parallel the insert function. If the place is filled, check if the key matches. Yes: return the pointer; no: increment the hash value and check again.

```

<Hashtables: procedures> +=
function hashtable_lookup (hashtable, key) result (ptr)
  type(hash_data_t), pointer :: ptr
  type(hashtable_t), intent(in) :: hashtable
  integer(i8), dimension(:), intent(in) :: key
  ptr => hashtable_lookup_rec (hashtable, hash (key), key)
end function hashtable_lookup

```

```

(Hashtables: procedures) +=
recursive function hashtable_lookup_rec (hashtable, h, key) result (ptr)
  type(hash_data_t), pointer :: ptr
  type(hashtable_t), intent(in) :: hashtable
  integer(i32), intent(in) :: h
  integer(i8), dimension(:), intent(in) :: key
  integer(i32) :: i
  i = iand (h, hashtable%mask)
  if (associated (hashtable%entry(i)%data)) then
    if (size (hashtable%entry(i)%key) == size (key)) then
      if (all (hashtable%entry(i)%key == key)) then
        ptr => hashtable%entry(i)%data
      else
        ptr => hashtable_lookup_rec (hashtable, h + 1, key)
      end if
    else
      ptr => hashtable_lookup_rec (hashtable, h + 1, key)
    end if
  else
    ptr => null ()
  end if
end function hashtable_lookup_rec

```

```

(Hashtables: public) =
public :: hashtable_test

```

```

(Hashtables: procedures) +=
subroutine hashtable_test ()
  type(hash_data_t), pointer :: data
  type(hashtable_t) :: hashtable
  integer(i8) :: i
  call hashtable_init (hashtable, 16, 0.25)
  do i = 1, 10
    allocate (data)
    data%i = i*i
    call hashtable_insert (hashtable, (/i, i+i/), data)
  end do
  call hashtable_insert (hashtable, (/2_i8, 4_i8/), data)
  call hashtable_write (hashtable)
  data => hashtable_lookup (hashtable, (/5_i8, 10_i8/))
  if (associated (data)) then
    print *, "lookup:", data%i
  else
    print *, "lookup: --"
  end if
  data => hashtable_lookup (hashtable, (/6_i8, 12_i8/))
  if (associated (data)) then
    print *, "lookup:", data%i
  else
    print *, "lookup: --"
  end if
  data => hashtable_lookup (hashtable, (/4_i8, 9_i8/))
  if (associated (data)) then

```

```

        print *, "lookup:", data%i
    else
        print *, "lookup: --"
    end if
    call hashtable_final (hashtable)
end subroutine hashtable_test

```

2.7 Message handling

We are not so ambitious as to do proper exception handling in WHIZARD, but at least it may be useful to have a common interface for diagnostics: Results, messages, warnings, and such. As module variables we keep a buffer where the current message may be written to and a level indicator which tells which messages should be written on screen and which ones should be skipped. Alternatively, a string may be directly supplied to the message routine: this overrides the buffer, avoiding the necessity of formatted I/O in trivial cases.

```

<diagnostics.f90>≡
<File header>

module diagnostics

    use iso_c_binding !NODEP!
    use system_dependencies !NODEP!
    use kinds, only: i64 !NODEP!
    <Use strings>
    use limits, only: BUFFER_SIZE, MAX_ERRORS !NODEP!
    use file_utils !NODEP!

    <Standard module head>

    <Diagnostics: public>

    <Diagnostics: parameters>

    <Diagnostics: types>

    <Diagnostics: variables>

    <Diagnostics: interfaces>

contains

    <Diagnostics: procedures>

end module diagnostics
Diagnostics levels:
<Diagnostics: parameters>≡
    integer, parameter :: &
        & TERMINATE=-2, BUG=-1, &
        & FATAL=1, ERROR=2, WARNING=3, MESSAGE=4, RESULT=5, DEBUG=6

```

```

<Diagnostics: variables>≡
    integer, save :: msg_level = RESULT

```

Mask fatal errors so that are treated as normal errors. Useful for interactive mode.

```

<Diagnostics: public>≡
    public :: mask_fatal_errors

<Diagnostics: variables>+≡
    logical, save :: mask_fatal_errors = .false.

```

How to handle bugs and unmasked fatal errors. Either execute a normal stop statement, or call the C `exit()` function, or try to cause a program crash by dereferencing a null pointer.

```

<Diagnostics: parameters>+≡
    integer, parameter :: TERM_STOP = 0, TERM_EXIT = 1, TERM_CRASH = 2

<Diagnostics: variables>+≡
    integer, save :: handle_fatal_errors = TERM_EXIT

```

Keep track of errors. This might be used for exception handling, later. The counter is incremented only for screen messages, to avoid double counting.

```

<Diagnostics: public>+≡
    public :: msg_count

<Diagnostics: variables>+≡
    integer, dimension(TERMINATE:DEBUG), save :: msg_count = 0

```

Keep a list of all errors and warnings. Since we do not know the number of entries beforehand, we use a linked list.

```

<Diagnostics: types>≡
    type :: string_list
        character(len=BUFFER_SIZE) :: string
        type(string_list), pointer :: next
    end type string_list
    type :: string_list_pointer
        type(string_list), pointer :: first, last
    end type string_list_pointer

<Diagnostics: variables>+≡
    type(string_list_pointer), dimension(TERMINATE:WARNING), save :: &
        & msg_list = string_list_pointer (null(), null())

```

Add the current message buffer contents to the internal list.

```

<Diagnostics: procedures>≡
    subroutine msg_add (level)
        integer, intent(in) :: level
        type(string_list), pointer :: message
        select case (level)
        case (TERMINATE:WARNING)
            allocate (message)
            message%string = msg_buffer
            nullify (message%next)
            if (.not.associated (msg_list(level)%first)) &
                & msg_list(level)%first => message
            if (associated (msg_list(level)%last)) &
                & msg_list(level)%last%next => message

```

```

        msg_list(level)%last => message
        msg_count(level) = msg_count(level) + 1
    end select
end subroutine msg_add

```

Initialization:

```

<Diagnostics: public>+≡
    public :: msg_list_clear

<Diagnostics: procedures>+≡
    subroutine msg_list_clear
        integer :: level
        type(string_list), pointer :: message
        do level = TERMINATE, WARNING
            do while (associated (msg_list(level)%first))
                message => msg_list(level)%first
                msg_list(level)%first => message%next
                deallocate (message)
            end do
            nullify (msg_list(level)%last)
        end do
        msg_count = 0
    end subroutine msg_list_clear

```

Display the summary of errors and warnings (no need to count fatals...)

```

<Diagnostics: public>+≡
    public :: msg_summary

<Diagnostics: procedures>+≡
    subroutine msg_summary (unit)
        integer, intent(in), optional :: unit
        call expect_summary (unit)
1    format (A,1x,I2,1x,A,I2,1x,A)
        if (msg_count(ERROR) > 0 .and. msg_count(WARNING) > 0) then
            write (msg_buffer, 1) "There were", &
                & msg_count(ERROR), "error(s) and", &
                & msg_count(WARNING), "warning(s)."
            call msg_message (unit=unit)
        else if (msg_count(ERROR) > 0) then
            write (msg_buffer, 1) "There were", &
                & msg_count(ERROR), "error(s) and no warnings."
            call msg_message (unit=unit)
        else if (msg_count(WARNING) > 0) then
            write (msg_buffer, 1) "There were no errors and", &
                & msg_count(WARNING), "warning(s)."
            call msg_message (unit=unit)
        end if
    end subroutine msg_summary

```

Print the list of all messages of a given level.

```

<Diagnostics: public>+≡
    public :: msg_listing

```

```

<Diagnostics: procedures>+≡
subroutine msg_listing (level, unit, prefix)
  integer, intent(in) :: level
  integer, intent(in), optional :: unit
  character(len=*), intent(in), optional :: prefix
  type(string_list), pointer :: message
  integer :: u
  u = output_unit (unit); if (u < 0) return
  if (present (unit)) u = unit
  message => msg_list(level)%first
  do while (associated (message))
    if (present (prefix)) then
      write (u, "(A)") prefix // trim (message%string)
    else
      write (u, "(A)") trim (message%string)
    end if
    message => message%next
  end do
end subroutine msg_listing

```

There is a hard limit on the line length which we should export. This buffer size is used both by the message handler and by the lexer below.

```

<Limits: public parameters>+≡
integer, parameter, public :: BUFFER_SIZE = 1000

```

The message buffer:

```

<Diagnostics: public>+≡
public :: msg_buffer

<Diagnostics: variables>+≡
character(len=BUFFER_SIZE), save :: msg_buffer = " "

```

After a message is issued, the buffer should be cleared:

```

<Diagnostics: procedures>+≡
subroutine buffer_clear
  msg_buffer = " "
end subroutine buffer_clear

```

The generic handler for messages. If the unit is omitted (or = 6), the message is written to standard output if the precedence is sufficiently high (as determined by the value of `msg_level`). If the string is omitted, the buffer is used. In any case, the buffer is cleared after printing. In accordance with FORTRAN custom, the first column in the output is left blank. For messages and warnings, an additional exclamation mark and a blank is prepended. Furthermore, each message is appended to the internal message list (without prepending anything).

```

<Diagnostics: procedures>+≡
subroutine message_print (level, string, unit, logfile)
  integer, intent(in) :: level
  character(len=*), intent(in), optional :: string
  integer, intent(in), optional :: unit
  logical, intent(in), optional :: logfile
  type(string_t) :: prep_string
  integer :: lu

```

```

!   integer :: proc_id
!   call mpi90_rank (proc_id)
!   if (proc_id==WHIZARD_ROOT) then
      select case (level)
      case (TERMINATE)
        prep_string = ""
      case (BUG)
        prep_string = "*** WHIZARD bug: "
      case (FATAL)
        prep_string = "*** Fatal error: "
      case (ERROR)
        prep_string = "*** Error: "
      case (WARNING)
        prep_string = "Warning: "
      case (MESSAGE, DEBUG)
        prep_string = "| "
      case default
        prep_string = ""
      end select
      if (present(string)) msg_buffer = string
      lu = log_unit
      if (present(unit)) then
        if (unit/=6) then
          write (unit, "(A,A)") char(prepare_string), trim(msg_buffer)
          lu = -1
        else if (level <= msg_level) then
          print "(A,A)", char(prepare_string), trim(msg_buffer)
          if (unit == log_unit) lu = -1
        end if
      else if (level <= msg_level) then
        print "(A,A)", char(prepare_string), trim(msg_buffer)
      end if
      if (present (logfile)) then
        if (.not. logfile) lu = -1
      end if
      if (lu >= 0) then
        write (lu, "(A,A)") char(prepare_string), trim(msg_buffer)
        flush (lu)
      end if
!   end if
      call msg_add (level)
      call buffer_clear
end subroutine message_print

```

The specific handlers. In the case of fatal errors, bugs (failed assertions) and normal termination execution is stopped. For non-fatal errors a message is printed to standard output if no unit is given. Only if the number of `MAX_ERRORS` errors is reached, we abort the program. There are no further actions in the other cases, but this may change.

```

<Diagnostics: public>+≡
  public :: msg_terminate
  public :: msg_bug, msg_fatal, msg_error, msg_warning
  public :: msg_message, msg_result, msg_debug

```

<Diagnostics: procedures>+≡

```

subroutine msg_terminate (string, unit, quit_code)
  integer, intent(in), optional :: unit
  character(len=*), intent(in), optional :: string
  integer, intent(in), optional :: quit_code
  integer(c_int) :: return_code
  if (present (quit_code)) then
    return_code = quit_code
  else
    return_code = 0
  end if
  call msg_summary (unit)
  if (return_code == 0 .and. expect_failures /= 0) then
    return_code = 5
    call message_print (MESSAGE, &
      "WHIZARD run finished with 'expect' failure(s).", unit)
  else
    call message_print (MESSAGE, "WHIZARD run finished.", unit)
  end if
  call message_print (0, &
    "|=====|", unit)
  call logfile_final ()
  if (return_code /= 0) then
    call exit (return_code)
  else
    stop
  end if
end subroutine msg_terminate

subroutine msg_bug (string, unit)
  integer, intent(in), optional :: unit
  character(len=*), intent(in), optional :: string
  logical, pointer :: crash_ptr => null ()
  call message_print (BUG, string, unit)
  call msg_summary (unit)
  select case (handle_fatal_errors)
  case (TERM_EXIT)
    call message_print (TERMINATE, "WHIZARD run aborted.", unit)
    ! call flush_all ()
    call exit (-1_c_int)
  case (TERM_CRASH)
    print *, "*** Intentional crash ***"
    print *, crash_ptr
  end select
  stop "WHIZARD run aborted."
end subroutine msg_bug

recursive subroutine msg_fatal (string, unit)
  integer, intent(in), optional :: unit
  character(len=*), intent(in), optional :: string
  logical, pointer :: crash_ptr => null ()
  if (mask_fatal_errors) then
    call msg_error (string, unit)
  else

```

```

        call message_print (FATAL, string, unit)
        call msg_summary (unit)
        select case (handle_fatal_errors)
        case (TERM_EXIT)
            call message_print (TERMINATE, "WHIZARD run aborted.", unit)
            ! call flush_all ()
            call exit (1_c_int)
        case (TERM_CRASH)
            print *, "*** Intentional crash ***"
            print *, crash_ptr
        end select
        stop "WHIZARD run aborted."
    end if
end subroutine msg_fatal

subroutine msg_error (string, unit)
    integer, intent(in), optional :: unit
    character(len=*), intent(in), optional :: string
    call message_print (ERROR, string, unit)
    if (msg_count(ERROR) >= MAX_ERRORS) then
        mask_fatal_errors = .false.
        call msg_fatal (" Too many errors encountered.")
!     else if (.not.present(unit) .and. .not.mask_fatal_errors) then
!         call message_print (MESSAGE, "                (WHIZARD run continues)")
    end if
end subroutine msg_error

subroutine msg_warning (string, unit)
    integer, intent(in), optional :: unit
    character(len=*), intent(in), optional :: string
    call message_print (WARNING, string, unit)
end subroutine msg_warning

subroutine msg_message (string, unit, logfile)
    integer, intent(in), optional :: unit
    character(len=*), intent(in), optional :: string
    logical, intent(in), optional :: logfile
    call message_print (MESSAGE, string, unit, logfile)
end subroutine msg_message

subroutine msg_result (string, unit, logfile)
    integer, intent(in), optional :: unit
    character(len=*), intent(in), optional :: string
    logical, intent(in), optional :: logfile
    call message_print (RESULT, string, unit, logfile)
end subroutine msg_result

subroutine msg_debug (string, unit)
    integer, intent(in), optional :: unit
    character(len=*), intent(in), optional :: string
    call message_print (DEBUG, string, unit)
end subroutine msg_debug

```

Interface to the standard clib exit function

<Diagnostics: interfaces>+≡

```
interface
  subroutine exit (status) bind (C)
    use iso_c_binding !NODEP!
    integer(c_int), value :: status
  end subroutine exit
end interface
```

<Limits: public parameters>+≡

```
integer, parameter, public :: MAX_ERRORS = 10
```

Print the WHIZARD banner:

<Diagnostics: public>+≡

```
public :: msg_banner
```

<Diagnostics: procedures>+≡

```
subroutine msg_banner (unit)
  integer, intent(in), optional :: unit
  call message_print (0, &
    "|=====|", unit)
  call message_print (0, &
    "|                                WHIZARD " &
    // WHIZARD_VERSION, unit)
  call message_print (0, &
    "|=====|", unit)
end subroutine msg_banner
```

There are several reasons for terminating the process at the next possible time:

<Diagnostics: parameters>+≡

```
integer, parameter :: &
  & CONTINUE=0, KILLED=1, INTERRUPTED=2, &
  & OS_TIME_EXCEEDED=3, TIME_EXCEEDED=4, &
  & MAX_FILE_COUNT_EXCEEDED=5
```

<Diagnostics: variables>+≡

```
integer, save :: terminate_status = CONTINUE
```

Prepare for termination:

<Diagnostics: public>+≡

```
public :: terminate_soon
```

<Diagnostics: procedures>+≡

```
subroutine terminate_soon (reason)
  integer, intent(in) :: reason
  terminate_status = reason
end subroutine terminate_soon
```

Terminate now if requested. If `n_events` is specified, we are in the simulation pass, and we should display the number of events generated so far.

<Diagnostics: public>+≡

```
public :: terminate_now_maybe
```

```

<Diagnostics: procedures>+≡
subroutine terminate_now_maybe (n_events)
integer(i64), intent(in), optional :: n_events
if (terminate_status /= CONTINUE) then
  if (present (n_events)) then
    write (msg_buffer, "(1x,A,1x,I12,1x,A)" &
      & "Generated", n_events, "events."
    call msg_message
  end if
  select case (terminate_status)
  case (KILLED)
    call msg_terminate (" *** Process killed by external signal: Terminating.")
  case (INTERRUPTED)
    call msg_terminate (" *** Process interrupted by external signal: Terminating.")
  case (OS_TIME_EXCEEDED)
    call msg_terminate (" *** Process received signal SIGXCPU (time exceeded): Terminating.")
  case (TIME_EXCEEDED)
    call msg_terminate (" *** User-defined time limit exceeded: Terminating.")
  case (MAX_FILE_COUNT_EXCEEDED)
    call msg_terminate (" *** User-defined limit for event file count exceeded: Terminating.")
  case default
    call msg_bug (" Process terminates for unknown reason")
  end select
end if
end subroutine terminate_now_maybe

```

2.7.1 Logfile

All screen output should be duplicated in the logfile, unless requested otherwise.

```

<Diagnostics: variables>+≡
integer, save :: log_unit = -1

<Diagnostics: public>+≡
public :: logfile_init

<Diagnostics: procedures>+≡
subroutine logfile_init (filename)
type(string_t), intent(in) :: filename
call msg_message ("Writing log to '" // char (filename) // "'")
log_unit = free_unit ()
open (file = char (filename), unit = log_unit, &
  action = "write", status = "replace")
end subroutine logfile_init

<Diagnostics: public>+≡
public :: logfile_final

<Diagnostics: procedures>+≡
subroutine logfile_final ()
if (log_unit >= 0) then
  close (log_unit)
  log_unit = -1
end if
end subroutine logfile_final

```

This returns the valid logfile unit only if the default is write to screen, and if logfile is not set false.

```

<Diagnostics: public>+≡
    public :: logfile_unit

<Diagnostics: procedures>+≡
    function logfile_unit (unit, logfile)
        integer :: logfile_unit
        integer, intent(in), optional :: unit
        logical, intent(in), optional :: logfile
        if (present (unit)) then
            if (unit == 6) then
                logfile_unit = log_unit
            else
                logfile_unit = -1
            end if
        else if (present (logfile)) then
            if (logfile) then
                logfile_unit = log_unit
            else
                logfile_unit = -1
            end if
        else
            logfile_unit = log_unit
        end if
    end function logfile_unit

```

2.7.2 Checking values

The `expect` function does not just check a value for correctness (actually, it checks if a logical expression is true); it records its result here. If failures are present when the program terminates, the exit code is nonzero.

```

<Diagnostics: variables>+≡
    integer, save :: expect_total = 0
    integer, save :: expect_failures = 0

<Diagnostics: public>+≡
    public :: expect_record

<Diagnostics: procedures>+≡
    subroutine expect_record (success)
        logical, intent(in) :: success
        expect_total = expect_total + 1
        if (.not. success) expect_failures = expect_failures + 1
    end subroutine expect_record

<Diagnostics: public>+≡
    public :: expect_clear

```

```

<Diagnostics: procedures>+≡
  subroutine expect_clear ()
    expect_total = 0
    expect_failures = 0
  end subroutine expect_clear

<Diagnostics: public>+≡
  public :: expect_summary

<Diagnostics: procedures>+≡
  subroutine expect_summary (unit)
    integer, intent(in), optional :: unit
    if (expect_total /= 0) then
      call msg_message ("Summary of value checks:", unit)
      write (msg_buffer, "(2x,A,1x,I0,1x,A,1x,A,1x,I0)" &
        "Failures:", expect_failures, "/", "Total:", expect_total)
      call msg_message (unit=unit)
    end if
  end subroutine expect_summary

```

2.8 Bytes and such

In a few instances we will need the notion of a byte (8-bit) and a word (32 bit), even a 64-bit word. A block of 512 bit is also needed (for MD5).

We rely on integers up to 64 bit being supported by the processor. The main difference to standard integers is the interpretation as unsigned integers.

```

<bytes.f90>≡
  <File header>

  module bytes

    use kinds, only: i8, i32, i64 !NODEP!
    <Use file utils>

    <Standard module head>

    <Bytes: public>

    <Bytes: types>

    <Bytes: parameters>

    <Bytes: interfaces>

    contains

    <Bytes: procedures>

  end module bytes

```

2.8.1 8-bit words: bytes

This is essentially a wrapper around 8-bit integers. The wrapper emphasises their special interpretation as a sequence of bits. However, we interpret bytes as unsigned integers.

```
<Bytes: public>≡  
    public :: byte_t
```

```
<Bytes: types>≡  
    type :: byte_t  
        private  
            integer(i8) :: i  
    end type byte_t
```

```
<Bytes: public>+≡  
    public :: byte_zero
```

```
<Bytes: parameters>≡  
    type(byte_t), parameter :: byte_zero = byte_t (0_i8)
```

Set a byte from 8-bit integer:

```
<Bytes: public>+≡  
    public :: assignment(=)
```

```
<Bytes: interfaces>≡  
    interface assignment(=)  
        module procedure set_byte_from_i8  
    end interface
```

```
<Bytes: procedures>≡  
    subroutine set_byte_from_i8 (b, i)  
        type(byte_t), intent(out) :: b  
        integer(i8), intent(in) :: i  
        b%i = i  
    end subroutine set_byte_from_i8
```

Write a byte in one of two formats: either as a hexadecimal number (two digits, default) or as a decimal number (one to three digits). The decimal version is nontrivial because bytes are unsigned integers. Optionally append a newline.

```
<Bytes: public>+≡  
    public :: byte_write
```

```
<Bytes: interfaces>+≡  
    interface byte_write  
        module procedure byte_write_unit, byte_write_string  
    end interface
```

```
<Bytes: procedures>+≡  
    subroutine byte_write_unit (b, unit, decimal, newline)  
        type(byte_t), intent(in), optional :: b  
        integer, intent(in), optional :: unit  
        logical, intent(in), optional :: decimal, newline  
        logical :: dc, nl  
        type(word32_t) :: w  
        integer :: u
```

```

u = output_unit (unit); if (u < 0) return
dc = .false.; if (present (decimal)) dc = decimal
nl = .false.; if (present (newline)) nl = newline
if (dc) then
    w = b
    write (u, '(I3)', advance='no') w%i
else
    write (u, '(z2.2)', advance='no') b%i
end if
if (nl) write (u, *)
end subroutine byte_write_unit

```

The string version is hex-only

```

<Bytes: procedures>+≡
subroutine byte_write_string (b, s)
    type(byte_t), intent(in) :: b
    character(len=2), intent(inout) :: s
    write (s, '(z2.2)') b%i
end subroutine byte_write_string

```

2.8.2 32-bit words

This is not exactly a 32-bit integer. A word is to be filled with bytes, and it may be partially filled. The filling is done lowest-byte first, highest-byte last. We count the bits, so `fill` should be either 0, 8, 16, 24, or 32. In printing words, we correspondingly distinguish between printing zeros and printing blanks.

```

<Bytes: public>+≡
public :: word32_t

<Bytes: types>+≡
type :: word32_t
    private
    integer(i32) :: i
    integer :: fill = 0
end type word32_t

```

Assignment: the word is filled by inserting a 32-bit integer

```

<Bytes: interfaces>+≡
interface assignment(=)
    module procedure word32_set_from_i32
    module procedure word32_set_from_byte
end interface

<Bytes: procedures>+≡
subroutine word32_set_from_i32 (w, i)
    type(word32_t), intent(out) :: w
    integer(i32), intent(in) :: i
    w%i = i
    w%fill = 32
end subroutine word32_set_from_i32

```

Filling with a 8-bit integer is slightly tricky, because in this interpretation integers are unsigned.

```

<Bytes: procedures>+≡
  subroutine word32_set_from_byte (w, b)
    type(word32_t), intent(out) :: w
    type(byte_t), intent(in) :: b
    if (b%i >= 0_i8) then
      w%i = b%i
    else
      w%i = 2_i32*(huge(0_i8)+1_i32) + b%i
    end if
    w%fill = 32
  end subroutine word32_set_from_byte

```

Check the fill status

```

<Bytes: public>+≡
  public :: word32_empty, word32_filled, word32_fill

<Bytes: procedures>+≡
  function word32_empty (w)
    type(word32_t), intent(in) :: w
    logical :: word32_empty
    word32_empty = (w%fill == 0)
  end function word32_empty

  function word32_filled (w)
    type(word32_t), intent(in) :: w
    logical :: word32_filled
    word32_filled = (w%fill == 32)
  end function word32_filled

  function word32_fill (w)
    type(word32_t), intent(in) :: w
    integer :: word32_fill
    word32_fill = w%fill
  end function word32_fill

```

Partial assignment: append a byte to a partially filled word. (Note: no assignment if the word is filled, so check this before if necessary.)

```

<Bytes: public>+≡
  public :: word32_append_byte

<Bytes: procedures>+≡
  subroutine word32_append_byte (w, b)
    type(word32_t), intent(inout) :: w
    type(byte_t), intent(in) :: b
    type(word32_t) :: w1
    if (.not. word32_filled (w)) then
      w1 = b
      call mvbits (w1%i, 0, 8, w%i, w%fill)
      w%fill = w%fill + 8
    end if
  end subroutine word32_append_byte

```

Extract a byte from a word. The argument *i* is the position, which may be 0, 1, 2, or 3.

```

<Bytes: public>+≡
    public :: byte_from_word32

<Bytes: procedures>+≡
    function byte_from_word32 (w, i) result (b)
        type(word32_t), intent(in) :: w
        integer, intent(in) :: i
        type(byte_t) :: b
        integer(i32) :: j
        j = 0
        if (i >= 0 .and. i*8 < w%fill) then
            call mvbits (w%i, i*8, 8, j, 0)
        end if
        b%i = j
    end function byte_from_word32

```

Write a word to file or STDOUT. We understand words as unsigned integers, therefore we cannot use the built-in routine unchanged. However, we can make use of the existence of 64-bit integers and their output routine.

In hexadecimal format, the default version prints eight hex characters, highest-first. The **bytes** version prints four bytes (two-hex characters), lowest first, with spaces in-between. The decimal bytes version is analogous. In the **bytes** version, missing bytes are printed as whitespace.

```

<Bytes: public>+≡
    public :: word32_write

<Bytes: interfaces>+≡
    interface word32_write
        module procedure word32_write_unit
    end interface

<Bytes: procedures>+≡
    subroutine word32_write_unit (w, unit, bytes, decimal, newline)
        type(word32_t), intent(in) :: w
        integer, intent(in), optional :: unit
        logical, intent(in), optional :: bytes, decimal, newline
        logical :: dc, by, nl
        type(word64_t) :: ww
        integer :: i, u
        u = output_unit (unit); if (u < 0) return
        by = .false.; if (present (bytes)) by = bytes
        dc = .false.; if (present (decimal)) dc = decimal
        nl = .false.; if (present (newline)) nl = newline
        if (by) then
            do i = 0, 3
                if (i>0) write (u, '(1x)', advance='no')
                if (8*i < w%fill) then
                    call byte_write (byte_from_word32 (w, i), unit, decimal=decimal)
                else if (dc) then
                    write (u, '(3x)', advance='no')
                else
                    write (u, '(2x)', advance='no')
                end if
            end do
        end if
    end subroutine word32_write_unit

```

```

        end if
    end do
    else if (dc) then
        ww = w
        write (u, '(I10)', advance='no') ww%i
    else
        select case (w%fill)
        case ( 0)
        case ( 8); write (6, '(1x,z8.2)', advance='no') ibits (w%i, 0, 8)
        case (16); write (6, '(1x,z8.4)', advance='no') ibits (w%i, 0,16)
        case (24); write (6, '(1x,z8.6)', advance='no') ibits (w%i, 0,24)
        case (32); write (6, '(1x,z8.8)', advance='no') ibits (w%i, 0,32)
        end select
    end if
    if (nl) write (u, *)
end subroutine word32_write_unit

```

2.8.3 Operations on 32-bit words

Define the usual logical operations, as well as addition (mod 2^{32}). We assume that all operands are completely filled.

<Bytes: public>+≡
 public :: not, ior, ieor, iand, ishftc, operator(+)

<Bytes: interfaces>+≡
 interface not
 module procedure word_not
 end interface
 interface ior
 module procedure word_or
 end interface
 interface ieor
 module procedure word_eor
 end interface
 interface iand
 module procedure word_and
 end interface
 interface ishftc
 module procedure word_shftc
 end interface
 interface operator(+)
 module procedure word_add
 end interface

<Bytes: procedures>+≡
 function word_not (w1) result (w2)
 type(word32_t), intent(in) :: w1
 type(word32_t) :: w2
 w2 = not (w1%i)
end function word_not

function word_or (w1, w2) result (w3)
 type(word32_t), intent(in) :: w1, w2

```

        type(word32_t) :: w3
        w3 = ior (w1%i, w2%i)
    end function word_or

function word_eor (w1, w2) result (w3)
    type(word32_t), intent(in) :: w1, w2
    type(word32_t) :: w3
    w3 = ieor (w1%i, w2%i)
end function word_eor

function word_and (w1, w2) result (w3)
    type(word32_t), intent(in) :: w1, w2
    type(word32_t) :: w3
    w3 = iand (w1%i, w2%i)
end function word_and

function word_shftc (w1, s) result (w2)
    type(word32_t), intent(in) :: w1
    integer, intent(in) :: s
    type(word32_t) :: w2
    w2 = ishftc (w1%i, s, 32)
end function word_shftc

function word_add (w1, w2) result (w3)
    type(word32_t), intent(in) :: w1, w2
    type(word32_t) :: w3
    w3 = w1%i + w2%i
end function word_add

```

2.8.4 64-bit words

These objects consist of two 32-bit words. They thus can hold integer numbers larger than 2^{32} (to be exact, 2^{31} since FORTRAN integers are signed). The order is low-word, high-word.

```

<Bytes: public>+≡
    public :: word64_t

<Bytes: types>+≡
    type :: word64_t
        private
        integer(i64) :: i
    end type word64_t

```

Set a 64 bit word:

```

<Bytes: interfaces>+≡
    interface assignment(=)
        module procedure word64_set_from_i64
        module procedure word64_set_from_word32
    end interface

<Bytes: procedures>+≡
    subroutine word64_set_from_i64 (ww, i)

```

```

    type(word64_t), intent(out) :: ww
    integer(i64), intent(in) :: i
    ww%i = i
end subroutine word64_set_from_i64

```

Filling with a 32-bit word:

```

<Bytes: procedures>+≡
subroutine word64_set_from_word32 (ww, w)
    type(word64_t), intent(out) :: ww
    type(word32_t), intent(in) :: w
    if (w%i >= 0_i32) then
        ww%i = w%i
    else
        ww%i = 2_i64*(huge(0_i32)+1_i64) + w%i
    end if
end subroutine word64_set_from_word32

```

Extract a byte from a word. The argument *i* is the position, which may be between 0 and 7.

```

<Bytes: public>+≡
public :: byte_from_word64, word32_from_word64

<Bytes: procedures>+≡
function byte_from_word64 (ww, i) result (b)
    type(word64_t), intent(in) :: ww
    integer, intent(in) :: i
    type(byte_t) :: b
    integer(i64) :: j
    j = 0
    if (i >= 0 .and. i*8 < 64) then
        call mvbits (ww%i, i*8, 8, j, 0)
    end if
    b%i = j
end function byte_from_word64

```

Extract a 32-bit word from a 64-bit word. The position is either 0 or 1.

```

<Bytes: procedures>+≡
function word32_from_word64 (ww, i) result (w)
    type(word64_t), intent(in) :: ww
    integer, intent(in) :: i
    type(word32_t) :: w
    integer(i64) :: j
    j = 0
    select case (i)
    case (0); call mvbits (ww%i, 0, 32, j, 0)
    case (1); call mvbits (ww%i, 32, 32, j, 0)
    end select
    w = int (j, kind=i32)
end function word32_from_word64

```

Print a 64-bit word. Decimal version works up to 2^{63} . The `words` version uses the 'word32' printout, separated by two spaces. The low-word is printed first.

The `bytes` version also uses the 'word32' printout. This implies that the lowest byte is first. The default version prints a hexadecimal number without spaces, highest byte first.

```

<Bytes: public>+≡
    public :: word64_write

<Bytes: interfaces>+≡
    interface word64_write
        module procedure word64_write_unit
    end interface

<Bytes: procedures>+≡
    subroutine word64_write_unit (ww, unit, words, bytes, decimal, newline)
        type(word64_t), intent(in) :: ww
        integer, intent(in), optional :: unit
        logical, intent(in), optional :: words, bytes, decimal, newline
        logical :: wo, by, dc, nl
        integer :: u
        u = output_unit (unit); if (u < 0) return
        wo = .false.; if (present (words))    wo = words
        by = .false.; if (present (bytes))    by = bytes
        dc = .false.; if (present (decimal))  dc = decimal
        nl = .false.; if (present (newline))  nl = newline
        if (wo .or. by) then
            call word32_write_unit (word32_from_word64 (ww, 0), unit, by, dc)
            write (u, '(2x)', advance='no')
            call word32_write_unit (word32_from_word64 (ww, 1), unit, by, dc)
        else if (dc) then
            write (u, '(I19)', advance='no') ww%i
        else
            write (u, '(Z16)', advance='no') ww%i
        end if
        if (nl) write (u, *)
    end subroutine word64_write_unit

```

2.9 MD5 Checksums

It is a bit of an overkill, but implementing MD5 checksums allows us to check input/file integrity on the basis of a well-known standard. The building blocks have been introduced in the `bytes` module.

```

<md5.f90>≡
<File header>

module md5

    use kinds, only: i8, i32, i64 !NODEP!
<Use file utils>
    use diagnostics !NODEP!
    use bytes
    use limits, only: LF, EOR, EOF !NODEP!

<Standard module head>

```

```

<MD5: public>

<MD5: types>

<MD5: variables>

<MD5: interfaces>

contains

<MD5: procedures>

end module md5

```

2.9.1 Blocks

A block is a sequence of 16 words (64 bytes or 512 bits). We anticipate that blocks will be linked, so include a pointer to the next block. There is a fill status (word counter), as there is one for each word. The fill status is equal to the number of bytes that are in, so it may be between 0 and 64.

```

<MD5: types>≡
  type :: block_t
    private
      type(word32_t), dimension(0:15) :: w
      type(block_t), pointer :: next => null ()
      integer :: fill = 0
    end type block_t

```

Check if a block is completely filled or empty:

```

<MD5: procedures>≡
  function block_is_empty (b)
    type(block_t), intent(in) :: b
    logical :: block_is_empty
    block_is_empty = (b%fill == 0 .and. word32_empty (b%w(0)))
  end function block_is_empty

  function block_is_filled (b)
    type(block_t), intent(in) :: b
    logical :: block_is_filled
    block_is_filled = (b%fill == 64)
  end function block_is_filled

```

Append a single byte to a block. Works only if the block is not yet filled.

```

<MD5: procedures>+≡
  subroutine block_append_byte (bl, by)
    type(block_t), intent(inout) :: bl
    type(byte_t), intent(in) :: by
    if (.not. block_is_filled (bl)) then
      call word32_append_byte (bl%w(bl%fill/4), by)
      bl%fill = bl%fill + 1
    end if

```

```
end subroutine block_append_byte
```

The printing routine allows for printing as sequences of words or bytes, decimal or hex.

(MD5: interfaces)≡

```
interface block_write
  module procedure block_write_unit
end interface
```

(MD5: procedures)+≡

```
subroutine block_write_unit (b, unit, bytes, decimal)
  type(block_t), intent(in) :: b
  integer, intent(in), optional :: unit
  logical, intent(in), optional :: bytes, decimal
  logical :: by, dc
  integer :: i, u
  u = output_unit (unit); if (u < 0) return
  by = .false.; if (present (bytes)) by = bytes
  dc = .false.; if (present (decimal)) dc = decimal
  do i = 0, b%fill/4 - 1
    call newline_or_blank (u, i, by, dc)
    call word32_write (b%w(i), unit, bytes, decimal)
  end do
  if (.not. block_is_filled (b)) then
    i = b%fill/4
    if (.not. word32_empty (b%w(i))) then
      call newline_or_blank (u, i, by, dc)
      call word32_write (b%w(i), unit, bytes, decimal)
    end if
  end if
  write (u, *)
contains
  subroutine newline_or_blank (u, i, bytes, decimal)
    integer, intent(in) :: u, i
    logical, intent(in) :: bytes, decimal
    if (decimal) then
      select case (i)
        case (0)
        case (2,4,6,8,10,12,14); write (u, *)
        case default
          write (u, '(2x)', advance='no')
        end select
    else if (bytes) then
      select case (i)
        case (0)
        case (4,8,12); write (u, *)
        case default
          write (u, '(2x)', advance='no')
        end select
    else
      if (i == 8) write (u, *)
    end if
  end subroutine newline_or_blank
end subroutine block_write_unit
```

2.9.2 Messages

A message (within this module) is a linked list of blocks.

(MD5: types)+≡

```
type :: message_t
  private
  type(block_t), pointer :: first => null ()
  type(block_t), pointer :: last => null ()
  integer :: n_blocks = 0
end type message_t
```

Clear the message list

(MD5: procedures)+≡

```
subroutine message_clear (m)
  type(message_t), intent(inout) :: m
  type(block_t), pointer :: b
  nullify (m%last)
  do
    b => m%first
    if (.not.(associated (b))) exit
    m%first => b%next
    deallocate (b)
  end do
  m%n_blocks = 0
end subroutine message_clear
```

Append an empty block to the message list

(MD5: procedures)+≡

```
subroutine message_append_new_block (m)
  type(message_t), intent(inout) :: m
  if (associated (m%last)) then
    allocate (m%last%next)
    m%last => m%last%next
    m%n_blocks = m%n_blocks + 1
  else
    allocate (m%first)
    m%last => m%first
    m%n_blocks = 1
  end if
end subroutine message_append_new_block
```

Initialize: clear and allocate the first (empty) block.

(MD5: procedures)+≡

```
subroutine message_init (m)
  type(message_t), intent(inout) :: m
  call message_clear (m)
  call message_append_new_block (m)
end subroutine message_init
```

Append a single byte to a message. If necessary, allocate a new block. If the message is empty, initialize it.

(MD5: procedures)+≡

```
subroutine message_append_byte (m, b)
  type(message_t), intent(inout) :: m
  type(byte_t), intent(in) :: b
  if (.not. associated (m%last)) then
    call message_init (m)
  else if (block_is_filled (m%last)) then
    call message_append_new_block (m)
  end if
  call block_append_byte (m%last, b)
end subroutine message_append_byte
```

Append zero bytes until the current block is filled up to the required position. If we are already beyond that, append a new block and fill that one.

(MD5: procedures)+≡

```
subroutine message_pad_zero (m, i)
  type(message_t), intent(inout) :: m
  integer, intent(in) :: i
  type(block_t), pointer :: b
  integer :: j
  if (associated (m%last)) then
    b => m%last
    if (b%fill > i) then
      do j = b%fill + 1, 64 + i
        call message_append_byte (m, byte_zero)
      end do
    else
      do j = b%fill + 1, i
        call message_append_byte (m, byte_zero)
      end do
    end if
  end if
end subroutine message_pad_zero
```

This returns the number of bits within a message. We need a 64-bit word for the result since it may be more than 2^{31} . This is also required by the MD5 standard.

(MD5: procedures)+≡

```
function message_bits (m) result (length)
  type(message_t), intent(in) :: m
  type(word64_t) :: length
  type(block_t), pointer :: b
  integer(i64) :: n_blocks_filled, n_bytes_extra
  if (m%n_blocks > 0) then
    b => m%last
    if (block_is_filled (b)) then
      n_blocks_filled = m%n_blocks
      n_bytes_extra = 0
    else
      n_blocks_filled = m%n_blocks - 1
    end if
  end if
end function message_bits
```

```

        n_bytes_extra = b%fill
    end if
    length = n_blocks_filled * 512 + n_bytes_extra * 8
else
    length = 0_i64
end if
end function message_bits

```

2.9.3 Message I/O

Append the contents of a string to a message. We first cast the character string into a 8-bit integer array and then append this byte by byte.

(MD5: procedures)+≡

```

subroutine message_append_string (m, s)
    type(message_t), intent(inout) :: m
    character(len=*), intent(in) :: s
    integer(i64) :: i, n_bytes
    integer(i8), dimension(:), allocatable :: buffer
    integer(i8), dimension(1) :: mold
    type(byte_t) :: b
    n_bytes = size (transfer (s, mold))
    allocate (buffer (n_bytes))
    buffer = transfer (s, mold)
    do i = 1, size (buffer)
        b = buffer(i)
        call message_append_byte (m, b)
    end do
    deallocate (buffer)
end subroutine message_append_string

```

Append the contents of a 32-bit integer to a message. We first cast the 32-bit integer into a 8-bit integer array and then append this byte by byte.

(MD5: procedures)+≡

```

subroutine message_append_i32 (m, x)
    type(message_t), intent(inout) :: m
    integer(i32), intent(in) :: x
    integer(i8), dimension(4) :: buffer
    type(byte_t) :: b
    integer :: i
    buffer = transfer (x, buffer, size(buffer))
    do i = 1, size (buffer)
        b = buffer(i)
        call message_append_byte (m, b)
    end do
end subroutine message_append_i32

```

Append one line from file to a message. Include the newline character.

(MD5: procedures)+≡

```

!   subroutine message_append_from_unit (m, u, iostat)
!       type(message_t), intent(inout) :: m
!       integer, intent(in) :: u

```

```

!      integer, intent(out) :: iostat
!      character(len=BUFFER_SIZE) :: buffer
!      read (u, *, iostat=iostat) buffer
!      call message_append_string (m, trim (buffer))
!      call message_append_string (m, LF)
!      end subroutine message_append_from_unit

```

Fill a message from file. (Each line counts as a string.)

<MD5: procedures>+≡

```

!      subroutine message_read_from_file (m, f)
!      type(message_t), intent(inout) :: m
!      character(len=*), intent(in) :: f
!      integer :: u, iostat
!      u = free_unit ()
!      open (file=f, unit=u, action='read')
!      do
!          call message_append_from_unit (m, u, iostat=iostat)
!          if (iostat < 0) exit
!      end do
!      close (u)
!      end subroutine message_read_from_file

```

Write a message. After each block, insert an empty line.

<MD5: interfaces>+≡

```

interface message_write
    module procedure message_write_unit
end interface

```

<MD5: procedures>+≡

```

subroutine message_write_unit (m, unit, bytes, decimal)
    type(message_t), intent(in) :: m
    integer, intent(in), optional :: unit
    logical, intent(in), optional :: bytes, decimal
    type(block_t), pointer :: b
    integer :: u
    u = output_unit (unit); if (u < 0) return
    b => m%first
    if (associated (b)) then
        do
            call block_write_unit (b, unit, bytes, decimal)
            b => b%next
            if (.not. associated (b)) exit
            write (u, *)
        end do
    end if
end subroutine message_write_unit

```

2.9.4 Auxiliary functions

These four functions on three words are defined in the MD5 standard:

<MD5: procedures>+≡

```

function ff (x, y, z)

```

```

    type(word32_t), intent(in) :: x, y, z
    type(word32_t) :: ff
    ff = ior (iand (x, y), iand (not (x), z))
end function ff

function fg (x, y, z)
    type(word32_t), intent(in) :: x, y, z
    type(word32_t) :: fg
    fg = ior (iand (x, z), iand (y, not (z)))
end function fg

function fh (x, y, z)
    type(word32_t), intent(in) :: x, y, z
    type(word32_t) :: fh
    fh = ieor (ieor (x, y), z)
end function fh

function fi (x, y, z)
    type(word32_t), intent(in) :: x, y, z
    type(word32_t) :: fi
    fi = ieor (y, ior (x, not (z)))
end function fi

```

2.9.5 Auxiliary stuff

This defines and initializes the table of transformation constants:

```

<MD5: variables>≡
    type(word32_t), dimension(64), save :: t
    logical, save :: table_initialized = .false.

<MD5: procedures>+≡
    subroutine table_init
        type(word64_t) :: ww
        integer :: i
        if (.not.table_initialized) then
            do i = 1, 64
                ww = int (4294967296d0 * abs (sin (i * 1d0)), kind=i64)
                t(i) = word32_from_word64 (ww, 0)
            end do
            table_initialized = .true.
        end if
    end subroutine table_init

```

This encodes the message digest (4 words) into a 32-character string.

```

<MD5: procedures>+≡
    function digest_string (aa) result (s)
        type(word32_t), dimension (0:3), intent(in) :: aa
        character(len=32) :: s
        integer :: i, j
        do i = 0, 3
            do j = 0, 3
                call byte_write (byte_from_word32 (aa(i), j), s(i*8+j*2+1:i*8+j*2+2))
            end do
        end do
    end function digest_string

```

```

        end do
    end do
end function digest_string

```

2.9.6 MD5 algorithm

Pad the message with a byte x80 and then pad zeros up to a full block minus two words; in these words, insert the message length (before padding) as a 64-bit word, low-word first.

<MD5: procedures>+≡

```

subroutine message_pad (m)
    type(message_t), intent(inout) :: m
    type(word64_t) :: length
    integer(i8), parameter :: ipad = -128 ! z'80'
    type(byte_t) :: b
    integer :: i
    length = message_bits (m)
    b = ipad
    call message_append_byte (m, b)
    call message_pad_zero (m, 56)
    do i = 0, 7
        call message_append_byte (m, byte_from_word64 (length, i))
    end do
end subroutine message_pad

```

Apply a series of transformations onto a state a,b,c,d, where the transform function uses each word of the message together with the predefined words. Finally, encode the state as a 32-character string.

<MD5: procedures>+≡

```

subroutine message_digest (m, s)
    type(message_t), intent(in) :: m
    character(len=32), intent(out) :: s
    integer(i32), parameter :: ia = 1732584193 ! z'67452301'
    integer(i32), parameter :: ib = -271733879 ! z'efcdab89'
    integer(i32), parameter :: ic = -1732584194 ! z'98badcfe'
    integer(i32), parameter :: id = 271733878 ! z'10325476'
    type(word32_t) :: a, b, c, d
    type(word32_t) :: aa, bb, cc, dd
    type(word32_t), dimension(0:15) :: x
    type(block_t), pointer :: bl
    call table_init
    a = ia; b = ib; c = ic; d = id
    bl => m%first
    do
        if (.not.associated (bl)) exit
        x = bl%w
        aa = a; bb = b; cc = c; dd = d
        call transform (ff, a, b, c, d, 0, 7, 1)
        call transform (ff, d, a, b, c, 1, 12, 2)
        call transform (ff, c, d, a, b, 2, 17, 3)
        call transform (ff, b, c, d, a, 3, 22, 4)
    end do

```

```

call transform (ff, a, b, c, d, 4, 7, 5)
call transform (ff, d, a, b, c, 5, 12, 6)
call transform (ff, c, d, a, b, 6, 17, 7)
call transform (ff, b, c, d, a, 7, 22, 8)
call transform (ff, a, b, c, d, 8, 7, 9)
call transform (ff, d, a, b, c, 9, 12, 10)
call transform (ff, c, d, a, b, 10, 17, 11)
call transform (ff, b, c, d, a, 11, 22, 12)
call transform (ff, a, b, c, d, 12, 7, 13)
call transform (ff, d, a, b, c, 13, 12, 14)
call transform (ff, c, d, a, b, 14, 17, 15)
call transform (ff, b, c, d, a, 15, 22, 16)
call transform (fg, a, b, c, d, 1, 5, 17)
call transform (fg, d, a, b, c, 6, 9, 18)
call transform (fg, c, d, a, b, 11, 14, 19)
call transform (fg, b, c, d, a, 0, 20, 20)
call transform (fg, a, b, c, d, 5, 5, 21)
call transform (fg, d, a, b, c, 10, 9, 22)
call transform (fg, c, d, a, b, 15, 14, 23)
call transform (fg, b, c, d, a, 4, 20, 24)
call transform (fg, a, b, c, d, 9, 5, 25)
call transform (fg, d, a, b, c, 14, 9, 26)
call transform (fg, c, d, a, b, 3, 14, 27)
call transform (fg, b, c, d, a, 8, 20, 28)
call transform (fg, a, b, c, d, 13, 5, 29)
call transform (fg, d, a, b, c, 2, 9, 30)
call transform (fg, c, d, a, b, 7, 14, 31)
call transform (fg, b, c, d, a, 12, 20, 32)
call transform (fh, a, b, c, d, 5, 4, 33)
call transform (fh, d, a, b, c, 8, 11, 34)
call transform (fh, c, d, a, b, 11, 16, 35)
call transform (fh, b, c, d, a, 14, 23, 36)
call transform (fh, a, b, c, d, 1, 4, 37)
call transform (fh, d, a, b, c, 4, 11, 38)
call transform (fh, c, d, a, b, 7, 16, 39)
call transform (fh, b, c, d, a, 10, 23, 40)
call transform (fh, a, b, c, d, 13, 4, 41)
call transform (fh, d, a, b, c, 0, 11, 42)
call transform (fh, c, d, a, b, 3, 16, 43)
call transform (fh, b, c, d, a, 6, 23, 44)
call transform (fh, a, b, c, d, 9, 4, 45)
call transform (fh, d, a, b, c, 12, 11, 46)
call transform (fh, c, d, a, b, 15, 16, 47)
call transform (fh, b, c, d, a, 2, 23, 48)
call transform (fi, a, b, c, d, 0, 6, 49)
call transform (fi, d, a, b, c, 7, 10, 50)
call transform (fi, c, d, a, b, 14, 15, 51)
call transform (fi, b, c, d, a, 5, 21, 52)
call transform (fi, a, b, c, d, 12, 6, 53)
call transform (fi, d, a, b, c, 3, 10, 54)
call transform (fi, c, d, a, b, 10, 15, 55)
call transform (fi, b, c, d, a, 1, 21, 56)
call transform (fi, a, b, c, d, 8, 6, 57)
call transform (fi, d, a, b, c, 15, 10, 58)

```

```

        call transform (fi, c, d, a, b, 6, 15, 59)
        call transform (fi, b, c, d, a, 13, 21, 60)
        call transform (fi, a, b, c, d, 4, 6, 61)
        call transform (fi, d, a, b, c, 11, 10, 62)
        call transform (fi, c, d, a, b, 2, 15, 63)
        call transform (fi, b, c, d, a, 9, 21, 64)
        a = a + aa
        b = b + bb
        c = c + cc
        d = d + dd
        bl => bl%next
    end do
    s = digest_string ((/a, b, c, d/))
contains
<MD5: Internal subroutine transform>≡
end subroutine message_digest

```

And this is the actual transformation that depends on one of the previous functions, four words, and three integers. The implicit arguments are **x**, the word from the message to digest, and **t**, the entry in the predefined table.

```

<MD5: Internal subroutine transform>≡
subroutine transform (f, a, b, c, d, k, s, i)
    interface
        function f (x, y, z)
            import word32_t
            type(word32_t), intent(in) :: x, y, z
            type(word32_t) :: f
        end function f
    end interface
    type(word32_t), intent(inout) :: a
    type(word32_t), intent(in) :: b, c, d
    integer, intent(in) :: k, s, i
    a = b + ishftc (a + f(b, c, d) + x(k) + t(i), s)
end subroutine transform

```

2.9.7 User interface

```

<MD5: public>≡
public :: md5sum

<MD5: interfaces>+≡
interface md5sum
    module procedure md5sum_from_string
    module procedure md5sum_from_unit
end interface

```

This function computes the MD5 sum of the input string and returns it as a 32-character string

```

<MD5: procedures>+≡
function md5sum_from_string (s) result (digest)
    character(len=*), intent(in) :: s
    character(len=32) :: digest
    type(message_t) :: m

```

```

    call message_append_string (m, s)
    call message_pad (m)
    call message_digest (m, digest)
    call message_clear (m)
end function md5sum_from_string

```

This funct. reads from unit u (an unformatted sequence of integers) and computes the MD5 sum.

$$\langle MD5: procedures \rangle + \equiv$$

```

function md5sum_from_unit (u) result (digest)
  integer, intent(in) :: u
  character(len=32) :: digest
  type(message_t) :: m
  character :: char
  integer :: iostat
  READ_CHARS: do
    read (u, "(A)", advance="no", iostat=iostat) char
    select case (iostat)
    case (0)
      call message_append_string (m, char)
    case (EOR)
      call message_append_string (m, LF)
    case (EOF)
      exit READ_CHARS
    case default
      call msg_fatal &
        ("Computing MD5 sum: I/O error while reading from scratch file")
    end select
  end do READ_CHARS
  call message_pad (m)
  call message_digest (m, digest)
  call message_clear (m)
end function md5sum_from_unit

```

This funct checks the implementation by computing the checksum of certain strings and comparing them with the known values. If some inconsistency is detected, print a warning.

$$\langle MD5: public \rangle + \equiv$$

```
public :: md5_test
```

$$\langle MD5: procedures \rangle + \equiv$$
[illegible]

```

character(32), dimension(n) :: result
data result(1) /"D41D8CD98F00B204E9800998ECF8427E"/
data result(2) /"0CC175B9C0F1B6A831C399E269772661"/
data result(3) /"900150983CD24FB0D6963F7D28E17F72"/
data result(4) /"F96B697D7CB7938D525A2F31AAF161D0"/
data result(5) /"C3FCD3D76192E4007DFB496CCA67E13B"/
data result(6) /"D174AB98D277D9F5A5611C2C9F419D9F"/
data result(7) /"57EDF4A22BE3C955AC49DA2E2107B67A"/
do i = 1, n
  call msg_message ("string = " // ' '// trim (teststring(i)) // ' ')
  s = md5sum (trim (teststring(i)))
  call msg_message ("md5sum = " // trim (s))
  if (s == result(i)) then
    call msg_message ("-> ok")
  else
    call msg_message ("expect = " // trim (result(i)))
    call msg_bug (" MD5 sum self-test failed")
  end if
end do
call msg_message ("MD5 sum self-test successful.")
end subroutine md5_test

```

2.10 Permutations

<permutations.f90>≡
<File header>

module permutations

use kinds, only: TC !NODEP!

<Standard module head>

<Permutations: public>

<Permutations: types>

<Permutations: interfaces>

contains

<Permutations: procedures>

end module permutations

2.10.1 Permutations

A permutation is an array of integers. Each integer between one and `size` should occur exactly once.

<Permutations: public>≡
 public :: permutation_t

```

<Permutations: types>≡
  type :: permutation_t
  private
    integer, dimension(:), allocatable :: p
  end type permutation_t

```

Initialize with the identity permutation.

```

<Permutations: public>+≡
  public :: permutation_init
  public :: permutation_final

<Permutations: procedures>≡
  elemental subroutine permutation_init (p, size)
    type(permutation_t), intent(inout) :: p
    integer, intent(in) :: size
    integer :: i
    allocate (p%p (size))
    forall (i = 1:size)
      p%p(i) = i
    end forall
  end subroutine permutation_init

  elemental subroutine permutation_final (p)
    type(permutation_t), intent(inout) :: p
    deallocate (p%p)
  end subroutine permutation_final

```

I/O:

```

<Permutations: public>+≡
  public :: permutation_write

<Permutations: procedures>+≡
  subroutine permutation_write (p, u)
    type(permutation_t), intent (in) :: p
    integer, intent(in) :: u
    integer :: i
    do i = 1, size (p%p)
      if (size (p%p) < 10) then
        write (u,"(1x,I1)", advance="no") p%p(i)
      else
        write (u,"(1x,I3)", advance="no") p%p(i)
      end if
    end do
    write (u, *)
  end subroutine permutation_write

```

Administration:

```

<Permutations: public>+≡
  public :: permutation_size

<Permutations: procedures>+≡
  elemental function permutation_size (perm) result (s)
    type(permutation_t), intent(in) :: perm
    integer :: s

```

```

    s = size (perm%p)
end function permutation_size

```

Extract an entry in a permutation.

```

⟨Permutations: public⟩+≡
    public :: permute

⟨Permutations: procedures⟩+≡
    elemental function permute (i, p) result (j)
        integer, intent(in) :: i
        type(permutation_t), intent(in) :: p
        integer :: j
        if (i > 0 .and. i <= size (p%p)) then
            j = p%p(i)
        else
            j = 0
        end if
    end function permute

```

Check whether a permutation is valid: Each integer in the range occurs exactly once.

```

⟨Permutations: public⟩+≡
    public :: permutation_ok

⟨Permutations: procedures⟩+≡
    elemental function permutation_ok (perm) result (ok)
        type(permutation_t), intent(in) :: perm
        logical :: ok
        integer :: i
        logical, dimension(:), allocatable :: set
        ok = .true.
        allocate (set (size (perm%p)))
        set = .false.
        do i = 1, size (perm%p)
            ok = (perm%p(i) > 0 .and. perm%p(i) <= size (perm%p))
            if (.not.ok) return
            set(perm%p(i)) = .true.
        end do
        ok = all (set)
    end function permutation_ok

```

Find the permutation that transforms the second array into the first one. We assume that this is possible and unique and all bounds are set correctly.

This cannot be elemental.

```

⟨Permutations: public⟩+≡
    public :: permutation_find

⟨Permutations: procedures⟩+≡
    subroutine permutation_find (perm, a1, a2)
        type(permutation_t), intent(inout) :: perm
        integer, dimension(:), intent(in) :: a1, a2
        integer :: i, j
        if (allocated (perm%p)) deallocate (perm%p)
    end subroutine permutation_find

```

```

allocate (perm%p (size (a1)))
do i = 1, size (a1)
  do j = 1, size (a2)
    if (a1(i) == a2(j)) then
      perm%p(i) = j
      exit
    end if
    perm%p(i) = 0
  end do
end do
end subroutine permutation_find

```

Find all permutations that transform an array of integers into itself. The resulting permutation list is allocated with the correct length and filled.

The first step is to count the number of different entries in `code`. Next, we scan `code` again and assign a mask to each different entry, true for all identical entries. Finally, we recursively permute the identity for each possible mask.

The permutation is done as follows: A list of all permutations of the initial one with respect to the current mask is generated, then the permutations are generated in turn for each permutation in this list with the next mask. The result is always stored back into the main list, starting from the end of the current list.

```

(Permutations: public)+≡
  public :: permutation_array_make

(Permutations: procedures)+≡
  subroutine permutation_array_make (pa, code)
    type(permutation_t), dimension(:), allocatable, intent(out) :: pa
    integer, dimension(:), intent(in) :: code
    logical, dimension(size(code)) :: mask
    logical, dimension(:,:), allocatable :: imask
    integer, dimension(:), allocatable :: n_i
    type(permutation_t) :: p_init
    type(permutation_t), dimension(:), allocatable :: p_tmp
    integer :: psize, i, j, k, n_different, n, nn_k
    psize = size (code)
    mask = .true.
    n_different = 0
    do i=1, psize
      if (mask(i)) then
        n_different = n_different + 1
        mask = mask .and. (code /= code(i))
      end if
    end do
    allocate (imask(psize, n_different), n_i(n_different))
    mask = .true.
    k = 0
    do i=1, psize
      if (mask(i)) then
        k = k + 1
        imask(:,k) = (code == code(i))
        n_i(k) = factorial (count(imask(:,k)))
        mask = mask .and. (code /= code(i))
      end if
    end do
  end subroutine permutation_array_make

```

```

        end if
    end do
    n = product (n_i)
    allocate (pa (n))
    call permutation_init (p_init, psize)
    pa(1) = p_init
    nn_k = 1
    do k = 1, n_different
        allocate (p_tmp (n_i(k)))
        do i = nn_k, 1, -1
            call permutation_array_with_mask (p_tmp, imask(:,k), pa(i))
            do j = n_i(k), 1, -1
                pa((i-1)*n_i(k) + j) = p_tmp(j)
            end do
        end do
        deallocate (p_tmp)
        nn_k = nn_k * n_i(k)
    end do
    call permutation_final (p_init)
    deallocate (imask, n_i)
end subroutine permutation_array_make

```

Make a list of permutations of the elements marked true in the `mask` array. The final permutation list must be allocated with the correct length ($n!$). The third argument is the initial permutation to start with, which must have the same length as the `mask` array (this is not checked).

(Permutations: procedures)+≡

```

subroutine permutation_array_with_mask (pa, mask, p_init)
    type(permutation_t), dimension(:), intent(inout) :: pa
    logical, dimension(:), intent(in) :: mask
    type(permutation_t), intent(in) :: p_init
    integer :: plen
    integer :: i, ii, j, fac_i, k, x
    integer, dimension(:), allocatable :: index
    plen = size (pa)
    allocate (index(count(mask)))
    ii = 0
    do i = 1, size (mask)
        if (mask(i)) then
            ii = ii + 1
            index(ii) = i
        end if
    end do
    pa = p_init
    ii = 0
    fac_i = 1
    do i = 1, size (mask)
        if (mask(i)) then
            ii = ii + 1
            fac_i = fac_i * ii
            x = permute (i, p_init)
            do j = 1, plen
                k = ii - mod (((j-1)*fac_i)/plen, ii)

```

```

        call insert (pa(j), x, k, ii, index)
    end do
end if
end do
deallocate (index)
contains
subroutine insert (p, x, k, n, index)
    type(permutation_t), intent(inout) :: p
    integer, intent(in) :: x, k, n
    integer, dimension(:), intent(in) :: index
    integer :: i
    do i = n, k+1, -1
        p%p(index(i)) = p%p(index(i-1))
    end do
    p%p(index(k)) = x
end subroutine insert
end subroutine permutation_array_with_mask

```

The factorial function is needed for pre-determining the number of permutations that will be generated:

```

<Permutations: procedures>+≡
function factorial (n) result (f)
    integer, intent(in) :: n
    integer :: f
    integer :: i
    f = 1
    do i=2, abs(n)
        f = f*i
    end do
end function factorial

```

2.10.2 Operations on binary codes

Binary codes are needed for phase-space trees. Since the permutation function uses permutations, and no other special type is involved, we put the functions here.

This is needed for phase space trees: permute bits in a tree binary code. If no permutation is given, leave as is. (We may want to access the permutation directly here if this is efficiency-critical.)

```

<Permutations: public>+≡
public :: tc_permute

<Permutations: procedures>+≡
function tc_permute (k, perm, mask_in) result (pk)
    integer(TC), intent(in) :: k, mask_in
    type(permutation_t), intent(in) :: perm
    integer(TC) :: pk
    integer :: i
    pk = iand (k, mask_in)
    do i = 1, size (perm%p)
!       if (btest(k,i-1)) pk = ibset (pk, permute (perm,i) - 1)
        if (btest(k,i-1)) pk = ibset (pk, perm%p(i)-1)
    end do
end function tc_permute

```

```

        end do
    end function tc_permute

```

This routine returns the number of set bits in the tree code value `k`. Hence, it is the number of externals connected to the current line. If `mask` is present, the complement of the tree code is also considered, and the smaller number is returned. This gives the true distance from the external states, taking into account the initial particles. The complement number is increased by one, since for a scattering diagram the vertex with the sum of all final-state codes is still one point apart from the initial particles.

```

<Permutations: public>+=
    public :: tc_decay_level

<Permutations: interfaces>=
    interface tc_decay_level
        module procedure decay_level_simple
        module procedure decay_level_complement
    end interface

<Permutations: procedures>+=
    function decay_level_complement (k, mask) result (l)
        integer(TC), intent(in) :: k, mask
        integer :: l
        l = min (decay_level_simple (k), &
                & decay_level_simple (ieor (k, mask)) + 1)
    end function decay_level_complement

    function decay_level_simple (k) result(l)
        integer(TC), intent(in) :: k
        integer :: l
        integer :: i
        l = 0
        do i=0, bit_size(k)-1
            if (btest(k,i)) l = l+1
        end do
    end function decay_level_simple

```

2.11 Sorting

This small module provides functions for sorting integer or real arrays.

```

<sorting.f90>=
    <File header>

    module sorting

    <Use kinds>

    <Standard module head>

    <Sorting: public>

```

<Sorting: interfaces>

contains

<Sorting: procedures>

end module sorting

2.11.1 Implementation

The `sort` function returns, for a given integer or real array, the array sorted by increasing value. The current implementation is *mergesort*, which has $O(n \ln n)$ behavior in all cases, and is stable for elements of equal value.

<Sorting: public>≡

public :: sort

<Sorting: interfaces>≡

interface sort

module procedure sort_int

module procedure sort_real

end interface

The body is identical, just the interface differs.

<Sorting: procedures>≡

function sort_int (val_in) result (val)

integer, dimension(:), intent(in) :: val_in

integer, dimension(size(val_in)) :: val

<Sorting: sort>

end function sort_int

function sort_real (val_in) result (val)

real(default), dimension(:), intent(in) :: val_in

real(default), dimension(size(val_in)) :: val

<Sorting: sort>

end function sort_real

<Sorting: sort>≡

val = val_in(order (val))

The `order` function returns, for a given integer or real array, the array of indices of the elements sorted by increasing value.

<Sorting: public>+≡

public :: order

<Sorting: interfaces>+≡

interface order

module procedure order_int

module procedure order_real

end interface

```

<Sorting: procedures>+≡
  function order_int (val) result (idx)
    integer, dimension(:), intent(in) :: val
    integer, dimension(size(val)) :: idx
    <Sorting: order>
  end function order_int

  function order_real (val) result (idx)
    real(default), dimension(:), intent(in) :: val
    integer, dimension(size(val)) :: idx
    <Sorting: order>
  end function order_real

```

We start by individual elements, merge them to pairs, merge those to four-element subarrays, and so on. The last subarray can extend only up to the original array bound, of course, and the second of the subarrays to merge should contain at least one element.

```

<Sorting: order>≡
  integer :: n, i, s, b1, b2, e1, e2
  n = size (idx)
  forall (i = 1:n)
    idx(i) = i
  end forall
  s = 1
  do while (s < n)
    do b1 = 1, n-s, 2*s
      b2 = b1 + s
      e1 = b2 - 1
      e2 = min (e1 + s, n)
      call merge (idx(b1:e2), idx(b1:e1), idx(b2:e2), val)
    end do
    s = 2 * s
  end do

```

The merging step does the actual sorting. We take two sorted array sections and merge them to a sorted result array. We are working on the indices, and comparing is done by taking the associated `val` which is real or integer.

```

<Sorting: interfaces>+≡
  interface merge
    module procedure merge_int
    module procedure merge_real
  end interface

<Sorting: procedures>+≡
  subroutine merge_int (res, src1, src2, val)
    integer, dimension(:), intent(out) :: res
    integer, dimension(:), intent(in) :: src1, src2
    integer, dimension(:), intent(in) :: val
    integer, dimension(size(res)) :: tmp
    <Sorting: merge>
  end subroutine merge_int

  subroutine merge_real (res, src1, src2, val)

```

```

integer, dimension(:), intent(out) :: res
integer, dimension(:), intent(in) :: src1, src2
real(default), dimension(:), intent(in) :: val
integer, dimension(size(res)) :: tmp
<Sorting: merge>
end subroutine merge_real

```

```

<Sorting: merge>≡
integer :: i1, i2, i
i1 = 1
i2 = 1
do i = 1, size (tmp)
  if (val(src1(i1)) <= val(src2(i2))) then
    tmp(i) = src1(i1); i1 = i1 + 1
    if (i1 > size (src1)) then
      tmp(i+1:) = src2(i2:)
      exit
    end if
  else
    tmp(i) = src2(i2); i2 = i2 + 1
    if (i2 > size (src2)) then
      tmp(i+1:) = src1(i1:)
      exit
    end if
  end if
end do
res = tmp

```

2.11.2 Test

```

<Sorting: public>+≡
public :: sorting_test

<Sorting: procedures>+≡
subroutine sorting_test ()
  integer, parameter :: NMAX = 10
  real(default), dimension(NMAX) :: rval
  integer, dimension(NMAX) :: ival
  real, dimension(NMAX) :: harvest
  integer :: i
  print *, "Sorting real values:"
  do i = 1, NMAX
    print *
    call random_number (harvest(:i))
    rval(:i) = harvest(:i)
    print "(10(1x,F7.4))", rval(:i)
    rval(:i) = sort (rval(:i))
    print "(10(1x,F7.4))", rval(:i)
  end do
  print *
  print *, "Sorting integer values:"
  do i = 1, NMAX
    print *
    call random_number (harvest(:i))

```

```
        ival(:i) = harvest(:i) * NMAX * 2
        print "(10(1x,I2))", ival(:i)
        ival(:i) = sort (ival(:i))
        print "(10(1x,I2))", ival(:i)
    end do
end subroutine sorting_test
```

Chapter 3

Text handling

WHIZARD has to handle complex structures in input (and output) data. Doing this in a generic and transparent way requires a generic lexer and parser. The necessary modules are implemented here:

ifiles Implementation of line-oriented internal files in a more flexible way (linked lists of variable-length strings) than the Fortran builtin features.

lexers Read text and transform it into a token stream.

syntax_rules Define the rules for interpreting tokens, to be used by the parser.

parser Categorize tokens (keyword, string, number etc.) and use a set of syntax rules to transform the input into a parse tree.

3.1 Internal files

The internal files introduced here (`ifile`) are a replacement for the built-in internal files, which are fixed-size arrays of fixed-length character strings. The `ifile` type is a doubly-linked list of variable-length character strings with line numbers.

```
<ifiles.f90>≡  
  <File header>  
  
  module ifiles  
  
    <Use strings>  
    <Use file utils>  
    use limits, only: EOF !NODEP!  
  
    <Standard module head>  
  
    <Ifiles: public>  
  
    <Ifiles: types>  
  
    <Ifiles: interfaces>  
  
    contains  
  
    <Ifiles: subroutines>  
  
  end module ifiles
```

3.1.1 iostat codes

These are not specified in the standard, but apparently universal to current compilers (checked for ifort, gfortran, g95, f95):

```
<Limits: public parameters>+≡  
  integer, parameter, public :: EOF = -1, EOR = -2
```

3.1.2 The line type

The line entry type is for internal use, it is the list entry to be collected in an `ifile` object.

```
<Ifiles: types>≡  
  type :: line_entry_t  
    private  
    type(line_entry_t), pointer :: previous => null ()  
    type(line_entry_t), pointer :: next => null ()  
    type(string_t) :: string  
    integer :: index  
  end type line_entry_t
```

Create a new list entry, given a varying string as input. The line number and pointers are not set, these make sense only within an `ifile`.

```
<Ifiles: subroutines>+≡
subroutine line_entry_create (line, string)
  type(line_entry_t), pointer :: line
  type(string_t), intent(in) :: string
  allocate (line)
  line%string = string
end subroutine line_entry_create
```

Destroy a single list entry: Since the pointer components should not be deallocated explicitly, just deallocate the object itself.

```
<Ifiles: subroutines>+≡
subroutine line_entry_destroy (line)
  type(line_entry_t), pointer :: line
  deallocate (line)
end subroutine line_entry_destroy
```

3.1.3 The ifile type

The internal file is a linked list of line entries.

```
<Ifiles: public>≡
public :: ifile_t

<Ifiles: types>+≡
type :: ifile_t
  private
  type(line_entry_t), pointer :: first => null ()
  type(line_entry_t), pointer :: last => null ()
  integer :: n_lines = 0
end type ifile_t
```

We need no explicit initializer, but a routine which recursively deallocates the contents may be appropriate. After this, existing line pointers may become undefined, so they should be nullified before the file is destroyed.

```
<Ifiles: public>+≡
public :: ifile_clear

<Ifiles: subroutines>+≡
subroutine ifile_clear (ifile)
  type(ifile_t), intent(inout) :: ifile
  type(line_entry_t), pointer :: current
  do while (associated (ifile%first))
    current => ifile%first
    ifile%first => current%next
    call line_entry_destroy (current)
  end do
  nullify (ifile%last)
  ifile%n_lines = 0
end subroutine ifile_clear
```

The finalizer is just an alias for the above.

```

<Ifiles: public>+≡
    public :: ifile_final

<Ifiles: interfaces>≡
    interface ifile_final
        module procedure ifile_clear
    end interface

```

3.1.4 I/O on ifiles

Fill an ifile from an ordinary external file, i.e., I/O unit. If the ifile is not empty, the old contents will be destroyed. We can read a fixed-length character string, an ISO varying string, an ordinary internal file (character-string array), or from an external unit. In the latter case, lines are appended until EOF is reached. Finally, there is a variant which reads from another ifile, effectively copying it.

```

<Ifiles: public>+≡
    public :: ifile_read

<Ifiles: interfaces>+≡
    interface ifile_read
        module procedure ifile_read_from_string
        module procedure ifile_read_from_char
        module procedure ifile_read_from_unit
        module procedure ifile_read_from_char_array
        module procedure ifile_read_from_ifile
    end interface

<Ifiles: subroutines>+≡
    subroutine ifile_read_from_string (ifile, string)
        type(ifile_t), intent(inout) :: ifile
        type(string_t), intent(in) :: string
        call ifile_clear (ifile)
        call ifile_append (ifile, string)
    end subroutine ifile_read_from_string

    subroutine ifile_read_from_char (ifile, char)
        type(ifile_t), intent(inout) :: ifile
        character(*), intent(in) :: char
        call ifile_clear (ifile)
        call ifile_append (ifile, char)
    end subroutine ifile_read_from_char

    subroutine ifile_read_from_char_array (ifile, char)
        type(ifile_t), intent(inout) :: ifile
        character(*), dimension(:), intent(in) :: char
        call ifile_clear (ifile)
        call ifile_append (ifile, char)
    end subroutine ifile_read_from_char_array

    subroutine ifile_read_from_unit (ifile, unit, iostat)
        type(ifile_t), intent(inout) :: ifile
        integer, intent(in) :: unit
        integer, intent(out), optional :: iostat

```

```

        call ifile_clear (ifile)
        call ifile_append (ifile, unit, iostat)
    end subroutine ifile_read_from_unit

subroutine ifile_read_from_ifile (ifile, ifile_in)
    type(ifile_t), intent(inout) :: ifile
    type(ifile_t), intent(in) :: ifile_in
    call ifile_clear (ifile)
    call ifile_append (ifile, ifile_in)
end subroutine ifile_read_from_ifile

```

Append to an ifile. The same as reading, but without resetting the ifile. In addition, there is a routine for appending a whole ifile.

```

<Ifiles: public>+≡
    public :: ifile_append

<Ifiles: interfaces>+≡
    interface ifile_append
        module procedure ifile_append_from_string
        module procedure ifile_append_from_char
        module procedure ifile_append_from_unit
        module procedure ifile_append_from_char_array
        module procedure ifile_append_from_ifile
    end interface

<Ifiles: subroutines>+≡
subroutine ifile_append_from_string (ifile, string)
    type(ifile_t), intent(inout) :: ifile
    type(string_t), intent(in) :: string
    type(line_entry_t), pointer :: current
    call line_entry_create (current, string)
    current%index = ifile%n_lines + 1
    if (associated (ifile%last)) then
        current%previous => ifile%last
        ifile%last%next => current
    else
        ifile%first => current
    end if
    ifile%last => current
    ifile%n_lines = current%index
end subroutine ifile_append_from_string

subroutine ifile_append_from_char (ifile, char)
    type(ifile_t), intent(inout) :: ifile
    character(*), intent(in) :: char
    call ifile_append_from_string (ifile, var_str (trim (char)))
end subroutine ifile_append_from_char

subroutine ifile_append_from_char_array (ifile, char)
    type(ifile_t), intent(inout) :: ifile
    character(*), dimension(:), intent(in) :: char
    integer :: i
    do i = 1, size (char)
        call ifile_append_from_string (ifile, var_str (trim (char(i))))
    end do

```

```

end subroutine ifile_append_from_char_array

subroutine ifile_append_from_unit (ifile, unit, iostat)
  type(ifile_t), intent(inout) :: ifile
  integer, intent(in) :: unit
  integer, intent(out), optional :: iostat
  type(string_t) :: buffer
  integer :: ios
  ios = 0
  READ_LOOP: do
    call get (unit, buffer, iostat = ios)
    if (ios == EOF .or. ios > 0) exit READ_LOOP
    call ifile_append_from_string (ifile, buffer)
  end do READ_LOOP
  if (present (iostat)) then
    iostat = ios
  else if (ios > 0) then
    call get (unit, buffer) ! trigger error again
  end if
end subroutine ifile_append_from_unit

subroutine ifile_append_from_ifile (ifile, ifile_in)
  type(ifile_t), intent(inout) :: ifile
  type(ifile_t), intent(in) :: ifile_in
  type(line_entry_t), pointer :: current
  current => ifile_in%first
  do while (associated (current))
    call ifile_append_from_string (ifile, current%string)
    current => current%next
  end do
end subroutine ifile_append_from_ifile

```

Write the ifile contents to an external unit

```

<Ifiles: public>+≡
  public :: ifile_write

<Ifiles: subroutines>+≡
  subroutine ifile_write (ifile, unit, iostat)
    type(ifile_t), intent(in) :: ifile
    integer, intent(in), optional :: unit
    integer, intent(out), optional :: iostat
    integer :: u
    type(line_entry_t), pointer :: current
    u = output_unit (unit); if (u < 0) return
    current => ifile%first
    do while (associated (current))
      call put_line (u, current%string, iostat)
      current => current%next
    end do
  end subroutine ifile_write

```

Convert the ifile to an array of strings, which is allocated by this function:

```

<Ifiles: public>+≡
  public :: ifile_to_string_array

```

```

<Ifiles: subroutines>+≡
subroutine ifile_to_string_array (ifile, string)
  type(ifile_t), intent(in) :: ifile
  type(string_t), dimension(:), intent(inout), allocatable :: string
  type(line_entry_t), pointer :: current
  integer :: i
  allocate (string (ifile_get_length (ifile)))
  current => ifile%first
  do i = 1, ifile_get_length (ifile)
    string(i) = current%string
    current => current%next
  end do
end subroutine ifile_to_string_array

```

3.1.5 Ifile tools

```

<Ifiles: public>+≡
public :: ifile_get_length

<Ifiles: subroutines>+≡
function ifile_get_length (ifile) result (length)
  integer :: length
  type(ifile_t), intent(in) :: ifile
  length = ifile%n_lines
end function ifile_get_length

```

3.1.6 Line pointers

Instead of the implicit pointer used in ordinary file access, we define explicit pointers, so there can be more than one at a time.

```

<Ifiles: public>+≡
public :: line_p

<Ifiles: types>+≡
type :: line_p
  private
  type(line_entry_t), pointer :: p => null ()
end type line_p

```

Assign a file pointer to the first or last line in an ifile:

```

<Ifiles: public>+≡
public :: line_init

<Ifiles: subroutines>+≡
subroutine line_init (line, ifile, back)
  type(line_p), intent(inout) :: line
  type(ifile_t), intent(in) :: ifile
  logical, intent(in), optional :: back
  if (present (back)) then
    if (back) then
      line%p => ifile%last
    else

```

```

        line%p => ifile%first
    end if
else
    line%p => ifile%first
end if
end subroutine line_init

```

Remove the pointer association:

```

<Ifiles: public>+≡
    public :: line_final
<Ifiles: subroutines>+≡
    subroutine line_final (line)
        type(line_p), intent(inout) :: line
        nullify (line%p)
    end subroutine line_final

```

Go one step forward

```

<Ifiles: public>+≡
    public :: line_advance
<Ifiles: subroutines>+≡
    subroutine line_advance (line)
        type(line_p), intent(inout) :: line
        if (associated (line%p)) line%p => line%p%next
    end subroutine line_advance

```

Go one step backward

```

<Ifiles: public>+≡
    public :: line_backspace
<Ifiles: subroutines>+≡
    subroutine line_backspace (line)
        type(line_p), intent(inout) :: line
        if (associated (line%p)) line%p => line%p%previous
    end subroutine line_backspace

```

Check whether we are accessing a valid line

```

<Ifiles: public>+≡
    public :: line_is_associated
<Ifiles: subroutines>+≡
    function line_is_associated (line) result (ok)
        logical :: ok
        type(line_p), intent(in) :: line
        ok = associated (line%p)
    end function line_is_associated

```

3.1.7 Access lines via pointers

We do not need the ifile as an argument to these functions, because the `line` type will point to an existing ifile.

```
<Ifiles: public>+≡
    public :: line_get_string

<Ifiles: subroutines>+≡
    function line_get_string (line) result (string)
        type(string_t) :: string
        type(line_p), intent(in) :: line
        if (associated (line%p)) then
            string = line%p%string
        else
            string = ""
        end if
    end function line_get_string
```

Variant where the line pointer is advanced after reading.

```
<Ifiles: public>+≡
    public :: line_get_string_advance

<Ifiles: subroutines>+≡
    function line_get_string_advance (line) result (string)
        type(string_t) :: string
        type(line_p), intent(inout) :: line
        if (associated (line%p)) then
            string = line%p%string
            call line_advance (line)
        else
            string = ""
        end if
    end function line_get_string_advance
```

```
<Ifiles: public>+≡
    public :: line_get_index

<Ifiles: subroutines>+≡
    function line_get_index (line) result (index)
        integer :: index
        type(line_p), intent(in) :: line
        if (associated (line%p)) then
            index = line%p%index
        else
            index = 0
        end if
    end function line_get_index
```

```
<Ifiles: public>+≡
    public :: line_get_length

<Ifiles: subroutines>+≡
    function line_get_length (line) result (length)
        integer :: length
        type(line_p), intent(in) :: line
```

```
    if (associated (line%p)) then
        length = len (line%p%string)
    else
        length = 0
    end if
end function line_get_length
```

3.2 Lexer

The lexer purpose is to read from a line-separated character input stream (usually a file) and properly chop the stream into lexemes (tokens). [The parser will transform lexemes into meaningful tokens, to be stored in a parse tree, therefore we do not use the term 'token' here.] The input is read line-by-line, but interpreted free-form, except for quotes and the comment syntax. (Fortran 2003 would allow us to use a stream type for reading.)

In an object-oriented approach, we can dynamically create and destroy lexers, including the lexer setup.

The main lexer function is to return a lexeme according to the basic lexer rules (quotes, comments, whitespace, special classes). There is also a routine to write back a lexeme to the input stream (but only once).

For the rules, we separate the possible characters into classes. Whitespace usually consists of blank, tab, and line-feed, where any number of consecutive whitespace is equivalent to one. Quoted strings are enclosed by a pair of quote characters, possibly multiline. Comments are similar to quotes, but interpreted as whitespace. Numbers are identified (not distinguishing real and integer) but not interpreted. Other character classes make up identifiers.

```
<lexers.f90>≡  
  <File header>  
  
  module lexers  
  
    <Use strings>  
    <Use file utils>  
    use limits, only: EOF, EOR !NODEP!  
    use limits, only: LF !NODEP!  
    use limits, only: WHITESPACE_CHARS, LCLETTERS, UCLETTERS, DIGITS !NODEP!  
    use diagnostics !NODEP!  
    use ifiles, only: ifile_t  
    use ifiles, only: line_p, line_is_associated, line_init, line_final  
    use ifiles, only: line_get_string_advance  
  
    <Standard module head>  
  
    <Lexer: public>  
  
    <Lexer: parameters>  
  
    <Lexer: types>  
  
    <Lexer: interfaces>  
  
  contains  
  
    <Lexer: subroutines>  
  
  end module lexers
```

3.2.1 Input streams

For flexible input, we define a generic stream type that refers to either an external file, an external unit which is already open, a string, an `ifile` object (internal file, i.e., string list), or a line pointer to an `ifile` object. The stream type actually follows the idea of a formatted external file, which is line-oriented. Thus, the stream reader always returns a whole record (input line).

Note that only in the string version, the stream contents are stored inside the stream object. In the `ifile` version, the stream contains only the line pointer, while in the external-file case, the line pointer is implicitly created by the runtime library.

```
<Lexer: public>≡
    public :: stream_t

<Lexer: types>≡
    type :: stream_t
        type(string_t), pointer :: filename => null ()
        integer, pointer :: unit => null ()
        type(string_t), pointer :: string => null ()
        type(ifile_t), pointer :: ifile => null ()
        type(line_p), pointer :: line => null ()
        logical :: eof = .false.
    end type stream_t
```

The initializers refer to the specific version. The stream should be undefined before calling this.

```
<Lexer: public>+≡
    public :: stream_init

<Lexer: interfaces>≡
    interface stream_init
        module procedure stream_init_filename
        module procedure stream_init_unit
        module procedure stream_init_string
        module procedure stream_init_ifile
        module procedure stream_init_line
    end interface

<Lexer: subroutines>≡
    subroutine stream_init_filename (stream, filename)
        type(stream_t), intent(out) :: stream
        character(*), intent(in) :: filename
        integer :: unit
        allocate (stream%filename)
        stream%filename = filename
        unit = free_unit ()
        open (unit=unit, file=filename, status="old", action="read")
        call stream_init_unit (stream, unit)
    end subroutine stream_init_filename

    subroutine stream_init_unit (stream, unit)
        type(stream_t), intent(out) :: stream
        integer, intent(in) :: unit
        allocate (stream%unit)
```

```

        stream%unit = unit
        stream%eof = .false.
    end subroutine stream_init_unit

    subroutine stream_init_string (stream, string)
        type(stream_t), intent(out) :: stream
        type(string_t), intent(in) :: string
        allocate (stream%string)
        stream%string = string
    end subroutine stream_init_string

    subroutine stream_init_ifile (stream, ifile)
        type(stream_t), intent(out) :: stream
        type(ifile_t), intent(in) :: ifile
        type(line_p) :: line
        allocate (stream%ifile)
        stream%ifile = ifile
        call line_init (line, ifile)
        call stream_init_line (stream, line)
    end subroutine stream_init_ifile

    subroutine stream_init_line (stream, line)
        type(stream_t), intent(out) :: stream
        type(line_p), intent(in) :: line
        allocate (stream%line)
        stream%line = line
    end subroutine stream_init_line

```

The finalizer restores the initial state. If an external file was opened, it is closed.

```

<Lexer: public>+≡
    public :: stream_final

<Lexer: subroutines>+≡
    subroutine stream_final (stream)
        type(stream_t), intent(inout) :: stream
        if (associated (stream%filename)) then
            close (stream%unit)
            deallocate (stream%unit)
            deallocate (stream%filename)
        else if (associated (stream%unit)) then
            deallocate (stream%unit)
        else if (associated (stream%string)) then
            deallocate (stream%string)
        else if (associated (stream%ifile)) then
            call line_final (stream%line)
            deallocate (stream%line)
            deallocate (stream%ifile)
        else if (associated (stream%line)) then
            call line_final (stream%line)
            deallocate (stream%line)
        end if
    end subroutine stream_final

```

This returns the next record from the input stream. Depending on the stream type, the stream pointers are modified: Reading from external unit, the external file is advanced (implicitly). Reading from string, the string is replaced by an empty string. Reading from `ifile`, the line pointer is advanced. Note that the `iostat` argument is mandatory.

<Lexer: public>+≡

```
public :: stream_get_record
```

<Lexer: subroutines>+≡

```
subroutine stream_get_record (stream, string, iostat)
  type(stream_t), intent(inout) :: stream
  type(string_t), intent(out) :: string
  integer, intent(out) :: iostat
  if (associated (stream%unit)) then
    if (stream%eof) then
      iostat = EOF
    else
      call get (stream%unit, string, iostat=iostat)
      if (iostat == EOR) iostat = 0
      if (iostat == EOF) then
        iostat = 0
        stream%eof = .true.
      end if
    end if
  else if (associated (stream%string)) then
    if (len (stream%string) /= 0) then
      string = stream%string
      stream%string = ""
      iostat = 0
    else
      string = ""
      iostat = EOF
    end if
  else if (associated (stream%line)) then
    if (line_is_associated (stream%line)) then
      string = line_get_string_advance (stream%line)
      iostat = 0
    else
      string = ""
      iostat = EOF
    end if
  else
    call msg_bug (" Attempt to read from uninitialized input stream")
  end if
end subroutine stream_get_record
```

3.2.2 Keyword list

The lexer should be capable of identifying a token as a known keyword. To this end, we store a list of keywords:

<Lexer: public>+≡

```
public :: keyword_list_t
```

```

<Lexer: types>+=
  type :: keyword_entry_t
    private
    type(string_t) :: string
    type(keyword_entry_t), pointer :: next => null ()
  end type keyword_entry_t

  type :: keyword_list_t
    private
    type(keyword_entry_t), pointer :: first => null ()
    type(keyword_entry_t), pointer :: last => null ()
  end type keyword_list_t

```

Add a new string to the keyword list, unless it is already there:

```

<Lexer: public>+=
  public :: keyword_list_add

<Lexer: subroutines>+=
  subroutine keyword_list_add (keylist, string)
    type(keyword_list_t), intent(inout) :: keylist
    type(string_t), intent(in) :: string
    type(keyword_entry_t), pointer :: k_entry_new
    if (.not. keyword_list_contains (keylist, string)) then
      allocate (k_entry_new)
      k_entry_new%string = string
      if (associated (keylist%first)) then
        keylist%last%next => k_entry_new
      else
        keylist%first => k_entry_new
      end if
      keylist%last => k_entry_new
    end if
  end subroutine keyword_list_add

```

Return true if a string is a keyword.

```

<Lexer: public>+=
  public :: keyword_list_contains

<Lexer: subroutines>+=
  function keyword_list_contains (keylist, string) result (found)
    type(keyword_list_t), intent(in) :: keylist
    type(string_t), intent(in) :: string
    logical :: found
    found = .false.
    call check_rec (keylist%first)
  contains
    recursive subroutine check_rec (k_entry)
      type(keyword_entry_t), pointer :: k_entry
      if (associated (k_entry)) then
        if (k_entry%string /= string) then
          call check_rec (k_entry%next)
        else
          found = .true.
        end if
      end if
    end subroutine check_rec
  end function keyword_list_contains

```

```

        end if
    end subroutine check_rec
end function keyword_list_contains

```

Write the keyword list

```

<Lexer: public>+≡
    public :: keyword_list_write

<Lexer: interfaces>+≡
    interface keyword_list_write
        module procedure keyword_list_write_unit
    end interface

<Lexer: subroutines>+≡
    subroutine keyword_list_write_unit (keylist, unit)
        type(keyword_list_t), intent(in) :: keylist
        integer, intent(in) :: unit
        write (unit, "(A)") "Keyword list:"
        if (associated (keylist%first)) then
            call keyword_write_rec (keylist%first)
            write (unit, *)
        else
            write (unit, "(1x,A)") "[empty]"
        end if
    contains
        recursive subroutine keyword_write_rec (k_entry)
            type(keyword_entry_t), intent(in), pointer :: k_entry
            if (associated (k_entry)) then
                write (unit, "(1x,A)", advance="no") char (k_entry%string)
                call keyword_write_rec (k_entry%next)
            end if
        end subroutine keyword_write_rec
    end subroutine keyword_list_write_unit

```

Clear the keyword list

```

<Lexer: public>+≡
    public :: keyword_list_final

<Lexer: subroutines>+≡
    subroutine keyword_list_final (keylist)
        type(keyword_list_t), intent(inout) :: keylist
        call keyword_destroy_rec (keylist%first)
        nullify (keylist%last)
    contains
        recursive subroutine keyword_destroy_rec (k_entry)
            type(keyword_entry_t), pointer :: k_entry
            if (associated (k_entry)) then
                call keyword_destroy_rec (k_entry%next)
                deallocate (k_entry)
            end if
        end subroutine keyword_destroy_rec
    end subroutine keyword_list_final

```

3.2.3 Lexeme templates

This type is handled like a rudimentary regular expression. It determines the lexer behavior when matching a string. The actual objects made from this type and the corresponding matching routines are listed below.

```

<Lexer: types>+=
    type :: template_t
        private
            integer :: type
            character(256) :: charset1, charset2
            integer :: len1, len2
        end type template_t

```

These are the types that valid lexemes can have:

```

<Lexer: public>+=
    public :: T_KEYWORD, T_IDENTIFIER, T_QUOTED, T_NUMERIC

<Lexer: parameters>=
    integer, parameter :: T_KEYWORD = 1
    integer, parameter :: T_IDENTIFIER = 2, T_QUOTED = 3, T_NUMERIC = 4

```

These are special types:

```

<Lexer: parameters>+=
    integer, parameter :: EMPTY = 0, WHITESPACE = 10
    integer, parameter :: NO_MATCH = 11, IO_ERROR = 12, OVERFLOW = 13
    integer, parameter :: UNMATCHED_QUOTE = 14

```

In addition, we have EOF which is a negative integer, normally -1 . Printout for debugging:

```

<Lexer: subroutines>+=
    subroutine lexeme_type_write (type, unit)
        integer, intent(in) :: type
        integer, intent(in) :: unit
        select case (type)
            case (EMPTY);      write(unit,"(A)",advance="no") " EMPTY      "
            case (WHITESPACE); write(unit,"(A)",advance="no") " WHITESPACE "
            case (T_IDENTIFIER);write(unit,"(A)",advance="no") " IDENTIFIER "
            case (T_QUOTED);   write(unit,"(A)",advance="no") " QUOTED    "
            case (T_NUMERIC);  write(unit,"(A)",advance="no") " NUMERIC   "
            case (IO_ERROR);   write(unit,"(A)",advance="no") " IO_ERROR  "
            case (OVERFLOW);   write(unit,"(A)",advance="no") " OVERFLOW  "
            case (UNMATCHED_QUOTE); write(unit,"(A)",advance="no") " UNMATCHEDQ "
            case (NO_MATCH);   write(unit,"(A)",advance="no") " NO_MATCH   "
            case (EOF);        write(unit,"(A)",advance="no") " EOF        "
            case default;      write(unit,"(A)",advance="no") " [illegal]  "
        end select
    end subroutine lexeme_type_write

    subroutine template_write (tt, unit)
        type(template_t), intent(in) :: tt
        integer, intent(in) :: unit
        call lexeme_type_write (tt%type, unit)
        write (unit, "(A)", advance="no") " '" // tt%charset1(1:tt%len1) // "'"
        write (unit, "(A)", advance="no") " '" // tt%charset2(1:tt%len2) // "'"
    end subroutine template_write

```

The matching functions all return the number of matched characters in the provided string. If this number is zero, the match has failed.

The `template` functions are declared `pure` because they appear in `forall` loops below.

A template for whitespace:

```
<Lexer: subroutines>+≡
  pure function template_whitespace (chars) result (tt)
    character(*), intent(in) :: chars
    type(template_t) :: tt
    tt = template_t (WHITESPACE, chars, "", len (chars), 0)
  end function template_whitespace
```

Just match the string against the character set.

```
<Lexer: subroutines>+≡
  subroutine match_whitespace (tt, s, n)
    type(template_t), intent(in) :: tt
    character(*), intent(in) :: s
    integer, intent(out) :: n
    n = verify (s, tt%charset1(1:tt%len1)) - 1
    if (n < 0) n = len (s)
  end subroutine match_whitespace
```

A template for normal identifiers. To match, a lexeme should have a first character in class `chars1` and an arbitrary number of further characters in class `chars2`. If the latter is empty, we are looking for a single-character lexeme.

```
<Lexer: subroutines>+≡
  pure function template_identifier (chars1, chars2) result (tt)
    character(*), intent(in) :: chars1, chars2
    type(template_t) :: tt
    tt = template_t (T_IDENTIFIER, chars1, chars2, len(chars1), len(chars2))
  end function template_identifier
```

Here, the first letter must match, the others may or may not.

```
<Lexer: subroutines>+≡
  subroutine match_identifier (tt, s, n)
    type(template_t), intent(in) :: tt
    character(*), intent(in) :: s
    integer, intent(out) :: n
    if (verify (s(1:1), tt%charset1(1:tt%len1)) == 0) then
      n = verify (s(2:), tt%charset2(1:tt%len2))
      if (n == 0) n = len (s)
    else
      n = 0
    end if
  end subroutine match_identifier
```

A template for quoted strings. The same template applies for comments. The first character set indicates the left quote (could be a sequence of several characters), the second one the matching right quote.

```
<Lexer: subroutines>+≡
```

```

pure function template_quoted (chars1, chars2) result (tt)
  character(*), intent(in) :: chars1, chars2
  type(template_t) :: tt
  tt = template_t (T_QUOTED, chars1, chars2, len (chars1), len (chars2))
end function template_quoted

```

Here, the beginning of the string must exactly match the first character set, then we look for the second one. If found, return. If there is a first quote but no second one, return a negative number, indicating this error condition.

```

<Lexer: subroutines>+≡
subroutine match_quoted (tt, s, n, range)
  type(template_t), intent(in) :: tt
  character(*), intent(in) :: s
  integer, intent(out) :: n
  integer, dimension(2), intent(out) :: range
  character(tt%len1) :: ch1
  character(tt%len2) :: ch2
  integer :: i
  ch1 = tt%charset1
  if (s(1:tt%len1) == ch1) then
    ch2 = tt%charset2
    do i = tt%len1 + 1, len (s) - tt%len2 + 1
      if (s(i: i+tt%len2-1) == ch2) then
        n = i + tt%len2 - 1
        range(1) = tt%len1 + 1
        range(2) = i - 1
        return
      end if
    end do
    n = -1
    range = 0
  else
    n = 0
    range = 0
  end if
end subroutine match_quoted

```

A template for real numbers. The first character set is the set of allowed exponent letters. In accordance with the other functions we return the lexeme as a string but do not read it.

```

<Lexer: subroutines>+≡
pure function template_numeric (chars) result (tt)
  character(*), intent(in) :: chars
  type(template_t) :: tt
  tt = template_t (T_NUMERIC, chars, "", len (chars), 0)
end function template_numeric

```

A numeric lexeme may be real or integer. We purposely do not allow for a preceding sign. If the number is followed by an exponent, this is included, otherwise the rest is ignored.

There is a possible pitfall with this behavior: while the string `1e3` will be interpreted as a single number, the analogous string `1a3` will be split into the

number 1 and an identifier a3. There is no easy way around such an ambiguity. We should make sure that the syntax does not contain identifiers like a3 or e3.

```

(Lexer: subroutines)+≡
subroutine match_numeric (tt, s, n)
  type(template_t), intent(in) :: tt
  character(*), intent(in) :: s
  integer, intent(out) :: n
  integer :: i, n0
  character(10), parameter :: digits = "0123456789"
  character(2), parameter :: signs = "-+"
  n = verify (s, digits) - 1
  if (n < 0) then
    n = 0
    return
  else if (s(n+1:n+1) == ".") then
    i = verify (s(n+2:), digits) - 1
    if (i < 0) then
      n = len (s)
      return
    else if (i > 0 .or. n > 0) then
      n = n + 1 + i
    end if
  end if
  n0 = n
  if (n > 0) then
    if (verify (s(n+1:n+1), tt%charset1(1:tt%len1)) == 0) then
      n = n + 1
      if (verify (s(n+1:n+1), signs) == 0) n = n + 1
      i = verify (s(n+1:), digits) - 1
      if (i < 0) then
        n = len (s)
      else if (i == 0) then
        n = n0
      else
        n = n + i
      end if
    end if
  end if
end subroutine match_numeric

```

The generic matching routine. With Fortran 2003 we would define separate types and use a SELECT TYPE instead.

```

(Lexer: subroutines)+≡
subroutine match_template (tt, s, n, range)
  type(template_t), intent(in) :: tt
  character(*), intent(in) :: s
  integer, intent(out) :: n
  integer, dimension(2), intent(out) :: range
  select case (tt%type)
  case (WHITESPACE)
    call match_whitespace (tt, s, n)
    range = 0
  case (T_IDENTIFIER)

```

```

        call match_identifier (tt, s, n)
        range(1) = 1
        range(2) = len_trim (s)
    case (T_QUOTED)
        call match_quoted (tt, s, n, range)
    case (T_NUMERIC)
        call match_numeric (tt, s, n)
        range(1) = 1
        range(2) = len_trim (s)
    case default
        call msg_bug ("Invalid lexeme template encountered")
    end select
end subroutine match_template

```

Match against an array of templates. Return the index of the first template that matches together with the number of characters matched and the range of the relevant substring. If all fails, these numbers are zero.

(Lexer: subroutines)+≡

```

subroutine match (tt, s, n, range, ii)
    type(template_t), dimension(:), intent(in) :: tt
    character(*), intent(in) :: s
    integer, intent(out) :: n
    integer, dimension(2), intent(out) :: range
    integer, intent(out) :: ii
    integer :: i
    do i = 1, size (tt)
        call match_template (tt(i), s, n, range)
        if (n /= 0) then
            ii = i
            return
        end if
    end do
    n = 0
    ii = 0
end subroutine match

```

3.2.4 The lexer setup

This object contains information about character classes. As said above, one class consists of quoting chars (matching left and right), another one of comment chars (similar), a class of whitespace, and several classes of characters that make up identifiers. When creating the lexer setup, the character classes are transformed into lexeme templates which are to be matched in a certain predefined order against the input stream.

BLANK should always be taken as whitespace, some things may depend on this. TAB is also fixed by convention, but may in principle be modified. Newline (DOS!) and linefeed are also defined as whitespace.

(Limits: public parameters)+≡

```

character, parameter, public :: BLANK = ' ', TAB = achar(9)
character, parameter, public :: CR = achar(13), LF = achar(10)
character, parameter, public :: BACKSLASH = achar(92)

```

```

character(*), parameter, public :: WHITESPACE_CHARS = BLANK// TAB // CR // LF
character(*), parameter, public :: LCLETTERS = "abcdefghijklmnopqrstuvwxyz"
character(*), parameter, public :: UCLETTERS = "ABCDEFGHIJKLMNOPQRSTUVWXYZ"
character(*), parameter, public :: DIGITS = "0123456789"

```

The lexer setup, containing the list of lexeme templates. No defaults yet. The type with index zero will be assigned to the NO_MATCH lexeme.

The keyword list is not stored, just a pointer to it. We anticipate that the keyword list is part of the syntax table, and the lexer needs not alter it. Furthermore, the lexer is typically finished before the syntax table is.

```

<Lexer: parameters>+≡
    integer, parameter :: CASE_KEEP = 0, CASE_UP = 1, CASE_DOWN = 2

<Lexer: types>+≡
    type :: lexer_setup_t
    private
    type(template_t), dimension(:), allocatable :: tt
    integer, dimension(:), allocatable :: type
    integer :: keyword_case = CASE_KEEP
    type(keyword_list_t), pointer :: keyword_list => null ()
end type lexer_setup_t

```

Fill the lexer setup object. Some things are hardcoded here (whitespace, alphanumeric identifiers), some are free: comment chars (but these must be single, and comments must be terminated by line-feed), quote chars and matches (must be single), characters to be read as one-character lexeme, special classes (characters of one class that should be glued together as identifiers).

```

<Lexer: subroutines>+≡
    subroutine lexer_setup_init (setup, &
        comment_chars, quote_chars, quote_match, &
        single_chars, special_class, &
        keyword_list, upper_case_keywords)
    type(lexer_setup_t), intent(inout) :: setup
    character(*), intent(in) :: comment_chars
    character(*), intent(in) :: quote_chars, quote_match
    character(*), intent(in) :: single_chars
    character(*), dimension(:), intent(in) :: special_class
    type(keyword_list_t), pointer :: keyword_list
    logical, intent(in), optional :: upper_case_keywords
    integer :: n, i
    if (present (upper_case_keywords)) then
        if (upper_case_keywords) then
            setup%keyword_case = CASE_UP
        else
            setup%keyword_case = CASE_DOWN
        end if
    else
        setup%keyword_case = CASE_KEEP
    end if
    n = 1 + len (comment_chars) + len (quote_chars) + 1 &
        + len (single_chars) + size (special_class) + 1
    allocate (setup%tt(n))
    allocate (setup%type(0:n))

```

```

n = 0
setup%type(n) = NO_MATCH
n = n + 1
setup%tt(n) = template_whitespace (WHITESPACE_CHARS)
setup%type(n) = EMPTY
forall (i = 1:len(comment_chars))
    setup%tt(n+i) = template_quoted (comment_chars(i:i), LF)
    setup%type(n+i) = EMPTY
end forall
n = n + len (comment_chars)
forall (i = 1:len(quote_chars))
    setup%tt(n+i) = template_quoted (quote_chars(i:i), quote_match(i:i))
    setup%type(n+i) = T_QUOTED
end forall
n = n + len (quote_chars)
setup%tt(n+1) = template_numeric ("EeDd")
setup%type(n+1) = T_NUMERIC
n = n + 1
forall (i = 1:len (single_chars))
    setup%tt(n+i) = template_identifier (single_chars(i:i), "")
    setup%type(n+i) = T_IDENTIFIER
end forall
n = n + len (single_chars)
forall (i = 1:size (special_class))
    setup%tt(n+i) = template_identifier &
        (trim (special_class(i)), trim (special_class(i)))
    setup%type(n+i) = T_IDENTIFIER
end forall
n = n + size (special_class)
setup%tt(n+1) = template_identifier &
    (LCLETTERS//UCLETTERS, LCLETTERS//DIGITS//"_"/UCLETTERS)
setup%type(n+1) = T_IDENTIFIER
n = n + 1
if (n /= size (setup%tt)) &
    call msg_bug ("Size mismatch in lexer setup")
setup%keyword_list => keyword_list
end subroutine lexer_setup_init

```

The destructor is needed only if the object is not itself part of an allocatable array

```

<Lexer: subroutines>+≡
subroutine lexer_setup_final (setup)
    type(lexer_setup_t), intent(inout) :: setup
    deallocate (setup%tt, setup%type)
    setup%keyword_list => null ()
end subroutine lexer_setup_final

```

For debugging: Write the lexer setup

```

<Lexer: subroutines>+≡
subroutine lexer_setup_write (setup, unit)
    type(lexer_setup_t), intent(in) :: setup
    integer, intent(in) :: unit
    integer :: i

```

```

write (unit, "(A)") "Lexer setup:"
if (allocated (setup%tt)) then
  do i = 1, size (setup%tt)
    call template_write (setup%tt(i), unit)
    write (unit, '(A)', advance = "no") " -> "
    call lexeme_type_write (setup%type(i), unit)
    write (unit, *)
  end do
else
  write (unit, *) "[empty]"
end if
if (associated (setup%keyword_list)) then
  call keyword_list_write (setup%keyword_list, unit)
end if
end subroutine lexer_setup_write

```

3.2.5 The lexeme type

An object of this type is returned by the lexer. Apart from the lexeme string, it gives information about the relevant substring (first and last character index) and the lexeme type. Interpreting the string is up to the parser.

```

<Lexer: public>+≡
  public :: lexeme_t

<Lexer: types>+≡
  type :: lexeme_t
  private
    integer :: type = EMPTY
    type(string_t) :: s
    integer :: b = 0, e = 0
  end type lexeme_t

```

Debugging aid:

```

<Lexer: public>+≡
  public :: lexeme_write

<Lexer: subroutines>+≡
  subroutine lexeme_write (t, unit)
    type(lexeme_t), intent(in) :: t
    integer, intent(in) :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    select case (t%type)
    case (T_KEYWORD)
      write (u, *) "KEYWORD:   '" // char (t%s) // "'"
    case (T_IDENTIFIER)
      write (u, *) "IDENTIFIER: '" // char (t%s) // "'"
    case (T_QUOTED)
      write (u, *) "QUOTED:     '" // char (t%s) // "'"
    case (T_NUMERIC)
      write (u, *) "NUMERIC:     '" // char (t%s) // "'"
    case (UNMATCHED_QUOTE)
      write (u, *) "Unmatched quote: "// char (t%s)

```

```

case (OVERFLOW); write (u, *) "Overflow: " // char (t%s)
case (EMPTY);    write (u, *) "Empty lexeme"
case (NO_MATCH); write (u, *) "No match"
case (IO_ERROR); write (u, *) "IO error"
case (EOF);      write (u, *) "EOF"
case default
    write (u, *) "Error"
end select
end subroutine lexeme_write

```

Store string and type in a lexeme. The range determines the beginning and end of the relevant part of the string. Check for a keyword.

(Lexer: subroutines)+≡

```

subroutine lexeme_set (t, keyword_list, s, range, type, keyword_case)
    type(lexeme_t), intent(out) :: t
    type(keyword_list_t), pointer :: keyword_list
    type(string_t), intent(in) :: s
    type(string_t) :: keyword
    integer, dimension(2), intent(in) :: range
    integer, intent(in) :: type
    integer, intent(in), optional :: keyword_case
    t%type = type
    if (present (keyword_case)) then
        select case (keyword_case)
            case (CASE_KEEP);    keyword = s
            case (CASE_UP);      keyword = upper_case (s)
            case (CASE_DOWN);    keyword = lower_case (s)
        end select
    else
        keyword = s
    end if
    if (type == T_IDENTIFIER) then
        if (associated (keyword_list)) then
            if (keyword_list_contains (keyword_list, keyword)) &
                t%type = T_KEYWORD
        end if
    end if
    select case (t%type)
        case (T_KEYWORD); t%s = keyword
        case default;    t%s = s
    end select
    t%b = range(1)
    t%e = range(2)
end subroutine lexeme_set

subroutine lexeme_clear (t)
    type(lexeme_t), intent(out) :: t
    t%type = EMPTY
    t%s = ""
end subroutine lexeme_clear

```

Retrieve the lexeme string, the relevant part of it, and the type. The last function returns true if there is a break condition reached (error or EOF).

```

<Lexer: public>+≡
    public :: lexeme_get_string
    public :: lexeme_get_contents
    public :: lexeme_get_delimiters
    public :: lexeme_get_type
<Lexer: subroutines>+≡
    function lexeme_get_string (t) result (s)
        type(string_t) :: s
        type(lexeme_t), intent(in) :: t
        s = t%s
    end function lexeme_get_string

    function lexeme_get_contents (t) result (s)
        type(string_t) :: s
        type(lexeme_t), intent(in) :: t
        s = extract (t%s, t%b, t%e)
    end function lexeme_get_contents

    function lexeme_get_delimiters (t) result (del)
        type(string_t), dimension(2) :: del
        type(lexeme_t), intent(in) :: t
        del(1) = extract (t%s, finish = t%b-1)
        del(2) = extract (t%s, start = t%e+1)
    end function lexeme_get_delimiters

    function lexeme_get_type (t) result (type)
        integer :: type
        type(lexeme_t), intent(in) :: t
        type = t%type
    end function lexeme_get_type

```

Check for a generic break condition (error/eof) and for eof in particular.

```

<Lexer: public>+≡
    public :: lexeme_is_break
    public :: lexeme_is_eof
<Lexer: subroutines>+≡
    function lexeme_is_break (t) result (break)
        logical :: break
        type(lexeme_t), intent(in) :: t
        select case (t%type)
            case (EOF, IO_ERROR, OVERFLOW, NO_MATCH)
                break = .true.
            case default
                break = .false.
        end select
    end function lexeme_is_break

    function lexeme_is_eof (t) result (ok)
        logical :: ok
        type(lexeme_t), intent(in) :: t
        ok = t%type == EOF
    end function lexeme_is_eof

```

3.2.6 The lexer object

We store the current lexeme and the current line. The line buffer is set each time a new line is read from file. The working buffer has one character more, to hold any trailing blank. Pointers to line and column are for debugging, they will be used to make up readable error messages for the parser.

```
<Lexer: public>+≡  
    public :: lexer_t
```

```
<Lexer: types>+≡  
    type :: lexer_t  
        private  
        type(lexer_setup_t) :: setup  
        type(lexeme_t) :: lexeme  
        type(string_t) :: line_buffer  
        integer :: current_line  
        integer :: current_column  
        integer :: previous_column  
        type(string_t) :: buffer  
    end type lexer_t
```

Create-setup wrapper

```
<Lexer: public>+≡  
    public :: lexer_init  
  
<Lexer: subroutines>+≡  
    subroutine lexer_init (lexer, &  
        comment_chars, quote_chars, quote_match, &  
        single_chars, special_class, &  
        keyword_list, upper_case_keywords)  
        type(lexer_t), intent(inout) :: lexer  
        character(*), intent(in) :: comment_chars  
        character(*), intent(in) :: quote_chars, quote_match  
        character(*), intent(in) :: single_chars  
        character(*), dimension(:), intent(in) :: special_class  
        type(keyword_list_t), pointer :: keyword_list  
        logical, intent(in), optional :: upper_case_keywords  
        call lexer_setup_init (lexer%setup, &  
            comment_chars = comment_chars, &  
            quote_chars = quote_chars, &  
            quote_match = quote_match, &  
            single_chars = single_chars, &  
            special_class = special_class, &  
            keyword_list = keyword_list, &  
            upper_case_keywords = upper_case_keywords)  
        call lexer_clear (lexer)  
    end subroutine lexer_init
```

Clear the lexer state, but not the setup. This should be done when the lexing starts, but it is not known whether the lexer was used before.

```
<Lexer: public>+≡  
    public :: lexer_clear
```

```

<Lexer: subroutines>+≡
  subroutine lexer_clear (lexer)
    type(lexer_t), intent(inout) :: lexer
    call lexeme_clear (lexer%lexeme)
    lexer%line_buffer = ""
    lexer%current_line = 0
    lexer%current_column = 0
    lexer%previous_column = 0
    lexer%buffer = ""
  end subroutine lexer_clear

```

Reset lexer state and delete setup

```

<Lexer: public>+≡
  public :: lexer_final

<Lexer: subroutines>+≡
  subroutine lexer_final (lexer)
    type(lexer_t), intent(inout) :: lexer
    call lexer_clear (lexer)
    call lexer_setup_final (lexer%setup)
  end subroutine lexer_final

```

3.2.7 The lexer routine

The lexer. The lexer function takes the lexer and returns the currently stored lexeme. If there is none, it is read from buffer, matching against the lexeme templates in the lexer setup. Empty lexemes, i.e., comments and whitespace, are discarded and the buffer is read again until we have found a nonempty lexeme (which may also be EOF or an error condition).

The initial state of the lexer contains an empty lexeme, so reading from buffer is forced. The empty state is restored after returning the lexeme. A nonempty lexeme is present in the lexer only if `lex_back` has been executed before.

The workspace is the `lexer%buffer`, treated as a sort of input stream. We chop off lexemes from the beginning, adjusting the buffer to the left. Whenever the buffer is empty, or we are matching against an open quote which has not terminated, we read a new line and append it to the right. This may result in special conditions, which for simplicity are also returned as lexemes: I/O error, buffer overflow, end of file. If the latter happens during reading a quoted string, we return an unmatched-quote lexeme. Obviously, the special-condition lexemes have to be caught by the parser.

Note that reading further lines is only necessary when reading a quoted string. Otherwise, the line-feed that ends each line is interpreted as whitespace which terminates a preceding lexeme, so there are no other valid multiline lexemes.

To enable meaningful error messages, we also keep track of the line number of the last line read, and the beginning and the end of the current lexeme with respect to this line.

The lexer is implemented as a function that returns the next lexeme (i.e., token). It uses the `lexer` setup and modifies the buffers and pointers stored

within the lexer, a side effect. The lexer reads from an input stream object, which also is modified by this reading, e.g., a line pointer is advanced.

<Lexer: public>+≡

public :: lex

<Lexer: subroutines>+≡

```
subroutine lex (lexeme, lexer, stream)
  type(lexeme_t), intent(out) :: lexeme
  type(lexer_t), intent(inout) :: lexer
  type(stream_t), intent(inout) :: stream
  integer :: iostat1, iostat2
  integer :: pos !, offset
  integer, dimension(2) :: range
  integer :: template_index, type
  GET_LEXEME: do while (lexeme_get_type (lexer%lexeme) == EMPTY)
    if (len (lexer%buffer) /= 0) then
      iostat1 = 0
    else
      call lexer_read_line (lexer, stream, iostat1)
    end if
    select case (iostat1)
    case (0)
      MATCH_BUFFER: do
        call match (lexer%setup%tt, char (lexer%buffer), &
                   pos, range, template_index)
        if (pos >= 0) then
          type = lexer%setup%type(template_index)
          exit MATCH_BUFFER
        else
          pos = 0
          call lexer_read_line (lexer, stream, iostat2)
          select case (iostat2)
          case (EOF); type = UNMATCHED_QUOTE; exit MATCH_BUFFER
          case (1);   type = IO_ERROR;       exit MATCH_BUFFER
          case (2);   type = OVERFLOW;       exit MATCH_BUFFER
          end select
        end if
      end do MATCH_BUFFER
      case (EOF); type = EOF
      case (1);   type = IO_ERROR
      case (2);   type = OVERFLOW
    end select
    call lexeme_set (lexer%lexeme, lexer%setup%keyword_list, &
                   extract (lexer%buffer, finish=pos), range, type, &
                   lexer%setup%keyword_case)
    lexer%buffer = remove (lexer%buffer, finish=pos)
    ! offset = scan (lexer%buffer, LF, back=.true.)
    ! offset = scan (lexer%buffer(1:offset-1), LF, back=.true.)
    lexer%previous_column = max (lexer%current_column, 0)
    lexer%current_column = lexer%current_column + pos
  end do GET_LEXEME
  lexeme = lexer%lexeme
  call lexeme_clear (lexer%lexeme)
end subroutine lex
```

Read a line and append it to the input buffer. If the input buffer overflows, return `iostat=2`. Otherwise, `iostat=1` indicates an I/O error, and `iostat=-1` the EOF.

The input stream may either be an external unit or a `ifile` object. In the latter case, a line is read and the line pointer is advanced.

Note that inserting LF between input lines is the Unix convention. Since we are doing this explicitly when gluing lines together, we can pattern-match against LF without having to worry about the system.

```

(Lexer: subroutines)+≡
  subroutine lexer_read_line (lexer, stream, iostat)
    type(lexer_t), intent(inout) :: lexer
    type(stream_t), intent(inout) :: stream
    integer, intent(out) :: iostat
    call stream_get_record (stream, lexer%line_buffer, iostat)
    lexer%current_line = lexer%current_line + 1
    if (iostat == 0) then
      lexer%buffer = lexer%buffer // lexer%line_buffer // LF
    end if
  end subroutine lexer_read_line

```

Once in a while we have read one lexeme too many, which can be pushed back into the input stream. Do not do this more than once.

```

(Lexer: public)+≡
  public :: lexer_put_back

(Lexer: subroutines)+≡
  subroutine lexer_put_back (lexer, lexeme)
    type(lexer_t), intent(inout) :: lexer
    type(lexeme_t), intent(in) :: lexeme
    if (lexeme_get_type (lexer%lexeme) == EMPTY) then
      lexer%lexeme = lexeme
    else
      call msg_bug (" Lexer: lex_back fails; probably called twice")
    end if
  end subroutine lexer_put_back

```

3.2.8 Diagnostics

For debugging: print just the setup

```

(Lexer: public)+≡
  public :: lexer_write_setup

(Lexer: subroutines)+≡
  subroutine lexer_write_setup (lexer, unit)
    type(lexer_t), intent(in) :: lexer
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    call lexer_setup_write (lexer%setup, u)
  end subroutine lexer_write_setup

```

This is useful for error printing: show the current line with index and a pointer to the current column within the line.

```

<Lexer: public>+≡
    public :: lexer_show_location

<Lexer: subroutines>+≡
    subroutine lexer_show_location (lexer)
        type(lexer_t), intent(in) :: lexer
        character(12) :: line_str
        integer :: indent
        write (line_str, *) lexer%current_line
        line_str = adjustl (line_str)
        indent = 6 + len_trim (line_str)
        write (*, "(1x, 'Line ',A,': ',A)") &
            trim (line_str), char (lexer%line_buffer)
!       if (lexer%previous_column <= lexer%current_column) then
!           write (*, "(1x, A)") &
!               repeat (" ", indent + lexer%previous_column) // "^" &
!               // repeat ("-", lexer%current_column - lexer%previous_column) &
!               // "^"
!       else
!           write (*, "(1x, A)") &
!               repeat (" ", indent + lexer%current_column) // "^"
!       end if
    end subroutine lexer_show_location

```

Test the lexer by lexing and printing all lexemes from unit u, one per line, using preset conventions

```

<Lexer: public>+≡
    public :: lexer_test

<Lexer: subroutines>+≡
    subroutine lexer_test (lexer, unit)
        type(lexer_t), intent(inout) :: lexer
        integer, intent(in) :: unit
        type(stream_t) :: stream
        type(lexeme_t) :: lexeme
        call lexer_clear (lexer)
        call stream_init (stream, unit)
        do
            call lex (lexeme, lexer, stream)
            call lexeme_write (lexeme, 6)
            if (lexeme_is_break (lexeme)) exit
        end do
        call stream_final (stream)
    end subroutine lexer_test

```

3.3 Syntax rules

This module provides tools to handle syntax rules in an abstract way.

```
<syntax_rules.f90>≡  
  <File header>  
  
  module syntax_rules  
  
    <Use strings>  
    <Use file utils>  
    use limits, only: UNQUOTED !NODEP!  
    use diagnostics !NODEP!  
    use ifiles, only: line_p, line_init, line_get_string_advance, line_final  
    use ifiles, only: ifile_t, ifile_get_length  
    use lexers, only: stream_t, stream_init, stream_final  
    use lexers, only: keyword_list_t, keyword_list_add  
    use lexers, only: keyword_list_write, keyword_list_final  
    use lexers, only: lexer_t, lexer_init, lexer_clear, lexer_final, lex  
    use lexers, only: lexeme_t  
    use lexers, only: lexeme_get_contents, lexeme_get_string, lexeme_is_break  
    use lexers, only: lexer_show_location  
  
    <Standard module head>  
  
    <Syntax: public>  
  
    <Syntax: parameters>  
  
    <Syntax: types>  
  
    <Syntax: interfaces>  
  
    contains  
  
    <Syntax: subroutines>  
  
  end module syntax_rules
```

3.3.1 Syntax rules

Syntax rules are used by the parser. They determine how to translate the stream of lexemes as returned by the lexer into the parse tree node. A rule may be terminal, i.e., replace a matching lexeme into a terminal node. The node will contain the lexeme interpreted as a recognized token:

- a keyword: unquoted fixed character string;
- a real number, to be determined at runtime;
- an integer, to be determined at runtime;
- a boolean value, to be determined at runtime;
- a quoted token (e.g., string), to be determined at runtime;

- an identifier (unquoted string that is not a recognized keyword), to be determined at runtime.

It may be nonterminal, i.e., contain a sequence of child rules. These are matched consecutively (and recursively) against the input stream; the resulting node will be a branch node.

- the file, i.e., the input stream as a whole;
- a sequence of syntax elements, where the last syntax element may be optional, or optional repetitive;

Sequences carry a flag that tells whether the last child is optional or may be repeated an arbitrary number of times, corresponding to the regexp modifiers `?`, `*`, and `+`.

We also need an alternative rule; this will be replaced by the node generated by one of its children that matches; thus, it does not create a node of its own.

- an alternative of syntax elements.

We also define special types of sequences as convenience macros:

- a list: a sequence where the elements are separated by a separator keyword (e.g., commas), the separators are thrown away when parsing the list;
- a group: a sequence of three tokens, where the first and third ones are left and right delimiters, the delimiters are thrown away;
- an argument list: a delimited list, containing both delimiters and separators.

It would be great to have a polymorphic type for this purpose, but until Fortran 2003 is out we have to emulate this.

Here are the syntax element codes:

```

<Syntax: public>≡
public :: S_UNKNOWN
public :: S_LOGICAL, S_INTEGER, S_REAL, S_COMPLEX, S_QUOTED
public :: S_IDENTIFIER, S_KEYWORD
public :: S_SEQUENCE, S_LIST, S_GROUP, S_ARGS
public :: S_ALTERNATIVE
public :: S_IGNORE

<Syntax: parameters>≡
integer, parameter :: &
    S_UNKNOWN = 0, &
    S_LOGICAL = 1, S_INTEGER = 2, S_REAL = 3, S_COMPLEX = 4, &
    S_QUOTED = 5, S_IDENTIFIER = 6, S_KEYWORD = 7, &
    S_SEQUENCE = 8, S_LIST = 9, S_GROUP = 10, S_ARGS = 11, &
    S_ALTERNATIVE = 12, &
    S_IGNORE = 99

```

We need arrays of rule pointers, therefore this construct.

```

<Syntax: types>≡
type :: rule_p
private
type(syntax_rule_t), pointer :: p => null ()
end type rule_p

```

Return the association status of the rule pointer:

```

<Syntax: subroutines>≡
  elemental function rule_is_associated (rp) result (ok)
    logical :: ok
    type (rule_p), intent(in) :: rp
    ok = associated (rp%p)
  end function rule_is_associated

```

The rule type is one of the types listed above, represented by an integer code. The keyword, for a non-keyword rule, is an identifier used for the printed syntax table. The array of children is needed for nonterminal rules. In that case, there is a modifier for the last element (blank, "?", "*", or "+"), mirrored in the flags **opt** and **rep**. Then, we have the character constants used as separators and delimiters for this rule. Finally, the **used** flag can be set to indicate that this rule is the child of another rule.

```

<Syntax: types>+≡
  public :: syntax_rule_t

<Syntax: types>+≡
  type :: syntax_rule_t
    private
    integer :: type = S_UNKNOWN
    logical :: used = .false.
    type(string_t) :: keyword
    type(string_t) :: separator
    type(string_t), dimension(2) :: delimiter
    type(rule_p), dimension(:), allocatable :: child
    character(1) :: modifier = ""
    logical :: opt = .false., rep = .false.
  end type syntax_rule_t

```

Initializer: Set type and key for a rule, but do not (yet) allocate anything.

Finalizer: not needed (no pointer components).

```

<Syntax: subroutines>+≡
  subroutine syntax_rule_init (rule, key, type)
    type(syntax_rule_t), intent(inout) :: rule
    type(string_t), intent(in) :: key
    integer, intent(in) :: type
    rule%keyword = key
    rule%type = type
    select case (rule%type)
    case (S_GROUP)
      call syntax_rule_set_delimiter (rule)
    case (S_LIST)
      call syntax_rule_set_separator (rule)
    case (S_ARGS)
      call syntax_rule_set_delimiter (rule)
      call syntax_rule_set_separator (rule)
    end select
  end subroutine syntax_rule_init

```

3.3.2 I/O

These characters will not be enclosed in quotes when writing syntax rules:

```
<Limits: public parameters>+≡
    character(*), parameter, public :: &
        UNQUOTED = "(),|_"/LCLETTERS/UCLETTERS/DIGITS
```

Write an account of the rule. Setting `short` true will suppress the node type. Setting `key_only` true will suppress the definition. Setting `advance` false will suppress the trailing newline.

```
<Syntax: public>+≡
    public :: syntax_rule_write

<Syntax: subroutines>+≡
    subroutine syntax_rule_write (rule, unit, short, key_only, advance)
        type(syntax_rule_t), intent(in) :: rule
        integer, intent(in), optional :: unit
        logical, intent(in), optional :: short, key_only, advance
        logical :: typ, def, adv
        integer :: u
        u = output_unit (unit); if (u < 0) return
        typ = .true.; if (present (short)) typ = .not. short
        def = .true.; if (present (key_only)) def = .not. key_only
        adv = .true.; if (present (advance)) adv = advance
        select case (rule%type)
            case (S_UNKNOWN); call write_atom ("???", typ)
            case (S_IGNORE); call write_atom ("IGNORE", typ)
            case (S_LOGICAL); call write_atom ("LOGICAL", typ)
            case (S_INTEGER); call write_atom ("INTEGER", typ)
            case (S_REAL); call write_atom ("REAL", typ)
            case (S_COMPLEX); call write_atom ("COMPLEX", typ)
            case (S_IDENTIFIER); call write_atom ("IDENTIFIER", typ)
            case (S_KEYWORD); call write_atom ("KEYWORD", typ)
            case (S_QUOTED)
                call write_quotes (typ, def, del = rule%delimiter)
            case (S_SEQUENCE)
                call write_sequence ("SEQUENCE", typ, def, size (rule%child))
            case (S_GROUP)
                call write_sequence ("GROUP", typ, def, size (rule%child), &
                    del = rule%delimiter)
            case (S_LIST)
                call write_sequence ("LIST", typ, def, size (rule%child), &
                    sep = rule%separator)
            case (S_ARGS)
                call write_sequence ("ARGUMENTS", typ, def, size (rule%child), &
                    del = rule%delimiter, sep = rule%separator)
            case (S_ALTERNATIVE)
                call write_sequence ("ALTERNATIVE", typ, def, size (rule%child), &
                    sep = var_str ("|"))
        end select
        if (adv) write (u, *)
contains
    subroutine write_type (type)
        character(*), intent(in) :: type
        character(11) :: str
```

```

    str = type
    write (u, "(1x,A)", advance="no") str
end subroutine write_type
subroutine write_key
    write (u, "(1x,A)", advance="no") char (wkey (rule))
end subroutine write_key
subroutine write_atom (type, typ)
    character(*), intent(in) :: type
    logical, intent(in) :: typ
    if (typ) call write_type (type)
    call write_key
end subroutine write_atom
subroutine write_maybe_quoted (string)
    character(*), intent(in) :: string
    character, parameter :: q = '"'
    character, parameter :: qq = '''
    if (verify (string, UNQUOTED) == 0) then
        write (u, "(1x,A)", advance = "no") trim (string)
    else if (verify (string, q) == 0) then
        write (u, "(1x,A)", advance = "no") qq // trim (string) // qq
    else
        write (u, "(1x,A)", advance = "no") q // trim (string) // q
    end if
end subroutine write_maybe_quoted
subroutine write_quotes (typ, def, del)
    logical, intent(in) :: typ, def
    type(string_t), dimension(2), intent(in) :: del
    if (typ) call write_type ("QUOTED")
    call write_key
    if (def) then
        write (u, "(1x, '=')", advance="no")
        call write_maybe_quoted (char (del(1)))
        write (u, "(1x,A)", advance="no") "...
        call write_maybe_quoted (char (del(2)))
    end if
end subroutine write_quotes
subroutine write_sequence (type, typ, def, n, del, sep)
    character(*), intent(in) :: type
    logical, intent(in) :: typ, def
    integer, intent(in) :: n
    type(string_t), dimension(2), intent(in), optional :: del
    type(string_t), intent(in), optional :: sep
    integer :: i
    if (typ) call write_type (type)
    call write_key
    if (def) then
        write (u, "(1x, '=')", advance="no")
        if (present (del)) call write_maybe_quoted (char (del(1)))
        do i = 1, n
            if (i > 1 .and. present (sep)) &
                call write_maybe_quoted (char (sep))
            write (u, "(1x,A)", advance="no") &
                char (wkey (syntax_rule_get_sub_ptr(rule, i)))
            if (i == n) write (u, "(A)", advance="no") trim (rule%modifier)
        end do
    end if
end subroutine write_sequence

```

```

        end do
        if (present (del)) call write_maybe_quoted (char (del(2)))
    end if
end subroutine write_sequence
end subroutine syntax_rule_write

```

In the printed representation, the keyword strings are enclosed as <...>, unless they are bare keywords. Bare keywords are enclosed as '...' if they contain a character which is not a letter, digit, or underscore. If they contain a single-quote character, they are enclosed as "...". (A keyword must not contain both single- and double-quotes.)

```

<Syntax: subroutines>+≡
function wkey (rule) result (string)
    type(string_t) :: string
    type(syntax_rule_t), intent(in) :: rule
    select case (rule%type)
    case (S_KEYWORD)
        if (verify (rule%keyword, UNQUOTED) == 0) then
            string = rule%keyword
        else if (scan (rule%keyword, "'") == 0) then
            string = "'" // rule%keyword // "'"
        else
            string = '...' // rule%keyword // '...'
        end if
    case default
        string = "<" // rule%keyword // ">"
    end select
end function wkey

```

3.3.3 Completing syntax rules

Set the separator and delimiter entries, using defaults:

```

<Syntax: subroutines>+≡
subroutine syntax_rule_set_separator (rule, separator)
    type(syntax_rule_t), intent(inout) :: rule
    type(string_t), intent(in), optional :: separator
    if (present (separator)) then
        rule%separator = separator
    else
        rule%separator = ","
    end if
end subroutine syntax_rule_set_separator

subroutine syntax_rule_set_delimiter (rule, delimiter)
    type(syntax_rule_t), intent(inout) :: rule
    type(string_t), dimension(2), intent(in), optional :: delimiter
    if (present (delimiter)) then
        rule%delimiter = delimiter
    else
        rule%delimiter = (/ "(", ")" /)
    end if
end subroutine syntax_rule_set_delimiter

```

```
end subroutine syntax_rule_set_delimiter
```

Set the modifier entry and corresponding flags:

<Syntax: subroutines>+≡

```
function is_modifier (string) result (ok)
  logical :: ok
  type(string_t), intent(in) :: string
  select case (char (string))
    case (" ", "?", "*", "+"); ok = .true.
    case default; ok = .false.
  end select
end function is_modifier

subroutine syntax_rule_set_modifier (rule, modifier)
  type(syntax_rule_t), intent(inout) :: rule
  type(string_t), intent(in) :: modifier
  rule%modifier = char (modifier)
  select case (rule%modifier)
    case (" ")
    case ("?"); rule%opt = .true.
    case ("*"); rule%opt = .true.; rule%rep = .true.
    case ("+"); rule%rep = .true.
    case default
      call msg_bug (" Syntax: sequence modifier '" // rule%modifier &
        // "' is not one of '+' '*' '?'")
  end select
end subroutine syntax_rule_set_modifier
```

Check a finalized rule for completeness

<Syntax: subroutines>+≡

```
subroutine syntax_rule_check (rule)
  type(syntax_rule_t), intent(in) :: rule
  if (rule%keyword == "") call msg_bug ("Rule key not set")
  select case (rule%type)
    case (S_UNKNOWN); call bug (" Undefined rule")
    case (S_IGNORE, S_LOGICAL, S_INTEGER, S_REAL, S_COMPLEX, &
      S_IDENTIFIER, S_KEYWORD)
    case (S_QUOTED)
      if (any (rule%delimiter == "")) call bug (" Missing quote character(s)")
    case (S_SEQUENCE)
    case (S_GROUP)
      if (any (rule%delimiter == "")) call bug (" Missing delimiter(s)")
    case (S_LIST)
      if (rule%separator == "") call bug (" Missing separator")
    case (S_ARGS)
      if (any (rule%delimiter == "")) call bug (" Missing delimiter(s)")
      if (rule%separator == "") call bug (" Missing separator")
    case (S_ALTERNATIVE)
    case default
      call bug (" Undefined syntax code")
  end select
  select case (rule%type)
    case (S_SEQUENCE, S_GROUP, S_LIST, S_ARGS, S_ALTERNATIVE)
```

```

        if (allocated (rule%child)) then
            if (.not.all (rule_is_associated (rule%child))) &
                call bug (" Child rules not all associated")
        else
            call bug (" Parent rule without children")
        end if
    case default
        if (allocated (rule%child)) call bug (" Non-parent rule with children")
    end select
contains
    subroutine bug (string)
        character(*), intent(in) :: string
        call msg_bug (" Syntax table: Rule " // char (rule%keyword) // ": " &
            // string)
    end subroutine bug
end subroutine syntax_rule_check

```

3.3.4 Accessing rules

This is the API for syntax rules:

```

<Syntax: public>+≡
    public :: syntax_rule_get_type

<Syntax: subroutines>+≡
    function syntax_rule_get_type (rule) result (type)
        integer :: type
        type(syntax_rule_t), intent(in) :: rule
        type = rule%type
    end function syntax_rule_get_type

<Syntax: public>+≡
    public :: syntax_rule_get_key

<Syntax: subroutines>+≡
    function syntax_rule_get_key (rule) result (key)
        type(string_t) :: key
        type(syntax_rule_t), intent(in) :: rule
        key = rule%keyword
    end function syntax_rule_get_key

<Syntax: public>+≡
    public :: syntax_rule_get_separator
    public :: syntax_rule_get_delimiter

<Syntax: subroutines>+≡
    function syntax_rule_get_separator (rule) result (separator)
        type(string_t) :: separator
        type(syntax_rule_t), intent(in) :: rule
        separator = rule%separator
    end function syntax_rule_get_separator

    function syntax_rule_get_delimiter (rule) result (delimiter)
        type(string_t), dimension(2) :: delimiter

```

```

    type(syntax_rule_t), intent(in) :: rule
    delimiter = rule%delimiter
end function syntax_rule_get_delimiter

```

Accessing child rules. If we use `syntax_rule_get_n_sub` for determining loop bounds, we do not need a check in the second routine.

```

<Syntax: public>+≡
    public :: syntax_rule_get_n_sub
    public :: syntax_rule_get_sub_ptr

<Syntax: subroutines>+≡
    function syntax_rule_get_n_sub (rule) result (n)
        integer :: n
        type(syntax_rule_t), intent(in) :: rule
        if (allocated (rule%child)) then
            n = size (rule%child)
        else
            n = 0
        end if
    end function syntax_rule_get_n_sub

    function syntax_rule_get_sub_ptr (rule, i) result (sub)
        type(syntax_rule_t), pointer :: sub
        type(syntax_rule_t), intent(in), target :: rule
        integer, intent(in) :: i
        sub => rule%child(i)%p
    end function syntax_rule_get_sub_ptr

    subroutine syntax_rule_set_sub (rule, i, sub)
        type(syntax_rule_t), intent(inout) :: rule
        integer, intent(in) :: i
        type(syntax_rule_t), intent(in), target :: sub
        rule%child(i)%p => sub
    end subroutine syntax_rule_set_sub

```

Return the modifier flags:

```

<Syntax: public>+≡
    public :: syntax_rule_last_optional
    public :: syntax_rule_last_repetitive

<Syntax: subroutines>+≡
    function syntax_rule_last_optional (rule) result (opt)
        logical :: opt
        type(syntax_rule_t), intent(in) :: rule
        opt = rule%opt
    end function syntax_rule_last_optional
    function syntax_rule_last_repetitive (rule) result (rep)
        logical :: rep
        type(syntax_rule_t), intent(in) :: rule
        rep = rule%rep
    end function syntax_rule_last_repetitive

```

Return true if the rule is atomic, i.e., logical, real, keyword etc.

```
<Syntax: public>+≡
    public :: syntax_rule_is_atomic

<Syntax: subroutines>+≡
    function syntax_rule_is_atomic (rule) result (atomic)
        logical :: atomic
        type(syntax_rule_t), intent(in) :: rule
        select case (rule%type)
            case (S_LOGICAL, S_INTEGER, S_REAL, S_COMPLEX, S_IDENTIFIER, &
                 S_KEYWORD, S_QUOTED)
                atomic = .true.
            case default
                atomic = .false.
        end select
    end function syntax_rule_is_atomic
```

3.3.5 Syntax tables

A syntax table contains the tree of syntax rules and, for direct parser access, the list of valid keywords.

Types

The syntax contains an array of rules and a list of keywords. The array is actually used as a tree, where the top rule is the first array element, and the other rules are recursively pointed to by this first rule. (No rule should be used twice or be unused.) The keyword list is derived from the rule tree.

Objects of this type need the target attribute if they are associated with a lexer. The keyword list will be pointed to by this lexer.

```
<Syntax: public>+≡
    public :: syntax_t

<Syntax: types>+≡
    type :: syntax_t
        private
        type(syntax_rule_t), dimension(:), allocatable :: rule
        type(keyword_list_t) :: keyword_list
    end type syntax_t
```

Constructor/destructor

Initialize and finalize syntax tables

```
<Syntax: public>+≡
    public :: syntax_init
    public :: syntax_final
```

There are two ways to create a syntax: hard-coded from rules or dynamically from file.

```

<Syntax: interfaces>≡
interface syntax_init
  module procedure syntax_init_from_ifile
end interface

```

The syntax definition is read from an ifile object which contains the syntax definitions in textual form, one rule per line. This interface allows for determining the number of rules beforehand.

To parse the rule definitions, we make up a temporary lexer. Obviously, we cannot use a generic parser yet, so we have to hardcode the parsing process.

```

<Syntax: subroutines>+=
subroutine syntax_init_from_ifile (syntax, ifile)
  type(syntax_t), intent(out), target :: syntax
  type(ifile_t), intent(in) :: ifile
  type(lexer_t) :: lexer
  type(line_p) :: line
  type(string_t) :: string
  integer :: n_token
  integer :: i
  call lexer_init (lexer, &
    comment_chars = "", &
    quote_chars = "<'\"", &
    quote_match = ">'\"", &
    single_chars = "?*+|=,()", &
    special_class = (/ "." /), &
    keyword_list = null ())
  allocate (syntax%rule (ifile_get_length (ifile)))
  call line_init (line, ifile)
  do i = 1, size (syntax%rule)
    string = line_get_string_advance (line)
    call set_rule_type_and_key (syntax%rule(i), string, lexer)
  end do
  call line_init (line, ifile)
  do i = 1, size (syntax%rule)
    string = line_get_string_advance (line)
    select case (syntax%rule(i)%type)
      case (S_QUOTED, S_SEQUENCE, S_GROUP, S_LIST, S_ARGS, S_ALTERNATIVE)
        n_token = get_n_token (string, lexer)
        call set_rule_contents &
          (syntax%rule(i), syntax, n_token, string, lexer)
    end select
  end do
  call line_final (line)
  call lexer_final (lexer)
  call syntax_make_keyword_list (syntax)
  if (.not. all (syntax%rule%used)) then
    do i = 1, size (syntax%rule)
      if (.not. syntax%rule(i)%used) then
        call syntax_rule_write (syntax%rule(i), 6)
      end if
    end do
  end if
end do

```

```

        call msg_bug (" Syntax table: unused rules")
    end if
end subroutine syntax_init_from_ifile

```

For a given rule defined in the input, the first task is to determine its type and key. With these, we can initialize the rule in the table, postponing the association of children.

```

<Syntax: subroutines>+=
subroutine set_rule_type_and_key (rule, string, lexer)
    type(syntax_rule_t), intent(inout) :: rule
    type(string_t), intent(in) :: string
    type(lexer_t), intent(inout) :: lexer
    type(stream_t) :: stream
    type(lexeme_t) :: lexeme
    type(string_t) :: key
    character(2) :: type
    call lexer_clear (lexer)
    call stream_init (stream, string)
    call lex (lexeme, lexer, stream)
    type = lexeme_get_string (lexeme)
    call lex (lexeme, lexer, stream)
    key = lexeme_get_contents (lexeme)
    call stream_final (stream)
    if (trim (key) /= "") then
        select case (type)
            case ("IG"); call syntax_rule_init (rule, key, S_IGNORE)
            case ("LO"); call syntax_rule_init (rule, key, S_LOGICAL)
            case ("IN"); call syntax_rule_init (rule, key, S_INTEGER)
            case ("RE"); call syntax_rule_init (rule, key, S_REAL)
            case ("CO"); call syntax_rule_init (rule, key, S_COMPLEX)
            case ("ID"); call syntax_rule_init (rule, key, S_IDENTIFIER)
            case ("KE"); call syntax_rule_init (rule, key, S_KEYWORD)
            case ("QU"); call syntax_rule_init (rule, key, S_QUOTED)
            case ("SE"); call syntax_rule_init (rule, key, S_SEQUENCE)
            case ("GR"); call syntax_rule_init (rule, key, S_GROUP)
            case ("LI"); call syntax_rule_init (rule, key, S_LIST)
            case ("AR"); call syntax_rule_init (rule, key, S_ARGS)
            case ("AL"); call syntax_rule_init (rule, key, S_ALTERNATIVE)
            case default
                call lexer_show_location (lexer)
                call msg_bug (" Syntax definition: unknown type '" // type // "'")
            end select
        else
            print *, char (string)
            call msg_bug (" Syntax definition: empty rule key")
        end if
    end subroutine set_rule_type_and_key

```

This function returns the number of tokens in an input line.

```

<Syntax: subroutines>+=
function get_n_token (string, lexer) result (n)
    integer :: n
    type(string_t), intent(in) :: string

```

```

type(lexer_t), intent(inout) :: lexer
type(stream_t) :: stream
type(lexeme_t) :: lexeme
integer :: i
call stream_init (stream, string)
call lexer_clear (lexer)
i = 0
do
    call lex (lexeme, lexer, stream)
    if (lexeme_is_break (lexeme)) exit
    i = i + 1
end do
n = i
call stream_final (stream)
end function get_n_token

```

This subroutine extracts the rule contents for an input line. There are three tasks: (1) determine the number of children, depending on the rule type; (2) find and set the separator and delimiter strings, if required; (3) scan the child rules, find them in the syntax table and associate the parent rule with them.

(Syntax: subroutines)+≡

```

subroutine set_rule_contents (rule, syntax, n_token, string, lexer)
type(syntax_rule_t), intent(inout) :: rule
type(syntax_t), intent(in), target :: syntax
integer, intent(in) :: n_token
type(string_t), intent(in) :: string
type(lexer_t), intent(inout) :: lexer
type(stream_t) :: stream
type(lexeme_t), dimension(n_token) :: lexeme
integer :: i, n_children
call lexer_clear (lexer)
call stream_init (stream, string)
do i = 1, n_token
    call lex (lexeme(i), lexer, stream)
end do
call stream_final (stream)
n_children = get_n_children ()
call set_delimiters
if (n_children > 1) call set_separator
if (n_children > 0) call set_children
contains
function get_n_children () result (n_children)
integer :: n_children
select case (rule%type)
case (S_QUOTED)
    if (n_token /= 6) call broken_rule (rule)
    n_children = 0
case (S_GROUP)
    if (n_token /= 6) call broken_rule (rule)
    n_children = 1
case (S_SEQUENCE)
    if (is_modifier (lexeme_get_string (lexeme(n_token)))) then
        if (n_token <= 4) call broken_rule (rule)

```

```

        call syntax_rule_set_modifier &
            (rule, lexeme_get_string (lexeme(n_token)))
        n_children = n_token - 4
    else
        if (n_token <= 3) call broken_rule (rule)
        n_children = n_token - 3
    end if
case (S_LIST)
    if (is_modifier (lexeme_get_string (lexeme(n_token)))) then
        if (n_token <= 4 .or. mod (n_token, 2) /= 1) &
            call broken_rule (rule)
        call syntax_rule_set_modifier &
            (rule, lexeme_get_string (lexeme(n_token)))
    else if (n_token <= 3 .or. mod (n_token, 2) /= 0) then
        call broken_rule (rule)
    end if
    n_children = (n_token - 2) / 2
case (S_ARGS)
    if (is_modifier (lexeme_get_string (lexeme(n_token-1)))) then
        if (n_token <= 6 .or. mod (n_token, 2) /= 1) &
            call broken_rule (rule)
        call syntax_rule_set_modifier &
            (rule, lexeme_get_string (lexeme(n_token-1)))
    else if (n_token <= 5 .or. mod (n_token, 2) /= 0) then
        call broken_rule (rule)
    end if
    n_children = (n_token - 4) / 2
case (S_ALTERNATIVE)
    if (n_token <= 3 .or. mod (n_token, 2) /= 0) call broken_rule (rule)
    n_children = (n_token - 2) / 2
end select
end function get_n_children
subroutine set_delimiters
    type(string_t), dimension(2) :: delimiter
    select case (rule%type)
    case (S_QUOTED, S_GROUP, S_ARGS)
        delimiter(1) = lexeme_get_contents (lexeme(4))
        delimiter(2) = lexeme_get_contents (lexeme(n_token))
        call syntax_rule_set_delimiter (rule, delimiter)
    end select
end subroutine set_delimiters
subroutine set_separator
    type(string_t) :: separator
    select case (rule%type)
    case (S_LIST)
        separator = lexeme_get_contents (lexeme(5))
        call syntax_rule_set_separator (rule, separator)
    case (S_ARGS)
        separator = lexeme_get_contents (lexeme(6))
        call syntax_rule_set_separator (rule, separator)
    end select
end subroutine set_separator
subroutine set_children
    allocate (rule%child(n_children))

```

```

select case (rule%type)
case (S_GROUP)
    call syntax_rule_set_sub (rule, 1, syntax_get_rule_ptr (syntax, &
        lexeme_get_contents (lexeme(5))))
case (S_SEQUENCE)
    do i = 1, n_children
        call syntax_rule_set_sub (rule, i, syntax_get_rule_ptr (syntax, &
            lexeme_get_contents (lexeme(i+3))))
    end do
case (S_LIST, S_ALTERNATIVE)
    do i = 1, n_children
        call syntax_rule_set_sub (rule, i, syntax_get_rule_ptr (syntax, &
            lexeme_get_contents (lexeme(2*i+2))))
    end do
case (S_ARGS)
    do i = 1, n_children
        call syntax_rule_set_sub (rule, i, syntax_get_rule_ptr (syntax, &
            lexeme_get_contents (lexeme(2*i+3))))
    end do
end select
end subroutine set_children
subroutine broken_rule (rule)
    type(syntax_rule_t), intent(in) :: rule
    call lexer_show_location (lexer)
    call msg_bug (" Syntax definition: broken rule '" &
        // char (wkey (rule)) // "'")
end subroutine broken_rule
end subroutine set_rule_contents

```

This routine completes the syntax table object. We assume that the rule array is set up. We associate the top rule with the first entry in the rule array and build up the keyword list.

The keyword list includes delimiters and separators. Filling it can only be done after all rules are set. We scan the rule tree. For each keyword that we find, we try to add it to the keyword list; the pointer to the last element is carried along with the recursive scanning. Before appending a keyword, we check whether it is already in the list.

(*Syntax: subroutines*) +=

```

subroutine syntax_make_keyword_list (syntax)
    type(syntax_t), intent(inout), target :: syntax
    type(syntax_rule_t), pointer :: rule
    rule => syntax%rule(1)
    call rule_scan_rec (rule, syntax%keyword_list)
contains
    recursive subroutine rule_scan_rec (rule, keyword_list)
        type(syntax_rule_t), pointer :: rule
        type(keyword_list_t), intent(inout) :: keyword_list
        integer :: i
        if (rule%used) return
        rule%used = .true.
        select case (rule%type)
        case (S_UNKNOWN)
            call msg_bug (" Syntax: rule tree contains undefined rule")

```

```

case (S_KEYWORD)
  call keyword_list_add (keyword_list, rule%keyword)
end select
select case (rule%type)
case (S_LIST, S_ARGS)
  call keyword_list_add (keyword_list, rule%separator)
end select
select case (rule%type)
case (S_GROUP, S_ARGS)
  call keyword_list_add (keyword_list, rule%delimiter(1))
  call keyword_list_add (keyword_list, rule%delimiter(2))
end select
select case (rule%type)
case (S_SEQUENCE, S_GROUP, S_LIST, S_ARGS, S_ALTERNATIVE)
  if (.not. allocated (rule%child)) &
    call msg_bug (" Syntax: Non-terminal rule without children")
case default
  if (allocated (rule%child)) &
    call msg_bug (" Syntax: Terminal rule with children")
end select
if (allocated (rule%child)) then
  do i = 1, size (rule%child)
    call rule_scan_rec (rule%child(i)%p, keyword_list)
  end do
end if
end subroutine rule_scan_rec
end subroutine syntax_make_keyword_list

```

The finalizer deallocates the rule pointer array and deletes the keyword list.

```

<Syntax: subroutines>+≡
subroutine syntax_final (syntax)
  type(syntax_t), intent(inout) :: syntax
  if (allocated (syntax%rule)) deallocate (syntax%rule)
  call keyword_list_final (syntax%keyword_list)
end subroutine syntax_final

```

3.3.6 Accessing the syntax table

Return a pointer to the top rule

```

<Syntax: public>+≡
public :: syntax_get_top_rule_ptr

<Syntax: subroutines>+≡
function syntax_get_top_rule_ptr (syntax) result (rule)
  type(syntax_rule_t), pointer :: rule
  type(syntax_t), intent(in), target :: syntax
  if (allocated (syntax%rule)) then
    rule => syntax%rule(1)
  else
    rule => null ()
  end if
end function syntax_get_top_rule_ptr

```

Assign the pointer to the rule associated with a given key (assumes that the rule array is allocated)

```

<Syntax: public>+≡
    public :: syntax_get_rule_ptr

<Syntax: subroutines>+≡
    function syntax_get_rule_ptr (syntax, key) result (rule)
        type(syntax_rule_t), pointer :: rule
        type(syntax_t), intent(in), target :: syntax
        type(string_t), intent(in) :: key
        integer :: i
        do i = 1, size (syntax%rule)
            if (syntax%rule(i)%keyword == key) then
                rule => syntax%rule(i)
                return
            end if
        end do
        call msg_bug (" Syntax table: Rule " // char (key) // " not found")
    end function syntax_get_rule_ptr

```

Return a pointer to the keyword list

```

<Syntax: public>+≡
    public :: syntax_get_keyword_list_ptr

<Syntax: subroutines>+≡
    function syntax_get_keyword_list_ptr (syntax) result (keyword_list)
        type(keyword_list_t), pointer :: keyword_list
        type(syntax_t), intent(in), target :: syntax
        keyword_list => syntax%keyword_list
    end function syntax_get_keyword_list_ptr

```

3.3.7 I/O

Write a readable representation of the syntax table

```

<Syntax: public>+≡
    public :: syntax_write

<Syntax: subroutines>+≡
    subroutine syntax_write (syntax, unit)
        type(syntax_t), intent(in) :: syntax
        integer, intent(in), optional :: unit
        integer :: u
        integer :: i
        u = output_unit (unit); if (u < 0) return
        write (u, "(A)") "Syntax table:"
        if (allocated (syntax%rule)) then
            do i = 1, size (syntax%rule)
                call syntax_rule_write (syntax%rule(i), u)
            end do
        else
            write (u, "(1x,A)") "[not allocated]"
        end if
        call keyword_list_write (syntax%keyword_list, u)
    end subroutine syntax_write

```

```
end subroutine syntax_write
```

3.4 The parser

On a small scale, the parser interprets the string tokens returned by the lexer; they are interpreted as numbers, keywords and such and stored as a typed object. On a large scale, a text is read, parsed, and a syntax rule set is applied such that the tokens are stored as a parse tree. Syntax errors are spotted in this process, so the resulting parse tree is syntactically correct by definition.

```
<parser.f90>≡  
  <File header>  
  
  module parser  
  
    <Use kinds>  
    <Use strings>  
    use limits, only: DIGITS !NODEP!  
    <Use file utils>  
    use diagnostics !NODEP!  
    use md5  
    use lexers  
    use syntax_rules  
  
    <Standard module head>  
  
    <Parser: public>  
  
    <Parser: types>  
  
    <Parser: interfaces>  
  
    contains  
  
    <Parser: procedures>  
  
  end module parser
```

3.4.1 The token type

Tokens are elements of the parsed input that carry a value: logical, integer, real, quoted string, (unquoted) identifier, or known keyword. Note that non-keyword tokens also have an abstract key attached to them.

This is an obvious candidate for polymorphism.

```
<Parser: types>≡  
  type :: token_t  
    private  
    integer :: type = S_UNKNOWN  
    logical, pointer :: lval => null ()  
    integer, pointer :: ival => null ()  
    real(default), pointer :: rval => null ()  
    complex(default), pointer :: cval => null ()  
    type(string_t), pointer :: sval => null ()  
    type(string_t), pointer :: kval => null ()  
    type(string_t), dimension(:), pointer :: quote => null ()
```

```
end type token_t
```

Create a token from the lexeme returned by the lexer: Allocate storage and try to interpret the lexeme according to the type that is requested by the parser. For a keyword token, match the lexeme against the requested key. If successful, set the token type, value, and key. Otherwise, set the type to S_UNKNOWN.

(Parser: procedures)≡

```
subroutine token_init (token, lexeme, requested_type, key)
  type(token_t), intent(out) :: token
  type(lexeme_t), intent(in) :: lexeme
  integer, intent(in) :: requested_type
  type(string_t), intent(in) :: key
  integer :: type
  type = lexeme_get_type (lexeme)
  token%type = S_UNKNOWN
  select case (requested_type)
  case (S_LOGICAL)
    if (type == T_IDENTIFIER) call read_logical &
      (char (lexeme_get_string (lexeme)))
  case (S_INTEGER)
    if (type == T_NUMERIC) call read_integer &
      (char (lexeme_get_string (lexeme)))
  case (S_REAL)
    if (type == T_NUMERIC) call read_real &
      (char (lexeme_get_string (lexeme)))
  case (S_COMPLEX)
    if (type == T_NUMERIC) call read_complex &
      (char (lexeme_get_string (lexeme)))
  case (S_IDENTIFIER)
    if (type == T_IDENTIFIER) call read_identifier &
      (lexeme_get_string (lexeme))
  case (S_KEYWORD)
    if (type == T_KEYWORD) call check_keyword &
      (lexeme_get_string (lexeme), key)
  case (S_QUOTED)
    if (type == T_QUOTED) call read_quoted &
      (lexeme_get_contents (lexeme), lexeme_get_delimiters (lexeme))
  case default
    print *, requested_type
    call msg_bug (" Invalid token type code requested by the parser")
  end select
  if (token%type /= S_UNKNOWN) then
    allocate (token%kval)
    token%kval = key
  end if
contains
  subroutine read_logical (s)
    character(*), intent(in) :: s
    select case (s)
    case ("t", "T", "true", "TRUE", "y", "Y", "yes", "YES")
      allocate (token%lval)
      token%lval = .true.
      token%type = S_LOGICAL
```

```

        case ("f", "F", "false", "FALSE", "n", "N", "no", "NO")
            allocate (token%lval)
            token%lval = .false.
            token%type = S_LOGICAL
        end select
    end subroutine read_logical
    subroutine read_integer (s)
        character(*), intent(in) :: s
        integer :: tmp, iostat
        if (verify (s, DIGITS) == 0) then
            read (s, *, iostat=iostat) tmp
            if (iostat == 0) then
                allocate (token%ival)
                token%ival = tmp
                token%type = S_INTEGER
            end if
        end if
    end subroutine read_integer
    subroutine read_real (s)
        character(*), intent(in) :: s
        real(default) :: tmp
        integer :: iostat
        read (s, *, iostat=iostat) tmp
        if (iostat == 0) then
            allocate (token%rval)
            token%rval = tmp
            token%type = S_REAL
        end if
    end subroutine read_real
    subroutine read_complex (s)
        character(*), intent(in) :: s
        complex(default) :: tmp
        integer :: iostat
        read (s, *, iostat=iostat) tmp
        if (iostat == 0) then
            allocate (token%cval)
            token%cval = tmp
            token%type = S_COMPLEX
        end if
    end subroutine read_complex
    subroutine read_identifier (s)
        type(string_t), intent(in) :: s
        allocate (token%sval)
        token%sval = s
        token%type = S_IDENTIFIER
    end subroutine read_identifier
    subroutine check_keyword (s, key)
        type(string_t), intent(in) :: s
        type(string_t), intent(in) :: key
        if (key == s) token%type = S_KEYWORD
    end subroutine check_keyword
    subroutine read_quoted (s, del)
        type(string_t), intent(in) :: s
        type(string_t), dimension(2), intent(in) :: del

```

```

        allocate (token%sval, token%quote(2))
        token%sval = s
        token%quote(1) = del(1)
        token%quote(2) = del(2)
        token%type = S_QUOTED
    end subroutine read_quoted
end subroutine token_init

```

Reset a token to an empty state, freeing allocated memory, and deallocate the token itself.

```

(Parser: procedures)+≡
subroutine token_final (token)
    type(token_t), intent(inout) :: token
    token%type = S_UNKNOWN
    if (associated (token%lval)) deallocate (token%lval)
    if (associated (token%ival)) deallocate (token%ival)
    if (associated (token%rval)) deallocate (token%rval)
    if (associated (token%sval)) deallocate (token%sval)
    if (associated (token%kval)) deallocate (token%kval)
    if (associated (token%quote)) deallocate (token%quote)
end subroutine token_final

```

Check for empty=valid token:

```

(Parser: procedures)+≡
function token_is_valid (token) result (valid)
    logical :: valid
    type(token_t), intent(in) :: token
    valid = token%type /= S_UNKNOWN
end function token_is_valid

```

Write the contents of a token.

```

(Parser: procedures)+≡
subroutine token_write (token, unit)
    type(token_t), intent(in) :: token
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    select case (token%type)
    case (S_LOGICAL)
        write (u, *) token%lval
    case (S_INTEGER)
        write (u, *) token%ival
    case (S_REAL)
        write (u, *) token%rval
    case (S_COMPLEX)
        write (u, *) token%cval
    case (S_IDENTIFIER)
        write (u, *) char (token%sval)
    case (S_KEYWORD)
        write (u, *) '[keyword] ' // char (token%kval)
    case (S_QUOTED)
        write (u, *) &

```

```

        char (token%quote(1)) // char (token%sval) // char (token%quote(2))
    case default
        write (u, *) '[empty]'
    end select
end subroutine token_write

```

Token assignment via deep copy. This is useful to avoid confusion when the token is transferred to some parse-tree node.

```

(Parser: interfaces)≡
    interface assignment(=)
        module procedure token_assign
    end interface

```

We need to copy only the contents that are actually assigned, the other pointers remain disassociated.

```

(Parser: procedures)+≡
    subroutine token_assign (token, token_in)
        type(token_t), intent(out) :: token
        type(token_t), intent(in) :: token_in
        token%type = token_in%type
        select case (token%type)
            case (S_LOGICAL);    allocate (token%lval); token%lval = token_in%lval
            case (S_INTEGER);    allocate (token%ival); token%ival = token_in%ival
            case (S_REAL);       allocate (token%rval); token%rval = token_in%rval
            case (S_COMPLEX);    allocate (token%cval); token%cval = token_in%cval
            case (S_IDENTIFIER); allocate (token%sval); token%sval = token_in%sval
            case (S_QUOTED);     allocate (token%sval); token%sval = token_in%sval
                                allocate (token%quote(2)); token%quote = token_in%quote
        end select
        if (token%type /= S_UNKNOWN) then
            allocate (token%kval); token%kval = token_in%kval
        end if
    end subroutine token_assign

```

3.4.2 Retrieve token contents

These functions all do a trivial sanity check that should avoid crashes.

```

(Parser: procedures)+≡
    function token_get_logical (token) result (lval)
        logical :: lval
        type(token_t), intent(in) :: token
        if (associated (token%lval)) then
            lval = token%lval
        else
            call token_mismatch (token, "logical")
        end if
    end function token_get_logical

    function token_get_integer (token) result (ival)
        integer :: ival
        type(token_t), intent(in) :: token

```

```

    if (associated (token%ival)) then
        ival = token%ival
    else
        call token_mismatch (token, "integer")
    end if
end function token_get_integer

function token_get_real (token) result (rval)
    real(default) :: rval
    type(token_t), intent(in) :: token
    if (associated (token%rval)) then
        rval = token%rval
    else
        call token_mismatch (token, "real")
    end if
end function token_get_real

function token_get_cmplx (token) result (cval)
    real(default) :: cval
    type(token_t), intent(in) :: token
    if (associated (token%cval)) then
        cval = token%cval
    else
        call token_mismatch (token, "complex")
    end if
end function token_get_cmplx

function token_get_string (token) result (sval)
    type(string_t) :: sval
    type(token_t), intent(in) :: token
    if (associated (token%sval)) then
        sval = token%sval
    else
        call token_mismatch (token, "string")
    end if
end function token_get_string

function token_get_key (token) result (kval)
    type(string_t) :: kval
    type(token_t), intent(in) :: token
    if (associated (token%kval)) then
        kval = token%kval
    else
        call token_mismatch (token, "keyword")
    end if
end function token_get_key

function token_get_quote (token) result (quote)
    type(string_t), dimension(2) :: quote
    type(token_t), intent(in) :: token
    if (associated (token%quote)) then
        quote = token%quote
    else
        call token_mismatch (token, "quote")
    end if
end function token_get_quote

```

```

    end if
end function token_get_quote

```

```

<Parser: procedures>+≡
subroutine token_mismatch (token, type)
  type(token_t), intent(in) :: token
  character(*), intent(in) :: type
  write (6, "(A)", advance="no") "Token: "
  call token_write (token)
  call msg_bug (" Token type mismatch; value required as " // type)
end subroutine token_mismatch

```

3.4.3 The parse tree: nodes

The parser will generate a parse tree from the input stream. Each node in this parse tree points to the syntax rule that was applied. (Since syntax rules are stored in a pointer-type array within the syntax table, they qualify as targets.) A leaf node contains a token. A branch node has subnodes. The subnodes are stored as a list, so each node also has a next pointer.

```

<Parser: public>≡
  public :: parse_node_t

<Parser: types>+≡
  type :: parse_node_t
  private
    type(syntax_rule_t), pointer :: rule => null ()
    type(token_t) :: token
    integer :: n_sub = 0
    type(parse_node_t), pointer :: sub_first => null ()
    type(parse_node_t), pointer :: sub_last => null ()
    type(parse_node_t), pointer :: next => null ()
  end type parse_node_t

```

Output. The first version writes a node together with its sub-node tree, organized by indentation.

```

<Parser: public>+≡
  public :: parse_node_write_rec

<Parser: procedures>+≡
  recursive subroutine parse_node_write_rec (node, unit, short, depth)
    type(parse_node_t), intent(in), target :: node
    integer, intent(in), optional :: unit
    logical, intent(in), optional :: short
    integer, intent(in), optional :: depth
    integer :: u, d
    type(parse_node_t), pointer :: current
    u = output_unit (unit); if (u < 0) return
    d = 0; if (present (depth)) d = depth
    call parse_node_write (node, u, short=short)
    current => node%sub_first
    do while (associated (current))
      write (u, "(A)", advance = "no") repeat ("| ", d)

```

```

        call parse_node_write_rec (current, unit, short, d+1)
        current => current%next
    end do
end subroutine parse_node_write_rec

```

This does the actual output for a single node, without recursion.

```

(Parser: public)+≡
    public :: parse_node_write

(Parser: procedures)+≡
    subroutine parse_node_write (node, unit, short)
        type(parse_node_t), intent(in) :: node
        integer, intent(in), optional :: unit
        logical, intent(in), optional :: short
        integer :: u
        type(parse_node_t), pointer :: current
        u = output_unit (unit); if (u < 0) return
        write (u, "(' + ')", advance = "no")
        if (associated (node%rule)) then
            call syntax_rule_write (node%rule, u, &
                short=short, key_only=.true., advance=.false.)
            if (token_is_valid (node%token)) then
                write (u, "(' = ')", advance="no")
                call token_write (node%token, u)
            else if (associated (node%sub_first)) then
                write (u, "(' = ')", advance="no")
                current => node%sub_first
                do while (associated (current))
                    call syntax_rule_write (current%rule, u, &
                        short=.true., key_only=.true., advance=.false.)
                    current => current%next
                end do
                write (u, *)
            else
                write (u, *)
            end if
        else
            write (u, *) "[empty]"
        end if
    end subroutine parse_node_write

```

Finalize the token and recursively finalize and deallocate all sub-nodes.

```

(Parser: procedures)+≡
    recursive subroutine parse_node_final (node)
        type(parse_node_t), intent(inout) :: node
        type(parse_node_t), pointer :: current
        call token_final (node%token)
        do while (associated (node%sub_first))
            current => node%sub_first
            node%sub_first => node%sub_first%next
            call parse_node_final (current)
            deallocate (current)
        end do
    end subroutine parse_node_final

```

```
end subroutine parse_node_final
```

3.4.4 Filling nodes

The constructors allocate and initialize the node. There are two possible initializers (in a later version, should correspond to different type extensions).

First, leaf (terminal) nodes. The token constructor does the actual work, looking at the requested type and key for the given rule and matching against the lexeme contents. If it fails, the token will keep the type `S_UNKNOWN` and remain empty. Otherwise, we have a valid node which contains the new token.

If the lexeme argument is absent, the token is left empty.

```
<Parser: procedures>+≡
subroutine parse_node_create_leaf (node, rule, lexeme)
  type(parse_node_t), pointer :: node
  type(syntax_rule_t), intent(in), target :: rule
  type(lexeme_t), intent(in) :: lexeme
  allocate (node)
  node%rule => rule
  call token_init (node%token, lexeme, &
    syntax_rule_get_type (rule), syntax_rule_get_key (rule))
  if (.not. token_is_valid (node%token)) deallocate (node)
end subroutine parse_node_create_leaf
```

Second, branch nodes. We first assign the rule:

```
<Parser: procedures>+≡
subroutine parse_node_create_branch (node, rule)
  type(parse_node_t), pointer :: node
  type(syntax_rule_t), intent(in), target :: rule
  allocate (node)
  node%rule => rule
end subroutine parse_node_create_branch
```

Append a sub-node. The sub-node must exist and be a valid target, otherwise nothing is done.

```
<Parser: procedures>+≡
subroutine parse_node_append_sub (node, sub)
  type(parse_node_t), intent(inout) :: node
  type(parse_node_t), pointer :: sub
  if (associated (sub)) then
    if (associated (node%sub_last)) then
      node%sub_last%next => sub
    else
      node%sub_first => sub
    end if
    node%sub_last => sub
  end if
end subroutine parse_node_append_sub
```

For easy access, once the list is complete we count the number of sub-nodes. If there are no subnodes, the whole node is deleted.

```

(Parser: procedures)+≡
subroutine parse_node_freeze_branch (node)
  type(parse_node_t), pointer :: node
  type(parse_node_t), pointer :: current
  node%n_sub = 0
  current => node%sub_first
  do while (associated (current))
    node%n_sub = node%n_sub + 1
    current => current%next
  end do
  if (node%n_sub == 0) deallocate (node)
end subroutine parse_node_freeze_branch

```

Replace the last subnode by a new target. Use with care, this invites to memory mismanagement.

```

(Parser: public)+≡
public :: parse_node_replace_last_sub

(Parser: procedures)+≡
subroutine parse_node_replace_last_sub (node, pn_target)
  type(parse_node_t), intent(inout), target :: node
  type(parse_node_t), intent(in), target :: pn_target
  type(parse_node_t), pointer :: current
  integer :: i
  select case (node%n_sub)
  case (1)
    node%sub_first => pn_target
  case (2:)
    current => node%sub_first
    do i = 1, node%n_sub - 2
      current => current%next
    end do
    current%next => pn_target
  case default
    call msg_bug ("'replace_last_sub' called for non-branch parse node")
  end select
  node%sub_last => pn_target
end subroutine parse_node_replace_last_sub

```

3.4.5 Accessing nodes

Return the node contents. Check if pointers are associated. No check when accessing a sub-node; assume that `parse_node_n_sub` is always used for the upper bound.

The token extractor returns a pointer.

```

(Parser: public)+≡
public :: parse_node_get_rule_ptr
public :: parse_node_get_n_sub
public :: parse_node_get_sub_ptr

```

```

public :: parse_node_get_next_ptr
public :: parse_node_get_last_sub_ptr

(Parser: procedures)+≡
function parse_node_get_rule_ptr (node) result (rule)
    type(syntax_rule_t), pointer :: rule
    type(parse_node_t), intent(in), target :: node
    if (associated (node%rule)) then
        rule => node%rule
    else
        rule => null ()
        call parse_node_undefined (node, "rule")
    end if
end function parse_node_get_rule_ptr

function parse_node_get_n_sub (node) result (n)
    integer :: n
    type(parse_node_t), intent(in) :: node
    n = node%n_sub
end function parse_node_get_n_sub

function parse_node_get_sub_ptr (node, n, tag, required) result (sub)
    type(parse_node_t), pointer :: sub
    type(parse_node_t), intent(in), target :: node
    integer, intent(in), optional :: n
    character(*), intent(in), optional :: tag
    logical, intent(in), optional :: required
    integer :: i
    sub => node%sub_first
    if (present (n)) then
        do i = 2, n
            if (associated (sub)) then
                sub => sub%next
            else
                return
            end if
        end do
    end if
    call parse_node_check (sub, tag, required)
end function parse_node_get_sub_ptr

function parse_node_get_next_ptr (sub, n, tag, required) result (next)
    type(parse_node_t), pointer :: next
    type(parse_node_t), intent(in), target :: sub
    integer, intent(in), optional :: n
    character(*), intent(in), optional :: tag
    logical, intent(in), optional :: required
    integer :: i
    next => sub%next
    if (present (n)) then
        do i = 2, n
            if (associated (next)) then
                next => next%next
            else
                exit
            end if
        end do
    end if
end function parse_node_get_next_ptr

```

```

        end if
    end do
end if
call parse_node_check (next, tag, required)
end function parse_node_get_next_ptr

function parse_node_get_last_sub_ptr (node, tag, required) result (sub)
    type(parse_node_t), pointer :: sub
    type(parse_node_t), intent(in), target :: node
    character(*), intent(in), optional :: tag
    logical, intent(in), optional :: required
    sub => node%sub_last
    call parse_node_check (sub, tag, required)
end function parse_node_get_last_sub_ptr

<Parser: procedures>+≡
subroutine parse_node_undefined (node, obj)
    type(parse_node_t), intent(in) :: node
    character(*), intent(in) :: obj
    call parse_node_write (node, 6)
    call msg_bug (" Parse-tree node: " // obj // " requested, but undefined")
end subroutine parse_node_undefined

```

Check if a parse node has a particular tag, and if it is associated:

```

<Parser: public>+≡
    public :: parse_node_check

<Parser: procedures>+≡
subroutine parse_node_check (node, tag, required)
    type(parse_node_t), pointer :: node
    character(*), intent(in), optional :: tag
    logical, intent(in), optional :: required
    if (associated (node)) then
        if (present (tag)) then
            if (parse_node_get_rule_key (node) /= tag) &
                call parse_node_mismatch (tag, node)
        end if
    else
        if (present (required)) then
            if (required) &
                call msg_bug (" Missing node, expected <" // tag // ">")
        end if
    end if
end subroutine parse_node_check

```

This is called by a parse-tree scanner if the expected and the actual nodes do not match

```

<Parser: public>+≡
    public :: parse_node_mismatch

<Parser: procedures>+≡
subroutine parse_node_mismatch (string, parse_node)
    character(*), intent(in) :: string

```

```

    type(parse_node_t), intent(in) :: parse_node
    call parse_node_write (parse_node)
    call msg_bug (" Syntax mismatch, expected <" // string // ">.")
end subroutine parse_node_mismatch

```

The following functions are wrappers for extracting the token contents.

(Parser: public)+≡

```

public :: parse_node_get_logical
public :: parse_node_get_integer
public :: parse_node_get_real
public :: parse_node_get_cmplx
public :: parse_node_get_string
public :: parse_node_get_key
public :: parse_node_get_rule_key

```

(Parser: procedures)+≡

```

function parse_node_get_logical (node) result (lval)
    logical :: lval
    type(parse_node_t), intent(in), target :: node
    lval = token_get_logical (parse_node_get_token_ptr (node))
end function parse_node_get_logical

function parse_node_get_integer (node) result (ival)
    integer :: ival
    type(parse_node_t), intent(in), target :: node
    ival = token_get_integer (parse_node_get_token_ptr (node))
end function parse_node_get_integer

function parse_node_get_real (node) result (rval)
    real(default) :: rval
    type(parse_node_t), intent(in), target :: node
    rval = token_get_real (parse_node_get_token_ptr (node))
end function parse_node_get_real

function parse_node_get_cmplx (node) result (cval)
    complex(default) :: cval
    type(parse_node_t), intent(in), target :: node
    cval = token_get_cmplx (parse_node_get_token_ptr (node))
end function parse_node_get_cmplx

function parse_node_get_string (node) result (sval)
    type(string_t) :: sval
    type(parse_node_t), intent(in), target :: node
    sval = token_get_string (parse_node_get_token_ptr (node))
end function parse_node_get_string

function parse_node_get_key (node) result (kval)
    type(string_t) :: kval
    type(parse_node_t), intent(in), target :: node
    kval = token_get_key (parse_node_get_token_ptr (node))
end function parse_node_get_key

function parse_node_get_rule_key (node) result (kval)
    type(string_t) :: kval

```

```

    type(parse_node_t), intent(in), target :: node
    kval = syntax_rule_get_key (parse_node_get_rule_ptr (node))
end function parse_node_get_rule_key

function parse_node_get_token_ptr (node) result (token)
    type(token_t), pointer :: token
    type(parse_node_t), intent(in), target :: node
    if (token_is_valid (node%token)) then
        token => node%token
    else
        call parse_node_undefined (node, "token")
    end if
end function parse_node_get_token_ptr

```

Return a MD5 sum for a parse node. The method is to write the node to a scratch file and to evaluate the MD5 sum of that file.

```

(Parser: public)+≡
    public :: parse_node_get_md5sum

(Parser: procedures)+≡
    function parse_node_get_md5sum (pn) result (md5sum_pn)
        character(32) :: md5sum_pn
        type(parse_node_t), intent(in) :: pn
        integer :: u
        u = free_unit ()
        open (unit = u, status = "scratch", action = "readwrite")
        call parse_node_write_rec (pn, unit=u)
        rewind (u)
        md5sum_pn = md5sum (u)
        close (u)
    end function parse_node_get_md5sum

```

3.4.6 The parse tree

The parse tree is a tree of nodes, where leaf nodes hold a valid token, while branch nodes point to a list of sub-nodes.

```

(Parser: public)+≡
    public :: parse_tree_t

(Parser: types)+≡
    type :: parse_tree_t
    private
    type(parse_node_t), pointer :: root_node => null ()
end type parse_tree_t

```

The parser. Its arguments are the parse tree (which should be empty initially), the lexer (which should be already set up), the syntax table (which should be valid), and the input stream. The input stream is completely parsed, using the lexer setup and the syntax rules as given, and the parse tree is built accordingly.

If `check_eof` is absent or true, the parser will complain about trailing garbage. Otherwise, it will ignore it.

By default, the input stream is matched against the top rule in the specified syntax. If `key` is given, it is matched against the rule with the specified key instead.

Failure at the top level means that no rule could match at all; in this case the error message will show the top rule.

```

(Parser: public)+≡
    public :: parse_tree_init

(Parser: procedures)+≡
    subroutine parse_tree_init &
        (parse_tree, syntax, lexer, stream, key, check_eof)
        type(parse_tree_t), intent(inout) :: parse_tree
        type(lexer_t), intent(inout) :: lexer
        type(syntax_t), intent(in), target :: syntax
        type(stream_t), intent(inout) :: stream
        type(string_t), intent(in), optional :: key
        logical, intent(in), optional :: check_eof
        type(syntax_rule_t), pointer :: rule
        type(lexeme_t) :: lexeme
        type(parse_node_t), pointer :: node
        logical :: ok, check
        check = .true.; if (present (check_eof)) check = check_eof
        call lexer_clear (lexer)
        if (present (key)) then
            rule => syntax_get_rule_ptr (syntax, key)
        else
            rule => syntax_get_top_rule_ptr (syntax)
        end if
        if (associated (rule)) then
            call parse_node_match_rule (node, rule, ok)
            if (ok) then
                parse_tree%root_node => node
            else
                call parse_error (rule, lexeme)
            end if
            if (check) then
                call lex (lexeme, lexer, stream)
                if (.not. lexeme_is_eof (lexeme)) then
                    call lexer_show_location (lexer); print *
                    call msg_fatal (" Parser could not interpret text from here")
                end if
            end if
        else
            call msg_bug (" Parser failed because syntax is empty")
        end if
    contains
    (Parser: internal subroutines of parse_tree_init)
    end subroutine parse_tree_init

```

The parser works recursively, following the rule tree, building the tree of nodes on the fly. If the given rule matches, the node is filled on return. If not, the node remains empty.

```

(Parser: internal subroutines of parse_tree_init)≡

```

```

recursive subroutine parse_node_match_rule (node, rule, ok)
  type(parse_node_t), pointer :: node
  type(syntax_rule_t), intent(in), target :: rule
  logical, intent(out) :: ok
  logical, parameter :: debug = .false.
  integer :: type
  if (debug) write (6, "(A)", advance="no") "Parsing rule: "
  if (debug) call syntax_rule_write (rule, 6)
  node => null ()
  type = syntax_rule_get_type (rule)
  if (syntax_rule_is_atomic (rule)) then
    call lex (lexeme, lexer, stream)
    if (debug) write (6, "(A)", advance="no") "Token: "
    if (debug) call lexeme_write (lexeme, 6)
    call parse_node_create_leaf (node, rule, lexeme)
    ok = associated (node)
    if (.not. ok) call lexer_put_back (lexer, lexeme)
  else
    select case (type)
    case (S_ALTERNATIVE); call parse_alternative (node, rule, ok)
    case (S_GROUP);       call parse_group (node, rule, ok)
    case (S_SEQUENCE);    call parse_sequence (node, rule, .false., ok)
    case (S_LIST);        call parse_sequence (node, rule, .true., ok)
    case (S_ARGS);        call parse_args (node, rule, ok)
    case (S_IGNORE);      call parse_ignore (node, ok)
    end select
  end if
  if (debug) then
    if (ok) then
      write (6, "(A)", advance="no") "Matched rule: "
    else
      write (6, "(A)", advance="no") "Failed rule: "
    end if
    call syntax_rule_write (rule)
    if (associated (node)) call parse_node_write (node)
  end if
end subroutine parse_node_match_rule

```

Parse an alternative: try each case. If the match succeeds, the node has been filled, so return. If nothing works, return failure.

(Parser: internal subroutines of parse_tree_init)+≡

```

recursive subroutine parse_alternative (node, rule, ok)
  type(parse_node_t), pointer :: node
  type(syntax_rule_t), intent(in), target :: rule
  logical, intent(out) :: ok
  integer :: i
  do i = 1, syntax_rule_get_n_sub (rule)
    call parse_node_match_rule (node, syntax_rule_get_sub_ptr (rule, i), ok)
    if (ok) return
  end do
  ok = .false.
end subroutine parse_alternative

```

Parse a group: the first and third lexemes have to be the delimiters, the second one is parsed as the actual node, using now the child rule. If the first match fails,

return with failure. If the other matches fail, issue an error, since we cannot lex back more than one item.

```

(Parser: internal subroutines of parse_tree_init)+≡
recursive subroutine parse_group (node, rule, ok)
  type(parse_node_t), pointer :: node
  type(syntax_rule_t), intent(in), target :: rule
  logical, intent(out) :: ok
  type(string_t), dimension(2) :: delimiter
  delimiter = syntax_rule_get_delimiter (rule)
  call lex (lexeme, lexer, stream)
  if (lexeme_get_string (lexeme) == delimiter(1)) then
    call parse_node_match_rule (node, syntax_rule_get_sub_ptr (rule, 1), ok)
    if (ok) then
      call lex (lexeme, lexer, stream)
      if (lexeme_get_string (lexeme) == delimiter(2)) then
        ok = .true.
      else
        call parse_error (rule, lexeme)
      end if
    else
      call parse_error (rule, lexeme)
    end if
  else
    call lexer_put_back (lexer, lexeme)
    ok = .false.
  end if
end subroutine parse_group

```

Parsing a sequence. The last rule element may be special: optional and/or repetitive. Each sub-node that matches is appended to the sub-node list of the parent node.

If sep is true, we look for a separator after each element.

```

(Parser: internal subroutines of parse_tree_init)+≡
recursive subroutine parse_sequence (node, rule, sep, ok)
  type(parse_node_t), pointer :: node
  type(syntax_rule_t), intent(in), target :: rule
  logical, intent(in) :: sep
  logical, intent(out) :: ok
  type(parse_node_t), pointer :: current
  integer :: i, n
  logical :: opt, rep, cont
  type(string_t) :: separator
  call parse_node_create_branch (node, rule)
  if (sep) separator = syntax_rule_get_separator (rule)
  n = syntax_rule_get_n_sub (rule)
  opt = syntax_rule_last_optional (rule)
  rep = syntax_rule_last_repetitive (rule)
  ok = .true.
  cont = .true.
  SCAN_RULE: do i = 1, n
    call parse_node_match_rule &
      (current, syntax_rule_get_sub_ptr (rule, i), cont)
    if (cont) then
      call parse_node_append_sub (node, current)
    end if
  end do
end subroutine parse_sequence

```

```

        if (sep .and. (i<n .or. rep)) then
            call lex (lexeme, lexer, stream)
            if (lexeme_get_string (lexeme) /= separator) then
                call lexer_put_back (lexer, lexeme)
                cont = .false.
                exit SCAN_RULE
            end if
        end if
    else
        if (i == n .and. opt) then
            exit SCAN_RULE
        else if (i == 1) then
            ok = .false.
            exit SCAN_RULE
        else
            call parse_error (rule, lexeme)
        end if
    end if
end do SCAN_RULE
if (rep) then
    do while (cont)
        call parse_node_match_rule &
            (current, syntax_rule_get_sub_ptr (rule, n), cont)
        if (cont) then
            call parse_node_append_sub (node, current)
            if (sep) then
                call lex (lexeme, lexer, stream)
                if (lexeme_get_string (lexeme) /= separator) then
                    call lexer_put_back (lexer, lexeme)
                    cont = .false.
                end if
            end if
        else
            if (sep) call parse_error (rule, lexeme)
        end if
    end do
    call parse_node_freeze_branch (node)
end subroutine parse_sequence

```

Argument list: We use the `parse_group` code, but call `parse_sequence` inside.

(Parser: internal subroutines of `parse_tree_init`) +=

```

recursive subroutine parse_args (node, rule, ok)
    type(parse_node_t), pointer :: node
    type(syntax_rule_t), intent(in), target :: rule
    logical, intent(out) :: ok
    type(string_t), dimension(2) :: delimiter
    delimiter = syntax_rule_get_delimiter (rule)
    call lex (lexeme, lexer, stream)
    if (lexeme_get_string (lexeme) == delimiter(1)) then
        call parse_sequence (node, rule, .true., ok)
    if (ok) then
        call lex (lexeme, lexer, stream)
        if (lexeme_get_string (lexeme) == delimiter(2)) then
            ok = .true.
        end if
    end if
end subroutine parse_args

```

```

        else
            call parse_error (rule, lexeme)
        end if
    else
        call parse_error (rule, lexeme)
    end if
else
    call lexer_put_back (lexer, lexeme)
    ok = .false.
end if
end subroutine parse_args

```

The IGNORE syntax reads one lexeme and discards it if it is numeric, logical or string/identifier (but not a keyword). This is a successful match. Otherwise, the match fails. The node pointer is returned disassociated in any case.

<Parser: internal subroutines of parse_tree_init>+≡

```

subroutine parse_ignore (node, ok)
    type(parse_node_t), pointer :: node
    logical, intent(out) :: ok
    call lex (lexeme, lexer, stream)
    select case (lexeme_get_type (lexeme))
    case (T_NUMERIC, T_IDENTIFIER, T_QUOTED)
        ok = .true.
    case default
        ok = .false.
    end select
    node => null ()
end subroutine parse_ignore

```

If the match fails and we cannot step back:

<Parser: internal subroutines of parse_tree_init>+≡

```

subroutine parse_error (rule, lexeme)
    type(syntax_rule_t), intent(in) :: rule
    type(lexeme_t), intent(in) :: lexeme
    call lexer_show_location (lexer)
    write (6, "(1x, A)", advance="no") "Expected syntax:"
    call syntax_rule_write (rule, 6)
    write (6, "(1x, A)", advance="no") "Found token:"
    call lexeme_write (lexeme, 6)
    call msg_fatal ("Syntax error in command script")
end subroutine parse_error

```

The finalizer recursively deallocates all nodes and their contents. For each node, `parse_node_final` is called on the sub-nodes, which in turn deallocates the token or sub-node array contained within each of them. At the end, only the top node remains to be deallocated.

<Parser: public>+≡

```

public :: parse_tree_final

```

<Parser: procedures>+≡

```

subroutine parse_tree_final (parse_tree)
    type(parse_tree_t), intent(inout) :: parse_tree
    if (associated (parse_tree%root_node)) then
        call parse_node_final (parse_tree%root_node)
        deallocate (parse_tree%root_node)
    end if
end subroutine parse_tree_final

```

```

        end if
    end subroutine parse_tree_final

```

Print the parse tree. Print one token per line, indented according to the depth of the node.

The `verbose` version includes type identifiers for the nodes.

```

(Parser: public)+≡
    public :: parse_tree_write

(Parser: procedures)+≡
    subroutine parse_tree_write (parse_tree, unit, verbose)
        type(parse_tree_t), intent(in) :: parse_tree
        integer, intent(in), optional :: unit
        logical, intent(in), optional :: verbose
        integer :: u
        logical :: short
        u = output_unit (unit); if (u < 0) return
        short = .true.; if (present (verbose)) short = .not. verbose
        write (u, "(A)") "Parse tree:"
        if (associated (parse_tree%root_node)) then
            call parse_node_write_rec (parse_tree%root_node, unit, short, 1)
        else
            write (u, *) "[empty]"
        end if
    end subroutine parse_tree_write

```

This is a generic error that can be issued if the parse tree does not meet the expectations of the parser. This most certainly indicates a bug.

```

(Parser: public)+≡
    public :: parse_tree_bug

(Parser: procedures)+≡
    subroutine parse_tree_bug (node, keys)
        type(parse_node_t), intent(in) :: node
        character(*), intent(in) :: keys
        call parse_node_write (node)
        call msg_bug (" Inconsistency in parse tree: expected " // keys)
    end subroutine parse_tree_bug

```

3.4.7 Access the parser

For scanning the parse tree we give access to the top node, as a node pointer. Of course, there should be no write access.

```

(Parser: public)+≡
    public :: parse_tree_get_root_ptr

(Parser: procedures)+≡
    function parse_tree_get_root_ptr (parse_tree) result (node)
        type(parse_node_t), pointer :: node
        type(parse_tree_t), intent(in), target :: parse_tree
        node => parse_tree%root_node
    end function parse_tree_get_root_ptr

```

3.4.8 Applications

For a file of the form

```
process foo, bar
  <something>
process xyz
  <something>
```

get the <something> entry node for the first matching process tag. If no matching entry is found, the node pointer remains unassociated.

```
<Parser: public>+≡
  public :: parse_tree_get_process_ptr

<Parser: procedures>+≡
  function parse_tree_get_process_ptr (parse_tree, process) result (node)
    type(parse_node_t), pointer :: node
    type(parse_tree_t), intent(in), target :: parse_tree
    type(string_t), intent(in) :: process
    type(parse_node_t), pointer :: node_root, node_process_def
    type(parse_node_t), pointer :: node_process_phs, node_process_list
    integer :: j
    node_root => parse_tree_get_root_ptr (parse_tree)
    if (associated (node_root)) then
      node_process_phs => parse_node_get_sub_ptr (node_root)
      SCAN_FILE: do while (associated (node_process_phs))
        node_process_def => parse_node_get_sub_ptr (node_process_phs)
        node_process_list => parse_node_get_sub_ptr (node_process_def, 2)
        do j = 1, parse_node_get_n_sub (node_process_list)
          if (parse_node_get_string &
              (parse_node_get_sub_ptr (node_process_list, j)) &
              == process) then
            node => parse_node_get_next_ptr (node_process_def)
            return
          end if
        end do
        node_process_phs => parse_node_get_next_ptr (node_process_phs)
      end do SCAN_FILE
    else
      node => null ()
    end if
  end function parse_tree_get_process_ptr
```

3.4.9 Test the parser

```
<Parser: public>+≡
  public :: parse_test

<Parser: procedures>+≡
  subroutine parse_test
    use ifiles
    use lexers

    type(ifile_t) :: ifile
```

```

type(syntax_t), target :: syntax
type(lexer_t) :: lexer
type(stream_t) :: stream
type(parse_tree_t), target :: parse_tree

print "(A)", "Parser test"
print *

call ifile_append (ifile, "SEQ expr = term addition*")
call ifile_append (ifile, "SEQ addition = plus_or_minus term")
call ifile_append (ifile, "SEQ term = factor multiplication*")
call ifile_append (ifile, "SEQ multiplication = times_or_over factor")
call ifile_append (ifile, "SEQ factor = atom exponentiation*")
call ifile_append (ifile, "SEQ exponentiation = '^' atom")
call ifile_append (ifile, "ALT atom = real | delimited_expr")
call ifile_append (ifile, "GRO delimited_expr = ( expr )")
call ifile_append (ifile, "ALT plus_or_minus = '+' | '-'")
call ifile_append (ifile, "ALT times_or_over = '*' | '/'")
call ifile_append (ifile, "KEY '+'")
call ifile_append (ifile, "KEY '-'")
call ifile_append (ifile, "KEY '*'")
call ifile_append (ifile, "KEY '/'")
call ifile_append (ifile, "KEY '^")
call ifile_append (ifile, "REA real")

print "(A)", "File contents (syntax definition):"
call ifile_write (ifile)
print "(A)", "EOF"
print *

call syntax_init (syntax, ifile)
call ifile_final (ifile)
call syntax_write (syntax)
print *

call lexer_init (lexer, &
  comment_chars = "", &
  quote_chars = "'", &
  quote_match = "'", &
  single_chars = "+-*/^()", &
  special_class = (/ "" /), &
  keyword_list = syntax_get_keyword_list_ptr (syntax))
call lexer_write_setup (lexer)
print *

call ifile_append (ifile, "(27+8^3-2/3)*(4+7)^2*99")
print "(A)", "File contents (input file):"
call ifile_write (ifile)
print "(A)", "EOF"
print *

call stream_init (stream, ifile)
call parse_tree_init (parse_tree, syntax, lexer, stream)
call stream_final (stream)

```

```

call parse_tree_write (parse_tree)
print *

print "(A)", "Cleanup, everything should now be empty:"
print *

call parse_tree_final (parse_tree)
call parse_tree_write (parse_tree)
print *

call lexer_final (lexer)
call lexer_write_setup (lexer)
print *

call ifile_final (ifile)
print "(A)", "File contents:"
call ifile_write (ifile)
print "(A)", "EOF"
print *

call syntax_final (syntax)
call syntax_write (syntax)

end subroutine parse_test

```

Chapter 4

Physics library

This part consists of two modules:

constants Physical and mathematical parameters that never change. The file has been moved to the **src/misc** subdirectory of the **WHIZARD** project.

lorentz Define three-vectors, four-vectors and Lorentz transformations and common operations for them.

sm_physics Here, running functions are stored for special kinematical setup like running coupling constants, Catani-Seymour dipoles, or Sudakov factors.

4.1 Lorentz algebra

Define Lorentz vectors, three-vectors, boosts, and some functions to manipulate them.

To make maximum use of this, all functions, if possible, are declared elemental (or pure, if this is not possible).

```
<lorentz.f90>≡  
  <File header>  
  
  module lorentz  
  
    <Use kinds>  
    use constants, only: pi, twopi, degree !NODEP!  
    <Use file utils>  
    use diagnostics !NODEP!  
  
    <Standard module head>  
  
    <Lorentz: public>  
  
    <Lorentz: public operators>  
  
    <Lorentz: public functions>  
  
    <Lorentz: types>  
  
    <Lorentz: parameters>  
  
    <Lorentz: interfaces>  
  
    contains  
  
    <Lorentz: subroutines>  
  end module lorentz
```

4.1.1 Three-vectors

First of all, let us introduce three-vectors in a trivial way. The functions and overloaded elementary operations clearly are too much overhead, but we like to keep the interface for three-vectors and four-vectors exactly parallel. By the way, we might attach a label to a vector by extending the type definition later.

```
<Lorentz: public>≡  
  public :: vector3_t  
  
<Lorentz: types>≡  
  type :: vector3_t  
    private  
    real(default), dimension(3) :: p  
  end type vector3_t
```

Output a vector

```
<Lorentz: public>+≡  
  public :: vector3_write
```

```

<Lorentz: subroutines>≡
  subroutine vector3_write (p, unit)
    type(vector3_t), intent(in) :: p
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write(u, *) 'P = ', p%p
  end subroutine vector3_write

```

This is a three-vector with zero components

```

<Lorentz: public>+≡
  public :: vector3_null

<Lorentz: parameters>≡
  type(vector3_t), parameter :: vector3_null = &
    vector3_t (/ 0._default, 0._default, 0._default /)

```

Canonical three-vector:

```

<Lorentz: public>+≡
  public :: vector3_canonical

<Lorentz: subroutines>+≡
  elemental function vector3_canonical (k) result (p)
    type(vector3_t) :: p
    integer, intent(in) :: k
    p = vector3_null
    p%p(k) = 1
  end function vector3_canonical

```

A moving particle (k -axis, or arbitrary axis). Note that the function for the generic momentum cannot be elemental.

```

<Lorentz: public>+≡
  public :: vector3_moving

<Lorentz: interfaces>≡
  interface vector3_moving
    module procedure vector3_moving_canonical
    module procedure vector3_moving_generic
  end interface

<Lorentz: subroutines>+≡
  elemental function vector3_moving_canonical (p, k) result(q)
    type(vector3_t) :: q
    real(default), intent(in) :: p
    integer, intent(in) :: k
    q = vector3_null
    q%p(k) = p
  end function vector3_moving_canonical
  pure function vector3_moving_generic (p) result(q)
    real(default), dimension(3), intent(in) :: p
    type(vector3_t) :: q
    q%p = p
  end function vector3_moving_generic

```

Equality and inequality

```

<Lorentz: public operators>+≡
    public :: operator(==), operator(/=)

<Lorentz: interfaces>+≡
    interface operator(==)
        module procedure vector3_eq
    end interface
    interface operator(/=)
        module procedure vector3_neq
    end interface

<Lorentz: subroutines>+≡
    elemental function vector3_eq (p, q) result (r)
        logical :: r
        type(vector3_t), intent(in) :: p,q
        r = all (p%p == q%p)
    end function vector3_eq
    elemental function vector3_neq (p, q) result (r)
        logical :: r
        type(vector3_t), intent(in) :: p,q
        r = any (p%p /= q%p)
    end function vector3_neq

```

Define addition and subtraction

```

<Lorentz: public operators>+≡
    public :: operator(+), operator(-)

<Lorentz: interfaces>+≡
    interface operator(+)
        module procedure add_vector3
    end interface
    interface operator(-)
        module procedure sub_vector3
    end interface

<Lorentz: subroutines>+≡
    elemental function add_vector3 (p, q) result (r)
        type(vector3_t) :: r
        type(vector3_t), intent(in) :: p,q
        r%p = p%p + q%p
    end function add_vector3
    elemental function sub_vector3 (p, q) result (r)
        type(vector3_t) :: r
        type(vector3_t), intent(in) :: p,q
        r%p = p%p - q%p
    end function sub_vector3

```

The multiplication sign is overloaded with scalar multiplication; similarly division:

```

<Lorentz: public operators>+≡
    public :: operator(*), operator(/)

```

```

<Lorentz: interfaces>+≡
  interface operator(*)
    module procedure prod_integer_vector3, prod_vector3_integer
    module procedure prod_real_vector3, prod_vector3_real
  end interface
  interface operator(/)
    module procedure div_vector3_real, div_vector3_integer
  end interface
<Lorentz: subroutines>+≡
  elemental function prod_real_vector3 (s, p) result (q)
    type(vector3_t) :: q
    real(default), intent(in) :: s
    type(vector3_t), intent(in) :: p
    q%p = s * p%p
  end function prod_real_vector3
  elemental function prod_vector3_real (p, s) result (q)
    type(vector3_t) :: q
    real(default), intent(in) :: s
    type(vector3_t), intent(in) :: p
    q%p = s * p%p
  end function prod_vector3_real
  elemental function div_vector3_real (p, s) result (q)
    type(vector3_t) :: q
    real(default), intent(in) :: s
    type(vector3_t), intent(in) :: p
    q%p = p%p/s
  end function div_vector3_real
  elemental function prod_integer_vector3 (s, p) result (q)
    type(vector3_t) :: q
    integer, intent(in) :: s
    type(vector3_t), intent(in) :: p
    q%p = s * p%p
  end function prod_integer_vector3
  elemental function prod_vector3_integer (p, s) result (q)
    type(vector3_t) :: q
    integer, intent(in) :: s
    type(vector3_t), intent(in) :: p
    q%p = s * p%p
  end function prod_vector3_integer
  elemental function div_vector3_integer (p, s) result (q)
    type(vector3_t) :: q
    integer, intent(in) :: s
    type(vector3_t), intent(in) :: p
    q%p = p%p/s
  end function div_vector3_integer

```

The multiplication sign can also indicate scalar products:

```

<Lorentz: interfaces>+≡
  interface operator(*)
    module procedure prod_vector3
  end interface
<Lorentz: subroutines>+≡
  elemental function prod_vector3 (p, q) result (s)

```

```

    real(default) :: s
    type(vector3_t), intent(in) :: p,q
    s = dot_product (p%p, q%p)
end function prod_vector3

```

```

<Lorentz: public functions>≡
    public :: cross_product

<Lorentz: interfaces>+≡
    interface cross_product
        module procedure vector3_cross_product
    end interface

<Lorentz: subroutines>+≡
    elemental function vector3_cross_product (p, q) result (r)
        type(vector3_t) :: r
        type(vector3_t), intent(in) :: p,q
        integer :: i
        do i=1,3
            r%p(i) = dot_product (p%p, matmul(epsilon_three(i,:,:), q%p))
        end do
    end function vector3_cross_product

```

Exponentiation is defined only for integer powers. Odd powers mean take the square root; so `p**1` is the length of `p`.

```

<Lorentz: public operators>+≡
    public :: operator(**)

<Lorentz: interfaces>+≡
    interface operator(**)
        module procedure power_vector3
    end interface

<Lorentz: subroutines>+≡
    elemental function power_vector3 (p, e) result (s)
        real(default) :: s
        type(vector3_t), intent(in) :: p
        integer, intent(in) :: e
        s = dot_product (p%p, p%p)
        if (e/=2) then
            if (mod(e,2)==0) then
                s = s**(e/2)
            else
                s = sqrt(s)**e
            end if
        end if
    end function power_vector3

```

Finally, we need a negation.

```

<Lorentz: interfaces>+≡
    interface operator(-)
        module procedure negate_vector3
    end interface

```

```

<Lorentz: subroutines>+≡
  elemental function negate_vector3 (p) result (q)
    type(vector3_t) :: q
    type(vector3_t), intent(in) :: p
    q%p = -p%p
  end function negate_vector3

```

The sum function can be useful:

```

<Lorentz: public functions>+≡
  public :: sum

<Lorentz: interfaces>+≡
  interface sum
    module procedure sum_vector3
  end interface

```

There used to be a mask here, but the Intel compiler crashes with it

```

<Lorentz: subroutines>+≡
  pure function sum_vector3 (p) result (q)
    type(vector3_t) :: q
    type(vector3_t), dimension(:), intent(in) :: p
    integer :: i
    do i=1, 3
      q%p(i) = sum (p%p(i))
    end do
  end function sum_vector3

! pure function sum_vector3_mask (p, mask) result (q)
!   type(vector3_t) :: q
!   type(vector3_t), dimension(:), intent(in) :: p
!   logical, dimension(:), intent(in) :: mask
!   integer :: i
!   do i=1, 3
!     q%p(i) = sum (p%p(i), mask=mask)
!   end do
! end function sum_vector3_mask

```

Any component:

```

<Lorentz: public>+≡
  public :: vector3_get_component

<Lorentz: subroutines>+≡
  elemental function vector3_get_component (p, k) result (c)
    type(vector3_t), intent(in) :: p
    integer, intent(in) :: k
    real(default) :: c
    c = p%p(k)
  end function vector3_get_component

```

Extract all components. This is not elemental.

```

<Lorentz: public>+≡
  public :: vector3_get_components

```

```

<Lorentz: subroutines>+≡
  pure function vector3_get_components (p) result (a)
    type(vector3_t), intent(in) :: p
    real(default), dimension(3) :: a
    a = p%p
  end function vector3_get_components

```

This function returns the direction of a three-vector, i.e., a normalized three-vector

```

<Lorentz: public functions>+≡
  public :: direction

<Lorentz: interfaces>+≡
  interface direction
    module procedure vector3_get_direction
  end interface

<Lorentz: subroutines>+≡
  elemental function vector3_get_direction (p) result (q)
    type(vector3_t) :: q
    type(vector3_t), intent(in) :: p
    q%p = p%p / p**1
  end function vector3_get_direction

```

4.1.2 Four-vectors

In four-vectors the zero-component needs special treatment, therefore we do not use the standard operations. Sure, we pay for the extra layer of abstraction by losing efficiency; so we have to assume that the time-critical applications do not involve four-vector operations.

```

<Lorentz: public>+≡
  public :: vector4_t

<Lorentz: types>+≡
  type :: vector4_t
    private
    real(default), dimension(0:3) :: p
  end type vector4_t

```

Output a vector

```

<Lorentz: public>+≡
  public :: vector4_write

<Lorentz: subroutines>+≡
  subroutine vector4_write (p, unit, show_mass)
    type(vector4_t), intent(in) :: p
    integer, intent(in), optional :: unit
    logical, intent(in), optional :: show_mass
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write(u, *) 'E = ', p%p(0)
    write(u, *) 'P = ', p%p(1:)
    if (present (show_mass)) then
      if (show_mass) &

```

```

        write (u, *) 'M = ', p**1
    end if
end subroutine vector4_write

```

Binary I/O

```

<Lorentz: public>+≡
    public :: vector4_write_raw
    public :: vector4_read_raw

<Lorentz: subroutines>+≡
    subroutine vector4_write_raw (p, u)
        type(vector4_t), intent(in) :: p
        integer, intent(in) :: u
        write (u) p%p
    end subroutine vector4_write_raw

    subroutine vector4_read_raw (p, u, iostat)
        type(vector4_t), intent(out) :: p
        integer, intent(in) :: u
        integer, intent(out), optional :: iostat
        read (u, iostat=iostat) p%p
    end subroutine vector4_read_raw

```

This is a four-vector with zero components

```

<Lorentz: public>+≡
    public :: vector4_null

<Lorentz: parameters>+≡
    type(vector4_t), parameter :: vector4_null = &
        vector4_t ((/ 0._default, 0._default, 0._default, 0._default /))

```

Canonical four-vector:

```

<Lorentz: public>+≡
    public :: vector4_canonical

<Lorentz: subroutines>+≡
    elemental function vector4_canonical (k) result (p)
        type(vector4_t) :: p
        integer, intent(in) :: k
        p = vector4_null
        p%p(k) = 1
    end function vector4_canonical

```

A particle at rest:

```

<Lorentz: public>+≡
    public :: vector4_at_rest

<Lorentz: subroutines>+≡
    elemental function vector4_at_rest (m) result (p)
        type(vector4_t) :: p
        real(default), intent(in) :: m
        p = vector4_t ((/ m, 0._default, 0._default, 0._default /))
    end function vector4_at_rest

```

A moving particle (k -axis, or arbitrary axis)

```

<Lorentz: public>+≡
    public :: vector4_moving

<Lorentz: interfaces>+≡
    interface vector4_moving
        module procedure vector4_moving_canonical
        module procedure vector4_moving_generic
    end interface

<Lorentz: subroutines>+≡
    elemental function vector4_moving_canonical (E, p, k) result (q)
        type(vector4_t) :: q
        real(default), intent(in) :: E, p
        integer, intent(in) :: k
        q = vector4_at_rest(E)
        q%p(k) = p
    end function vector4_moving_canonical
    elemental function vector4_moving_generic (E, p) result (q)
        type(vector4_t) :: q
        real(default), intent(in) :: E
        type(vector3_t), intent(in) :: p
        q%p(0) = E
        q%p(1:) = p%p
    end function vector4_moving_generic

```

Equality and inequality

```

<Lorentz: interfaces>+≡
    interface operator(==)
        module procedure vector4_eq
    end interface
    interface operator(/=)
        module procedure vector4_neq
    end interface

<Lorentz: subroutines>+≡
    elemental function vector4_eq (p, q) result (r)
        logical :: r
        type(vector4_t), intent(in) :: p,q
        r = all (p%p == q%p)
    end function vector4_eq
    elemental function vector4_neq (p, q) result (r)
        logical :: r
        type(vector4_t), intent(in) :: p,q
        r = any (p%p /= q%p)
    end function vector4_neq

```

Addition and subtraction:

```

<Lorentz: interfaces>+≡
    interface operator(+)
        module procedure add_vector4
    end interface
    interface operator(-)
        module procedure sub_vector4
    end interface

```

```

(Lorentz: subroutines)+≡
  elemental function add_vector4 (p,q) result (r)
    type(vector4_t) :: r
    type(vector4_t), intent(in) :: p,q
    r%p = p%p + q%p
  end function add_vector4
  elemental function sub_vector4 (p,q) result (r)
    type(vector4_t) :: r
    type(vector4_t), intent(in) :: p,q
    r%p = p%p - q%p
  end function sub_vector4

```

We also need scalar multiplication and division:

```

(Lorentz: interfaces)+≡
  interface operator(*)
    module procedure prod_real_vector4, prod_vector4_real
    module procedure prod_integer_vector4, prod_vector4_integer
  end interface
  interface operator(/)
    module procedure div_vector4_real
    module procedure div_vector4_integer
  end interface

(Lorentz: subroutines)+≡
  elemental function prod_real_vector4 (s, p) result (q)
    type(vector4_t) :: q
    real(default), intent(in) :: s
    type(vector4_t), intent(in) :: p
    q%p = s * p%p
  end function prod_real_vector4
  elemental function prod_vector4_real (p, s) result (q)
    type(vector4_t) :: q
    real(default), intent(in) :: s
    type(vector4_t), intent(in) :: p
    q%p = s * p%p
  end function prod_vector4_real
  elemental function div_vector4_real (p, s) result (q)
    type(vector4_t) :: q
    real(default), intent(in) :: s
    type(vector4_t), intent(in) :: p
    q%p = p%p/s
  end function div_vector4_real
  elemental function prod_integer_vector4 (s, p) result (q)
    type(vector4_t) :: q
    integer, intent(in) :: s
    type(vector4_t), intent(in) :: p
    q%p = s * p%p
  end function prod_integer_vector4
  elemental function prod_vector4_integer (p, s) result (q)
    type(vector4_t) :: q
    integer, intent(in) :: s
    type(vector4_t), intent(in) :: p
    q%p = s * p%p
  end function prod_vector4_integer

```

```

elemental function div_vector4_integer (p, s) result (q)
  type(vector4_t) :: q
  integer, intent(in) :: s
  type(vector4_t), intent(in) :: p
  q%p = p%p/s
end function div_vector4_integer

```

Scalar products and squares in the Minkowski sense:

```

<Lorentz: interfaces>+≡
  interface operator(*)
    module procedure prod_vector4
  end interface
  interface operator(**)
    module procedure power_vector4
  end interface

<Lorentz: subroutines>+≡
  elemental function prod_vector4 (p, q) result (s)
    real(default) :: s
    type(vector4_t), intent(in) :: p,q
    s = p%p(0)*q%p(0) - dot_product(p%p(1:), q%p(1:))
  end function prod_vector4

```

The power operation for four-vectors is signed, i.e., p^{**1} is positive for timelike and negative for spacelike vectors. Note that $(p^{**1})^{**2}$ is not necessarily equal to p^{**2} .

```

<Lorentz: subroutines>+≡
  elemental function power_vector4 (p, e) result (s)
    real(default) :: s
    type(vector4_t), intent(in) :: p
    integer, intent(in) :: e
    s = p*p
    if (e/=2) then
      if (mod(e,2)==0) then
        s = s**(e/2)
      elseif (s>=0) then
        s = sqrt(s)**e
      else
        s = -(sqrt(abs(s))**e)
      end if
    end if
  end function power_vector4

```

Finally, we introduce a negation

```

<Lorentz: interfaces>+≡
  interface operator(-)
    module procedure negate_vector4
  end interface

<Lorentz: subroutines>+≡
  elemental function negate_vector4 (p) result (q)
    type(vector4_t) :: q
    type(vector4_t), intent(in) :: p

```

```

    q%p = -p%p
end function negate_vector4

```

The sum function can be useful:

```

<Lorentz: interfaces>+≡
interface sum
    module procedure sum_vector4
end interface

```

There used to be a mask here, but the Intel compiler crashes with it

```

<Lorentz: subroutines>+≡
pure function sum_vector4 (p) result (q)
    type(vector4_t) :: q
    type(vector4_t), dimension(:), intent(in) :: p
    integer :: i
    do i=0, 3
        q%p(i) = sum (p%p(i))
    end do
end function sum_vector4
! pure function sum_vector4_mask (p, mask) result (q)
!     type(vector4_t) :: q
!     type(vector4_t), dimension(:), intent(in) :: p
!     logical, dimension(:), intent(in) :: mask
!     integer :: i
!     do i=0, 3
!         q%p(i) = sum (p%p(i), mask=mask)
!     end do
! end function sum_vector4_mask

```

4.1.3 Conversions

Any component:

```

<Lorentz: public>+≡
public :: vector4_get_component

<Lorentz: subroutines>+≡
elemental function vector4_get_component (p, k) result (c)
    real(default) :: c
    type(vector4_t), intent(in) :: p
    integer, intent(in) :: k
    c = p%p(k)
end function vector4_get_component

```

Extract all components. This is not elemental.

```

<Lorentz: public>+≡
public :: vector4_get_components

<Lorentz: subroutines>+≡
pure function vector4_get_components (p) result (a)
    real(default), dimension(0:3) :: a
    type(vector4_t), intent(in) :: p
    a = p%p

```

```
end function vector4_get_components
```

This function returns the space part of a four-vector, such that we can apply three-vector operations on it:

```
<Lorentz: public functions>+≡
  public :: space_part

<Lorentz: interfaces>+≡
  interface space_part
    module procedure vector4_get_space_part
  end interface

<Lorentz: subroutines>+≡
  elemental function vector4_get_space_part (p) result (q)
    type(vector3_t) :: q
    type(vector4_t), intent(in) :: p
    q%p = p%p(1:)
  end function vector4_get_space_part
```

This function returns the direction of a four-vector, i.e., a normalized three-vector

```
<Lorentz: interfaces>+≡
  interface direction
    module procedure vector4_get_direction
  end interface

<Lorentz: subroutines>+≡
  elemental function vector4_get_direction (p) result (q)
    type(vector3_t) :: q
    type(vector4_t), intent(in) :: p
    q%p = p%p(1:)
    q = q / q**1
  end function vector4_get_direction
```

This function returns the four-vector as an ordinary array. A second version for an array of four-vectors.

```
<Lorentz: public functions>+≡
  public :: array_from_vector4

<Lorentz: interfaces>+≡
  interface array_from_vector4
    module procedure array_from_vector4_1
    module procedure array_from_vector4_2
  end interface

<Lorentz: subroutines>+≡
  pure function array_from_vector4_1 (p) result (a)
    type(vector4_t), intent(in) :: p
    real(default), dimension(0:3) :: a
    a = p%p
  end function array_from_vector4_1

  pure function array_from_vector4_2 (p) result (a)
    type(vector4_t), dimension(:), intent(in) :: p
```

```

    real(default), dimension(0:3, size(p)) :: a
    integer :: i
    forall (i=1:size(p))
        a(0:3,i) = p(i)%p
    end forall
end function array_from_vector4_2

```

4.1.4 Angles

Return the angles in a canonical system. The angle ϕ is defined between $0 \leq \phi < 2\pi$. In degenerate cases, return zero.

```

<Lorentz: public functions>+≡
    public :: azimuthal_angle

<Lorentz: interfaces>+≡
    interface azimuthal_angle
        module procedure vector3_azimuthal_angle
        module procedure vector4_azimuthal_angle
    end interface

<Lorentz: subroutines>+≡
    elemental function vector3_azimuthal_angle (p) result (phi)
        real(default) :: phi
        type(vector3_t), intent(in) :: p
        if (any(p%p(1:2)/=0)) then
            phi = atan2(p%p(2), p%p(1))
            if (phi < 0) phi = phi + twopi
        else
            phi = 0
        end if
    end function vector3_azimuthal_angle
    elemental function vector4_azimuthal_angle (p) result (phi)
        real(default) :: phi
        type(vector4_t), intent(in) :: p
        phi = vector3_azimuthal_angle (space_part (p))
    end function vector4_azimuthal_angle

```

Azimuthal angle in degrees

```

<Lorentz: public functions>+≡
    public :: azimuthal_angle_deg

<Lorentz: interfaces>+≡
    interface azimuthal_angle_deg
        module procedure vector3_azimuthal_angle_deg
        module procedure vector4_azimuthal_angle_deg
    end interface

<Lorentz: subroutines>+≡
    elemental function vector3_azimuthal_angle_deg (p) result (phi)
        real(default) :: phi
        type(vector3_t), intent(in) :: p
        phi = vector3_azimuthal_angle (p) / degree
    end function vector3_azimuthal_angle_deg
    elemental function vector4_azimuthal_angle_deg (p) result (phi)

```

```

    real(default) :: phi
    type(vector4_t), intent(in) :: p
    phi = vector4_azimuthal_angle (p) / degree
end function vector4_azimuthal_angle_deg

```

The azimuthal distance of two vectors. This is the difference of the azimuthal angles, but cannot be larger than π : The result is between $-\pi < \Delta\phi \leq \pi$.

```

<Lorentz: public functions>+≡
    public :: azimuthal_distance

<Lorentz: interfaces>+≡
    interface azimuthal_distance
        module procedure vector3_azimuthal_distance
        module procedure vector4_azimuthal_distance
    end interface

<Lorentz: subroutines>+≡
    elemental function vector3_azimuthal_distance (p, q) result (dphi)
        real(default) :: dphi
        type(vector3_t), intent(in) :: p,q
        dphi = vector3_azimuthal_angle (q) - vector3_azimuthal_angle (p)
        if (dphi <= -pi) then
            dphi = dphi + twopi
        else if (dphi > pi) then
            dphi = dphi - twopi
        end if
    end function vector3_azimuthal_distance
    elemental function vector4_azimuthal_distance (p, q) result (dphi)
        real(default) :: dphi
        type(vector4_t), intent(in) :: p,q
        dphi = vector3_azimuthal_distance &
            (space_part (p), space_part (q))
    end function vector4_azimuthal_distance

```

The same in degrees:

```

<Lorentz: public functions>+≡
    public :: azimuthal_distance_deg

<Lorentz: interfaces>+≡
    interface azimuthal_distance_deg
        module procedure vector3_azimuthal_distance_deg
        module procedure vector4_azimuthal_distance_deg
    end interface

<Lorentz: subroutines>+≡
    elemental function vector3_azimuthal_distance_deg (p, q) result (dphi)
        real(default) :: dphi
        type(vector3_t), intent(in) :: p,q
        dphi = vector3_azimuthal_distance (p, q) / degree
    end function vector3_azimuthal_distance_deg
    elemental function vector4_azimuthal_distance_deg (p, q) result (dphi)
        real(default) :: dphi
        type(vector4_t), intent(in) :: p,q
        dphi = vector4_azimuthal_distance (p, q) / degree
    end function vector4_azimuthal_distance_deg

```

The polar angle is defined $0 \leq \theta \leq \pi$. Note that ATAN2 has the reversed order of arguments: ATAN2(Y,X). Here, x is the 3-component while y is the transverse momentum which is always nonnegative. Therefore, the result is nonnegative as well.

```

<Lorentz: public functions>+≡
  public :: polar_angle

<Lorentz: interfaces>+≡
  interface polar_angle
    module procedure polar_angle_vector3
    module procedure polar_angle_vector4
  end interface

<Lorentz: subroutines>+≡
  elemental function polar_angle_vector3 (p) result (theta)
    real(default) :: theta
    type(vector3_t), intent(in) :: p
    if (any(p%p/=0)) then
      theta = atan2 (sqrt(p%p(1)**2 + p%p(2)**2), p%p(3))
    else
      theta = 0
    end if
  end function polar_angle_vector3
  elemental function polar_angle_vector4 (p) result (theta)
    real(default) :: theta
    type(vector4_t), intent(in) :: p
    theta = polar_angle (space_part (p))
  end function polar_angle_vector4

```

This is the cosine of the polar angle: $-1 \leq \cos \theta \leq 1$.

```

<Lorentz: public functions>+≡
  public :: polar_angle_ct

<Lorentz: interfaces>+≡
  interface polar_angle_ct
    module procedure polar_angle_ct_vector3
    module procedure polar_angle_ct_vector4
  end interface

<Lorentz: subroutines>+≡
  elemental function polar_angle_ct_vector3 (p) result (ct)
    real(default) :: ct
    type(vector3_t), intent(in) :: p
    if (any(p%p/=0)) then
      ct = p%p(3) / p**1
    else
      ct = 1
    end if
  end function polar_angle_ct_vector3
  elemental function polar_angle_ct_vector4 (p) result (ct)
    real(default) :: ct
    type(vector4_t), intent(in) :: p
    ct = polar_angle_ct (space_part (p))
  end function polar_angle_ct_vector4

```

The polar angle in degrees.

```

<Lorentz: public functions>+≡
    public :: polar_angle_deg

<Lorentz: interfaces>+≡
    interface polar_angle_deg
        module procedure polar_angle_deg_vector3
        module procedure polar_angle_deg_vector4
    end interface

<Lorentz: subroutines>+≡
    elemental function polar_angle_deg_vector3 (p) result (theta)
        real(default) :: theta
        type(vector3_t), intent(in) :: p
        theta = polar_angle (p) / degree
    end function polar_angle_deg_vector3
    elemental function polar_angle_deg_vector4 (p) result (theta)
        real(default) :: theta
        type(vector4_t), intent(in) :: p
        theta = polar_angle (p) / degree
    end function polar_angle_deg_vector4

```

This is the angle enclosed between two three-momenta. If one of the momenta is zero, we return an angle of zero. The range of the result is $0 \leq \theta \leq \pi$. If there is only one argument, take the positive z axis as reference.

```

<Lorentz: public functions>+≡
    public :: enclosed_angle

<Lorentz: interfaces>+≡
    interface enclosed_angle
        module procedure enclosed_angle_vector3
        module procedure enclosed_angle_vector4
    end interface

<Lorentz: subroutines>+≡
    elemental function enclosed_angle_vector3 (p, q) result (theta)
        real(default) :: theta
        type(vector3_t), intent(in) :: p, q
        theta = acos (enclosed_angle_ct (p, q))
    end function enclosed_angle_vector3
    elemental function enclosed_angle_vector4 (p, q) result (theta)
        real(default) :: theta
        type(vector4_t), intent(in) :: p, q
        theta = enclosed_angle (space_part (p), space_part (q))
    end function enclosed_angle_vector4

```

The cosine of the enclosed angle.

```

<Lorentz: public functions>+≡
    public :: enclosed_angle_ct

<Lorentz: interfaces>+≡
    interface enclosed_angle_ct
        module procedure enclosed_angle_ct_vector3
        module procedure enclosed_angle_ct_vector4
    end interface

```

```

<Lorentz: subroutines>+≡
  elemental function enclosed_angle_ct_vector3 (p, q) result (ct)
    real(default) :: ct
    type(vector3_t), intent(in) :: p, q
    if (any(p%p/=0).and.any(q%p/=0)) then
      ct = p*q / (p**1 * q**1)
      if (ct>1) then
        ct = 1
      else if (ct<-1) then
        ct = -1
      end if
    else
      ct = 1
    end if
  end function enclosed_angle_ct_vector3
  elemental function enclosed_angle_ct_vector4 (p, q) result (ct)
    real(default) :: ct
    type(vector4_t), intent(in) :: p, q
    ct = enclosed_angle_ct (space_part (p), space_part (q))
  end function enclosed_angle_ct_vector4

```

The enclosed angle in degrees.

```

<Lorentz: public functions>+≡
  public :: enclosed_angle_deg

<Lorentz: interfaces>+≡
  interface enclosed_angle_deg
    module procedure enclosed_angle_deg_vector3
    module procedure enclosed_angle_deg_vector4
  end interface

<Lorentz: subroutines>+≡
  elemental function enclosed_angle_deg_vector3 (p, q) result (theta)
    real(default) :: theta
    type(vector3_t), intent(in) :: p, q
    theta = enclosed_angle (p, q) / degree
  end function enclosed_angle_deg_vector3
  elemental function enclosed_angle_deg_vector4 (p, q) result (theta)
    real(default) :: theta
    type(vector4_t), intent(in) :: p, q
    theta = enclosed_angle (p, q) / degree
  end function enclosed_angle_deg_vector4

```

The polar angle of the first momentum w.r.t. the second momentum, evaluated in the rest frame of the second momentum. If the second four-momentum is not timelike, return zero.

```

<Lorentz: public functions>+≡
  public :: enclosed_angle_rest_frame
  public :: enclosed_angle_ct_rest_frame
  public :: enclosed_angle_deg_rest_frame

<Lorentz: interfaces>+≡
  interface enclosed_angle_rest_frame
    module procedure enclosed_angle_rest_frame_vector4

```

```

end interface
interface enclosed_angle_ct_rest_frame
  module procedure enclosed_angle_ct_rest_frame_vector4
end interface
interface enclosed_angle_deg_rest_frame
  module procedure enclosed_angle_deg_rest_frame_vector4
end interface
<Lorentz: subroutines>+≡
elemental function enclosed_angle_rest_frame_vector4 (p, q) result (theta)
  type(vector4_t), intent(in) :: p, q
  real(default) :: theta
  theta = acos (enclosed_angle_ct_rest_frame (p, q))
end function enclosed_angle_rest_frame_vector4
elemental function enclosed_angle_ct_rest_frame_vector4 (p, q) result (ct)
  type(vector4_t), intent(in) :: p, q
  real(default) :: ct
  if (invariant_mass(q) > 0) then
    ct = enclosed_angle_ct ( &
      space_part (boost(-q, invariant_mass (q)) * p), &
      space_part (q))
  else
    ct = 1
  end if
end function enclosed_angle_ct_rest_frame_vector4
elemental function enclosed_angle_deg_rest_frame_vector4 (p, q) &
  result (theta)
  type(vector4_t), intent(in) :: p, q
  real(default) :: theta
  theta = enclosed_angle_rest_frame (p, q) / degree
end function enclosed_angle_deg_rest_frame_vector4

```

4.1.5 More kinematical functions (some redundant)

The scalar transverse momentum (assuming the z axis is longitudinal)

```

<Lorentz: public functions>+≡
  public :: transverse_part
<Lorentz: interfaces>+≡
  interface transverse_part
    module procedure transverse_part_vector4
  end interface
<Lorentz: subroutines>+≡
  elemental function transverse_part_vector4 (p) result (pT)
    real(default) :: pT
    type(vector4_t), intent(in) :: p
    pT = sqrt(p%p(1)**2 + p%p(2)**2)
  end function transverse_part_vector4

```

The scalar longitudinal momentum (assuming the z axis is longitudinal). Identical to `momentum_z_component`.

```

<Lorentz: public functions>+≡
  public :: longitudinal_part

```

```

<Lorentz: interfaces>+≡
  interface longitudinal_part
    module procedure longitudinal_part_vector4
  end interface

<Lorentz: subroutines>+≡
  elemental function longitudinal_part_vector4 (p) result (pL)
    real(default) :: pL
    type(vector4_t), intent(in) :: p
    pL = p%p(3)
  end function longitudinal_part_vector4

```

Absolute value of three-momentum

```

<Lorentz: public functions>+≡
  public :: space_part_norm

<Lorentz: interfaces>+≡
  interface space_part_norm
    module procedure space_part_norm_vector4
  end interface

<Lorentz: subroutines>+≡
  elemental function space_part_norm_vector4 (p) result (p3)
    real(default) :: p3
    type(vector4_t), intent(in) :: p
    p3 = sqrt (p%p(1)**2 + p%p(2)**2 + p%p(3)**2)
  end function space_part_norm_vector4

```

The energy (the zeroth component)

```

<Lorentz: public functions>+≡
  public :: energy

<Lorentz: interfaces>+≡
  interface energy
    module procedure energy_vector4
    module procedure energy_vector3
    module procedure energy_real
  end interface

<Lorentz: subroutines>+≡
  elemental function energy_vector4 (p) result (E)
    real(default) :: E
    type(vector4_t), intent(in) :: p
    E = p%p(0)
  end function energy_vector4

```

Alternative: The energy corresponding to a given momentum and mass. If the mass is omitted, it is zero

```

<Lorentz: subroutines>+≡
  elemental function energy_vector3 (p, mass) result (E)
    real(default) :: E
    type(vector3_t), intent(in) :: p
    real(default), intent(in), optional :: mass
    if (present (mass)) then
      E = sqrt (p**2 + mass**2)
    end if
  end function energy_vector3

```

```

    else
        E = p**1
    end if
end function energy_vector3

elemental function energy_real (p, mass) result (E)
    real(default) :: E
    real(default), intent(in) :: p
    real(default), intent(in), optional :: mass
    if (present (mass)) then
        E = sqrt (p**2 + mass**2)
    else
        E = abs (p)
    end if
end function energy_real

```

The invariant mass of four-momenta. Zero for lightlike, negative for spacelike momenta.

```

<Lorentz: public functions>+≡
    public :: invariant_mass

<Lorentz: interfaces>+≡
    interface invariant_mass
        module procedure invariant_mass_vector4
    end interface

<Lorentz: subroutines>+≡
    elemental function invariant_mass_vector4 (p) result (m)
        real(default) :: m
        type(vector4_t), intent(in) :: p
        real(default) :: msq
        msq = p*p
        if (msq >= 0) then
            m = sqrt (msq)
        else
            m = - sqrt (abs (msq))
        end if
    end function invariant_mass_vector4

```

The invariant mass squared. Zero for lightlike, negative for spacelike momenta.

```

<Lorentz: public functions>+≡
    public :: invariant_mass_squared

<Lorentz: interfaces>+≡
    interface invariant_mass_squared
        module procedure invariant_mass_squared_vector4
    end interface

<Lorentz: subroutines>+≡
    elemental function invariant_mass_squared_vector4 (p) result (msq)
        real(default) :: msq
        type(vector4_t), intent(in) :: p
        msq = p*p
    end function invariant_mass_squared_vector4

```

The transverse mass. If the mass squared is negative, this value also is negative.

```

<Lorentz: public functions>+≡
    public :: transverse_mass

<Lorentz: interfaces>+≡
    interface transverse_mass
        module procedure transverse_mass_vector4
    end interface

<Lorentz: subroutines>+≡
    elemental function transverse_mass_vector4 (p) result (m)
        real(default) :: m
        type(vector4_t), intent(in) :: p
        real(default) :: msq
        msq = p%p(0)**2 - p%p(1)**2 - p%p(2)**2
        if (msq >= 0) then
            m = sqrt (msq)
        else
            m = - sqrt (abs (msq))
        end if
    end function transverse_mass_vector4

```

The rapidity (defined if particle is massive or $p_{\perp} > 0$)

```

<Lorentz: public functions>+≡
    public :: rapidity

<Lorentz: interfaces>+≡
    interface rapidity
        module procedure rapidity_vector4
    end interface

<Lorentz: subroutines>+≡
    elemental function rapidity_vector4 (p) result (y)
        real(default) :: y
        type(vector4_t), intent(in) :: p
        y = .5 * log( (energy (p) + longitudinal_part (p)) &
            & / (energy (p) - longitudinal_part (p)))
    end function rapidity_vector4

```

The pseudorapidity (defined if $p_{\perp} > 0$)

```

<Lorentz: public functions>+≡
    public :: pseudorapidity

<Lorentz: interfaces>+≡
    interface pseudorapidity
        module procedure pseudorapidity_vector4
    end interface

<Lorentz: subroutines>+≡
    elemental function pseudorapidity_vector4 (p) result (eta)
        real(default) :: eta
        type(vector4_t), intent(in) :: p
        eta = -log( tan (.5 * polar_angle (p)))
    end function pseudorapidity_vector4

```

The rapidity distance (defined if both $p_{\perp} > 0$)

```

<Lorentz: public functions>+≡
    public :: rapidity_distance

<Lorentz: interfaces>+≡
    interface rapidity_distance
        module procedure rapidity_distance_vector4
    end interface

<Lorentz: subroutines>+≡
    elemental function rapidity_distance_vector4 (p, q) result (dy)
        type(vector4_t), intent(in) :: p, q
        real(default) :: dy
        dy = rapidity (q) - rapidity (p)
    end function rapidity_distance_vector4

```

The pseudorapidity distance (defined if both $p_{\perp} > 0$)

```

<Lorentz: public functions>+≡
    public :: pseudorapidity_distance

<Lorentz: interfaces>+≡
    interface pseudorapidity_distance
        module procedure pseudorapidity_distance_vector4
    end interface

<Lorentz: subroutines>+≡
    elemental function pseudorapidity_distance_vector4 (p, q) result (deta)
        real(default) :: deta
        type(vector4_t), intent(in) :: p, q
        deta = pseudorapidity (q) - pseudorapidity (p)
    end function pseudorapidity_distance_vector4

```

The distance on the $\eta - \phi$ cylinder:

```

<Lorentz: public functions>+≡
    public :: eta_phi_distance

<Lorentz: interfaces>+≡
    interface eta_phi_distance
        module procedure eta_phi_distance_vector4
    end interface

<Lorentz: subroutines>+≡
    elemental function eta_phi_distance_vector4 (p, q) result (dr)
        type(vector4_t), intent(in) :: p, q
        real(default) :: dr
        dr = sqrt ( &
            pseudorapidity_distance (p, q)**2 &
            + azimuthal_distance (p, q)**2)
    end function eta_phi_distance_vector4

```

4.1.6 Lorentz transformations

```

<Lorentz: public>+≡
    public :: lorentz_transformation_t

```

```

<Lorentz: types>+≡
  type :: lorentz_transformation_t
  private
    real(default), dimension(0:3, 0:3) :: L
  end type lorentz_transformation_t

```

Output:

```

<Lorentz: public>+≡
  public :: lorentz_transformation_write

<Lorentz: subroutines>+≡
  subroutine lorentz_transformation_write (L, unit)
    type(lorentz_transformation_t), intent(in) :: L
    integer, intent(in), optional :: unit
    integer :: u
    integer :: i
    u = output_unit (unit); if (u < 0) return
    write (u, *) 'Lorentz transformation:'
    write (u, *) 'L00:'
    write (u, *) L%L(0,0)
    write (u, *) 'L0j:', L%L(0,1:)
    write (u, *) 'Li0, Lij:'
    do i = 1, 3
      write (u, *) L%L(i,0)
      write (u, *) '      ', L%L(i,1:)
    end do
  end subroutine lorentz_transformation_write

```

Extract all components:

```

<Lorentz: public>+≡
  public :: lorentz_transformation_get_components

<Lorentz: subroutines>+≡
  pure function lorentz_transformation_get_components (L) result (a)
    type(lorentz_transformation_t), intent(in) :: L
    real(default), dimension(0:3,0:3) :: a
    a = L%L
  end function lorentz_transformation_get_components

```

4.1.7 Functions of Lorentz transformations

For the inverse, we make use of the fact that $\Lambda^{\mu\nu}\Lambda_{\mu\rho} = \delta_{\rho}^{\nu}$. So, lowering the indices and transposing is sufficient.

```

<Lorentz: public functions>+≡
  public :: inverse

<Lorentz: interfaces>+≡
  interface inverse
    module procedure lorentz_transformation_inverse
  end interface

```

```

<Lorentz: subroutines>+≡
  elemental function lorentz_transformation_inverse (L) result (IL)
    type(lorentz_transformation_t) :: IL
    type(lorentz_transformation_t), intent(in) :: L
    IL%L(0,0) = L%L(0,0)
    IL%L(0,1:) = -L%L(1:,0)
    IL%L(1:,0) = -L%L(0,1:)
    IL%L(1:,1:) = transpose(L%L(1:,1:))
  end function lorentz_transformation_inverse

```

4.1.8 Invariants

These are used below. The first array index is varying fastest in FORTRAN; therefore the extra minus in the odd-rank tensor epsilon.

```

<Lorentz: parameters>+≡
  integer, dimension(3,3), parameter :: delta_three = &
    & reshape( source = (/ 1,0,0, 0,1,0, 0,0,1 /), &
    &          shape = (/3,3/) )
  integer, dimension(3,3,3), parameter :: epsilon_three = &
    & reshape( source = (/ 0, 0,0, 0,0,-1, 0,1,0,&
    &                      0, 0,1, 0,0, 0, -1,0,0,&
    &                      0,-1,0, 1,0, 0, 0,0,0 /),&
    &          shape = (/3,3,3/) )

```

This could be of some use:

```

<Lorentz: public>+≡
  public :: identity

<Lorentz: parameters>+≡
  type(lorentz_transformation_t), parameter :: &
    & identity = &
    & lorentz_transformation_t ( &
    & reshape( source = (/ 1._default, 0._default, 0._default, 0._default, &
    &                      0._default, 1._default, 0._default, 0._default, &
    &                      0._default, 0._default, 1._default, 0._default, &
    &                      0._default, 0._default, 0._default, 1._default /),&
    &          shape = (/ 4,4 /) ) )

<Lorentz: public>+≡
  public :: space_reflection

<Lorentz: parameters>+≡
  type(lorentz_transformation_t), parameter :: &
    & space_reflection = &
    & lorentz_transformation_t ( &
    & reshape( source = (/ 1._default, 0._default, 0._default, 0._default, &
    &                      0._default,-1._default, 0._default, 0._default, &
    &                      0._default, 0._default,-1._default, 0._default, &
    &                      0._default, 0._default, 0._default,-1._default /),&
    &          shape = (/ 4,4 /) ) )

```

4.1.9 Boosts

We build Lorentz transformations from boosts and rotations. In both cases we can supply a three-vector which defines the axis and (hyperbolic) angle. For a boost, this is the vector $\vec{\beta} = \vec{p}/E$, such that a particle at rest with mass m is boosted to a particle with three-vector \vec{p} . Here, we have

$$\beta = \tanh \chi = p/E, \quad \gamma = \cosh \chi = E/m, \quad \beta\gamma = \sinh \chi = p/m \quad (4.1)$$

```

(Lorentz: public functions)+≡
  public :: boost

(Lorentz: interfaces)+≡
  interface boost
    module procedure boost_from_rest_frame
    module procedure boost_from_rest_frame_vector3
    module procedure boost_generic
    module procedure boost_canonical
  end interface

```

In the first form, the argument is some four-momentum, the space part of which determines a direction, and the associated mass (which is not checked against the four-momentum). The boost vector $\gamma\vec{\beta}$ is then given by \vec{p}/m . This boosts from the rest frame of a particle to the current frame. To be explicit, if \vec{p} is the momentum of a particle and m its mass, $L(\vec{p}/m)$ is the transformation that turns $(m; \vec{0})$ into $(E; \vec{p})$. Conversely, the inverse transformation boosts a vector *into* the rest frame of a particle, in particular $(E; \vec{p})$ into $(m; \vec{0})$.

```

(Lorentz: subroutines)+≡
  elemental function boost_from_rest_frame (p, m) result (L)
    type(lorentz_transformation_t) :: L
    type(vector4_t), intent(in) :: p
    real(default), intent(in) :: m
    L = boost_from_rest_frame_vector3 (space_part (p), m)
  end function boost_from_rest_frame
  elemental function boost_from_rest_frame_vector3 (p, m) result (L)
    type(lorentz_transformation_t) :: L
    type(vector3_t), intent(in) :: p
    real(default), intent(in) :: m
    type(vector3_t) :: beta_gamma
    real(default) :: bg2, g, c
    integer :: i,j
    if (m /= 0) then
      beta_gamma = p / m
      bg2 = beta_gamma**2
    else
      bg2 = 0
    end if
    if (bg2 /= 0) then
      g = sqrt(1 + bg2); c = (g-1)/bg2
      L%L(0,0) = g
      L%L(0,1:) = beta_gamma%p
      L%L(1:,0) = L%L(0,1:)
      do i=1,3
        do j=1,3
          L%L(i,j) = delta_three(i,j) + c*beta_gamma%p(i)*beta_gamma%p(j)
        end do
      end do
    end if
  end function boost_from_rest_frame_vector3

```

```

        end do
    end do
else
    L = identity
end if
end function boost_from_rest_frame_vector3

```

A canonical boost is a boost along one of the coordinate axes, which we may supply as an integer argument. Here, $\gamma\beta$ is scalar.

```

<Lorentz: subroutines>+≡
    elemental function boost_canonical (beta_gamma, k) result (L)
        type(lorentz_transformation_t) :: L
        real(default), intent(in) :: beta_gamma
        integer, intent(in) :: k
        real(default) :: g
        g = sqrt(1 + beta_gamma**2)
        L = identity
        L%L(0,0) = g
        L%L(0,k) = beta_gamma
        L%L(k,0) = L%L(0,k)
        L%L(k,k) = L%L(0,0)
    end function boost_canonical

```

Instead of a canonical axis, we can supply an arbitrary axis which need not be normalized. If it is zero, return the unit matrix.

```

<Lorentz: subroutines>+≡
    elemental function boost_generic (beta_gamma, axis) result (L)
        type(lorentz_transformation_t) :: L
        real(default), intent(in) :: beta_gamma
        type(vector3_t), intent(in) :: axis
        if (any(axis%p/=0)) then
            L = boost_from_rest_frame_vector3 (beta_gamma * axis, axis**1)
        else
            L = identity
        end if
    end function boost_generic

```

4.1.10 Rotations

For a rotation, the vector defines the rotation axis, and its length the rotation angle.

```

<Lorentz: public functions>+≡
    public :: rotation

<Lorentz: interfaces>+≡
    interface rotation
        module procedure rotation_generic
        module procedure rotation_canonical
        module procedure rotation_generic_cs
        module procedure rotation_canonical_cs
    end interface

```

If $\cos \phi$ and $\sin \phi$ is already known, we do not have to calculate them. Of course, the user has to ensure that $\cos^2 \phi + \sin^2 \phi = 1$, and that the given axis \mathbf{n} is normalized to one. In the second form, the length of `axis` is the rotation angle.

```

(Lorentz: subroutines)+≡
  elemental function rotation_generic_cs (cp, sp, axis) result (R)
    type(lorentz_transformation_t) :: R
    real(default), intent(in) :: cp, sp
    type(vector3_t), intent(in) :: axis
    integer :: i,j
    R = identity
    do i=1,3
      do j=1,3
        R%L(i,j) = cp*delta_three(i,j) + (1-cp)*axis%p(i)*axis%p(j) &
          & - sp*dot_product(epsilon_three(i,j,:), axis%p)
      end do
    end do
  end function rotation_generic_cs
  elemental function rotation_generic (axis) result (R)
    type(lorentz_transformation_t) :: R
    type(vector3_t), intent(in) :: axis
    real(default) :: phi
    if (any(axis%p/=0)) then
      phi = abs(axis**1)
      R = rotation_generic_cs (cos(phi), sin(phi), axis/phi)
    else
      R = identity
    end if
  end function rotation_generic

```

Alternatively, give just the angle and label the coordinate axis by an integer.

```

(Lorentz: subroutines)+≡
  elemental function rotation_canonical_cs (cp, sp, k) result (R)
    type(lorentz_transformation_t) :: R
    real(default), intent(in) :: cp, sp
    integer, intent(in) :: k
    integer :: i,j
    R = identity
    do i=1,3
      do j=1,3
        R%L(i,j) = -sp*epsilon_three(i,j,k)
      end do
      R%L(i,i) = cp
    end do
    R%L(k,k) = 1
  end function rotation_canonical_cs
  elemental function rotation_canonical (phi, k) result (R)
    type(lorentz_transformation_t) :: R
    real(default), intent(in) :: phi
    integer, intent(in) :: k
    R = rotation_canonical_cs(cos(phi), sin(phi), k)
  end function rotation_canonical

```

This is viewed as a method for the first argument (three-vector): Reconstruct the rotation that rotates it into the second three-vector.

```

<Lorentz: public functions>+≡
  public :: rotation_to_2nd

<Lorentz: interfaces>+≡
  interface rotation_to_2nd
    module procedure rotation_to_2nd_generic
    module procedure rotation_to_2nd_canonical
  end interface

<Lorentz: subroutines>+≡
  elemental function rotation_to_2nd_generic (p, q) result (R)
    type(lorentz_transformation_t) :: R
    type(vector3_t), intent(in) :: p, q
    type(vector3_t) :: a, b, ab
    real(default) :: ct, st
    if (any (p%p /= 0) .and. any (q%p /= 0)) then
      a = direction (p)
      b = direction (q)
      ab = cross_product(a,b)
      ct = a*b;  st = ab**1
      if (st /= 0) then
        R = rotation_generic_cs (ct, st, ab/st)
      else if (ct < 0) then
        R = space_reflection
      else
        R = identity
      end if
    else
      R = identity
    end if
  end function rotation_to_2nd_generic

```

The same for a canonical axis: The function returns the transformation that rotates the k -axis into the direction of p .

```

<Lorentz: subroutines>+≡
  elemental function rotation_to_2nd_canonical (k, p) result (R)
    type(lorentz_transformation_t) :: R
    integer, intent(in) :: k
    type(vector3_t), intent(in) :: p
    type(vector3_t) :: b, ab
    real(default) :: ct, st
    integer :: i, j
    if (any (p%p /= 0)) then
      b = direction (p)
      ab%p = 0
      do i = 1, 3
        do j = 1, 3
          ab%p(j) = ab%p(j) + b%p(i) * epsilon_three(i,j,k)
        end do
      end do
      ct = b%p(k);  st = ab**1
      if (st /= 0) then
        R = rotation_generic_cs (ct, st, ab/st)
      else if (ct < 0) then
        R = space_reflection
      else

```

```

        R = identity
    end if
else
    R = identity
end if
end function rotation_to_2nd_canonical

```

4.1.11 Composite Lorentz transformations

This function returns the transformation that, given a pair of vectors $p_{1,2}$, (a) boosts from the rest frame of the c.m. system (with invariant mass m) into the lab frame where p_i are defined, and (b) turns the given axis (or the canonical vectors $\pm e_k$) in the rest frame into the directions of $p_{1,2}$ in the lab frame. Note that the energy components are not used; for a consistent result one should have $(p_1 + p_2)^2 = m^2$.

```

<Lorentz: public functions>+≡
    public :: transformation

<Lorentz: interfaces>+≡
    interface transformation
        module procedure transformation_rec_generic
        module procedure transformation_rec_canonical
    end interface

<Lorentz: subroutines>+≡
    elemental function transformation_rec_generic (axis, p1, p2, m) result (L)
        type(vector3_t), intent(in) :: axis
        type(vector4_t), intent(in) :: p1, p2
        real(default), intent(in) :: m
        type(lorentz_transformation_t) :: L
        L = boost (p1 + p2, m)
        L = L * rotation_to_2nd (axis, space_part (inverse (L) * p1))
    end function transformation_rec_generic
    elemental function transformation_rec_canonical (k, p1, p2, m) result (L)
        integer, intent(in) :: k
        type(vector4_t), intent(in) :: p1, p2
        real(default), intent(in) :: m
        type(lorentz_transformation_t) :: L
        L = boost (p1 + p2, m)
        L = L * rotation_to_2nd (k, space_part (inverse (L) * p1))
    end function transformation_rec_canonical

```

4.1.12 Applying Lorentz transformations

Multiplying vectors and Lorentz transformations is straightforward.

```

<Lorentz: interfaces>+≡
    interface operator(*)
        module procedure prod_LT_vector4
        module procedure prod_LT_LT
        module procedure prod_vector4_LT
    end interface

```

```

<Lorentz: subroutines>+≡
  elemental function prod_LT_vector4 (L, p) result (np)
    type(vector4_t) :: np
    type(lorentz_transformation_t), intent(in) :: L
    type(vector4_t), intent(in) :: p
    np%p = matmul (L%L, p%p)
  end function prod_LT_vector4
  elemental function prod_LT_LT (L1, L2) result (NL)
    type(lorentz_transformation_t) :: NL
    type(lorentz_transformation_t), intent(in) :: L1,L2
    NL%L = matmul (L1%L, L2%L)
  end function prod_LT_LT
  elemental function prod_vector4_LT (p, L) result (np)
    type(vector4_t) :: np
    type(vector4_t), intent(in) :: p
    type(lorentz_transformation_t), intent(in) :: L
    np%p = matmul (p%p, L%L)
  end function prod_vector4_LT

```

4.1.13 Special Lorentz transformations

These routines have their application in the generation and extraction of angles in the phase-space sampling routine. Since this part of the program is time-critical, we calculate the composition of transformations directly instead of multiplying rotations and boosts.

This Lorentz transformation is the composition of a rotation by ϕ around the 3 axis, a rotation by θ around the 2 axis, and a boost along the 3 axis:

$$L = B_3(\beta\gamma) R_2(\theta) R_3(\phi) \quad (4.2)$$

Instead of the angles we provide sine and cosine.

```

<Lorentz: public functions>+≡
  public :: LT_compose_r3_r2_b3

<Lorentz: subroutines>+≡
  elemental function LT_compose_r3_r2_b3 &
    (cp, sp, ct, st, beta_gamma) result (L)
    type(lorentz_transformation_t) :: L
    real(default), intent(in) :: cp, sp, ct, st, beta_gamma
    real(default) :: gamma
    if (beta_gamma==0) then
      L%L(0,0) = 1
      L%L(1:,0) = 0
      L%L(0,1:) = 0
      L%L(1,1:) = (/ ct*cp, -ct*sp, st /)
      L%L(2,1:) = (/ sp, cp, 0._default /)
      L%L(3,1:) = (/ -st*cp, st*sp, ct /)
    else
      gamma = sqrt(1 + beta_gamma**2)
      L%L(0,0) = gamma
      L%L(1,0) = 0
      L%L(2,0) = 0
      L%L(3,0) = beta_gamma

```

```

        L%L(0,1:) = beta_gamma * (/ -st*cp, st*sp, ct /)
        L%L(1,1:) = (/ ct*cp, -ct*sp, st /)
        L%L(2,1:) = (/ sp, cp, 0._default /)
        L%L(3,1:) = gamma * (/ -st*cp, st*sp, ct /)
    end if
end function LT_compose_r3_r2_b3

```

Different ordering:

$$L = B_3(\beta\gamma) R_3(\phi) R_2(\theta) \quad (4.3)$$

```

<Lorentz: public functions>+≡
    public :: LT_compose_r2_r3_b3

<Lorentz: subroutines>+≡
    elemental function LT_compose_r2_r3_b3 &
        (ct, st, cp, sp, beta_gamma) result (L)
    type(lorentz_transformation_t) :: L
    real(default), intent(in) :: ct, st, cp, sp, beta_gamma
    real(default) :: gamma
    if (beta_gamma==0) then
        L%L(0,0) = 1
        L%L(1,0) = 0
        L%L(0,1:) = 0
        L%L(1,1:) = (/ ct*cp, -sp, st*cp /)
        L%L(2,1:) = (/ ct*sp, cp, st*sp /)
        L%L(3,1:) = (/ -st, 0._default, ct /)
    else
        gamma = sqrt(1 + beta_gamma**2)
        L%L(0,0) = gamma
        L%L(1,0) = 0
        L%L(2,0) = 0
        L%L(3,0) = beta_gamma
        L%L(0,1:) = beta_gamma * (/ -st, 0._default, ct /)
        L%L(1,1:) = (/ ct*cp, -sp, st*cp /)
        L%L(2,1:) = (/ ct*sp, cp, st*sp /)
        L%L(3,1:) = gamma * (/ -st, 0._default, ct /)
    end if
end function LT_compose_r2_r3_b3

```

This function returns the previous Lorentz transformation applied to an arbitrary four-momentum and extracts the space part of the result:

$$\vec{n} = [B_3(\beta\gamma) R_2(\theta) R_3(\phi) p]_{\text{space part}} \quad (4.4)$$

The second variant applies if there is no rotation

```

<Lorentz: public functions>+≡
    public :: axis_from_p_r3_r2_b3, axis_from_p_b3

<Lorentz: subroutines>+≡
    elemental function axis_from_p_r3_r2_b3 &
        (p, cp, sp, ct, st, beta_gamma) result (n)
    type(vector3_t) :: n
    type(vector4_t), intent(in) :: p
    real(default), intent(in) :: cp, sp, ct, st, beta_gamma

```

```

real(default) :: gamma, px, py
px = cp * p%p(1) - sp * p%p(2)
py = sp * p%p(1) + cp * p%p(2)
n%p(1) = ct * px + st * p%p(3)
n%p(2) = py
n%p(3) = -st * px + ct * p%p(3)
if (beta_gamma/=0) then
    gamma = sqrt(1 + beta_gamma**2)
    n%p(3) = n%p(3) * gamma + p%p(0) * beta_gamma
end if
end function axis_from_p_r3_r2_b3

elemental function axis_from_p_b3 (p, beta_gamma) result (n)
type(vector3_t) :: n
type(vector4_t), intent(in) :: p
real(default), intent(in) :: beta_gamma
real(default) :: gamma
n%p = p%p(1:3)
if (beta_gamma/=0) then
    gamma = sqrt(1 + beta_gamma**2)
    n%p(3) = n%p(3) * gamma + p%p(0) * beta_gamma
end if
end function axis_from_p_b3

```

4.1.14 Special functions

The standard phase space function:

```

(Lorentz: public functions)+≡
public :: lambda

(Lorentz: subroutines)+≡
elemental function lambda (m1sq, m2sq, m3sq)
real(default) :: lambda
real(default), intent(in) :: m1sq, m2sq, m3sq
lambda = (m1sq - m2sq - m3sq)**2 - 4*m2sq*m3sq
end function lambda

```

Return a pair of head-to-head colliding momenta, given the collider energy, particle masses, and optionally the momentum of the c.m. system.

```

(Lorentz: public functions)+≡
public :: colliding_momenta

(Lorentz: subroutines)+≡
function colliding_momenta (sqrts, m, p_cm) result (p)
type(vector4_t), dimension(2) :: p
real(default), intent(in) :: squrts
real(default), dimension(2), intent(in), optional :: m
real(default), intent(in), optional :: p_cm
real(default), dimension(2) :: dmsq
real(default) :: ch, sh
real(default), dimension(2) :: E0, p0
integer, dimension(2), parameter :: sgn = (/1, -1/)
if (sqrts <= 0) then

```

```

        call msg_fatal (" Colliding momenta: energy must be positive")
        p = vector4_null; return
    end if
    if (present (m)) then
        dmsq = sgn * (m(1)**2-m(2)**2)
        E0 = (sqrts + dmsq/sqrts) / 2
        if (any (E0 < m)) then
            call msg_fatal &
                (" Colliding momenta: energy is less than particle mass")
            p = vector4_null; return
        end if
        p0 = sgn * sqrt (E0**2 - m**2)
    else
        E0 = sqrts / 2
        p0 = sgn * E0
    end if
    if (present (p_cm)) then
        sh = p_cm / sqrts
        ch = sqrt (1 + sh**2)
        p = vector4_moving (E0 * ch + p0 * sh, E0 * sh + p0 * ch, 3)
    else
        p = vector4_moving (E0, p0, 3)
    end if
end function colliding_momenta

```

4.2 Special Physics functions

Define special kinematical functions like running α_s and e.g. Catani-Seymour dipole terms.

To make maximum use of this, all functions, if possible, are declared elemental (or pure, if this is not possible).

```

<sm_physics.f90>≡
  <File header>

  module sm_physics

    <Use kinds>
    use constants !NODEP!
    <Use file utils>
    use diagnostics !NODEP!
    use lorentz !NODEP!

    <Standard module head>

    <SM physics: public parameters>

    <SM physics: public functions>

    contains

    <SM physics: subroutines>
  end module sm_physics

```

First we set a reference value for $\alpha_s(M_Z) = 0.1178$.

```

<SM physics: public parameters>≡
  real(kind=default), public, parameter :: as_mz = 0.1178_default, &
    mass_z = 91.188_default

```

Then we define the coefficients of the beta function of QCD (as a reference cf. the Particle Data Group), where n_f is the number of active flavors in two different schemes:

$$\beta_0 = 11 - \frac{2}{3}n_f \quad (4.5)$$

$$\beta_1 = 51 - \frac{19}{3}n_f \quad (4.6)$$

$$\beta_2 = 2857 - \frac{5033}{9}n_f + \frac{325}{27}n_f^2 \quad (4.7)$$

$$b_0 = \frac{1}{12\pi} (11C_A - 2n_f) \quad (4.8)$$

$$b_1 = \frac{1}{24\pi^2} (17C_A^2 - 5C_An_f - 3C_Fn_f) \quad (4.9)$$

$$b_2 = \frac{1}{(4\pi)^3} \left(\frac{2857}{54}C_A^3 - \frac{1415}{54}C_A^2n_f - \frac{205}{18}C_AC_Fn_f + C_F^2n_f + \frac{79}{54}C_An_f^{**2} + \frac{11}{9}C_Fn_f^{**2} \right) \quad (4.10)$$

```

<SM physics: public functions>≡
  public :: beta0, beta1, beta2, coeff_b0, coeff_b1, coeff_b2

```

```

<SM physics: subroutines>≡
pure function beta0 (nf)
  real(kind=default), intent(in) :: nf
  real(kind=default) :: beta0
  beta0 = 11.0_default - two/three * nf
end function beta0

pure function beta1 (nf)
  real(kind=default), intent(in) :: nf
  real(kind=default) :: beta1
  beta1 = 51.0_default - 19.0_default/three * nf
end function beta1

pure function beta2 (nf)
  real(kind=default), intent(in) :: nf
  real(kind=default) :: beta2
  beta2 = 2857.0_default - 5033.0_default / 9.0_default * &
    nf + 325.0_default/27.0_default * nf**2
end function beta2

pure function coeff_b0 (nf)
  real(kind=default), intent(in) :: nf
  real(kind=default) :: coeff_b0
  coeff_b0 = (11.0_default * CA - two * nf) / (12.0_default * pi)
end function coeff_b0

pure function coeff_b1 (nf)
  real(kind=default), intent(in) :: nf
  real(kind=default) :: coeff_b1
  coeff_b1 = (17.0_default * CA**2 - five * CA * nf - three * CF * nf) / &
    (24.0_default * pi**2)
end function coeff_b1

pure function coeff_b2 (nf)
  real(kind=default), intent(in) :: nf
  real(kind=default) :: coeff_b2
  coeff_b2 = (2857.0_default/54.0_default * CA**3 - &
    1415.0_default/54.0_default * &
    CA**2 * nf - 205.0_default/18.0_default * CA*CF*nf &
    + 79.0_default/54.0_default * CA*nf**2 + &
    11.0_default/9.0_default * CF * nf**2) / (four*pi)**3
end function coeff_b2

```

There should be two versions of running α_s , one which takes the scale and Λ_{QCD} as input, and one which takes the scale and e.g. $\alpha_s(m_Z)$ as input. Here, we take the one which takes the QCD scale and scale as inputs from the PDG book.

```

<SM physics: public functions>+≡
public :: running_as, running_as_lam

<SM physics: subroutines>+≡
pure function running_as (scale,al_mz,mz,order,nf) result (ascale)
  real(kind=default), intent(in) :: scale
  real(kind=default), intent(in), optional :: al_mz, nf, mz
  integer, intent(in), optional :: order

```

```

integer :: ord
real(kind=default) :: az, m_z, as_log, n_f, b0, b1, b2, ascale
real(kind=default) :: as0, as1
if (present(mz)) then
    m_z = mz
else
    m_z = mass_z
end if
if (present(order)) then
    ord = order
else
    ord = 0
end if
if (present(al_mz)) then
    az = al_mz
else
    az = as_mz
end if
if (present(nf)) then
    n_f = nf
else
    n_f = 5
end if
b0 = coeff_b0 (n_f)
b1 = coeff_b1 (n_f)
b2 = coeff_b2 (n_f)
as_log = one + b0 * az * log(scale**2/m_z**2)
as0 = az / as_log
as1 = as0 - as0**2 * b1/b0 * log(as_log)
select case (ord)
    case (0)
        ascale = as0
    case (1)
        ascale = as1
    case (2)
        ascale = as1 + as0**3 * (b1**2/b0**2 * ((log(as_log))**2 - &
            log(as_log) + as_log - one) - b2/b0 * (as_log - one))
end select
end function running_as

pure function running_as_lam (nf,scale,lambda_qcd,order) result (ascale)
real(kind=default), intent(in) :: nf, scale, lambda_qcd
integer, intent(in), optional :: order
real(kind=default) :: as0, as1, logmul, b0, b1, b2, ascale
integer :: ord
if (present(order)) then
    ord = order
else
    ord = 0
end if
b0 = beta0(nf)
b1 = beta1(nf)
b2 = beta2(nf)
logmul = log(scale**2/lambda_qcd**2)

```

```

as0 = four*pi / b0 / logmul
as1 = as0 * (one - two* b1 / b0**2 * log(logmul) / logmul)
select case (ord)
  case (0)
    ascale = as0
  case (1)
    ascale = as1
  case (2)
    ascale = as1 + as0 * four * b1**2/b0**4/logmul**2 * &
      ( (log(logmul) - 0.5_default)**2 + &
        b2*b0/8.0_default/b1**2 - five/four)
end select
end function running_as_lam

```

These are fundamental constants of the Catani-Seymour dipole formalism. Since the corresponding parameters for the gluon case depend on the number of flavors which is treated as an argument, there we do have functions and not parameters.

$$\gamma_q = \gamma_{\bar{q}} = \frac{3}{2}C_F \quad \gamma_g = \frac{11}{6}C_A - \frac{2}{3}T_R N_f \quad (4.11)$$

$$K_q = K_{\bar{q}} = \left(\frac{7}{2} - \frac{\pi^2}{6}\right) C_F \quad K_g = \left(\frac{67}{18} - \frac{\pi^2}{6}\right) C_A - \frac{10}{9}T_R N_f \quad (4.12)$$

```

<SM physics: public parameters>+=
  real(kind=default), parameter, public :: gamma_q = three/two * CF, &
    k_q = (7.0_default/two - pi**2/6.0_default) * CF

<SM physics: public functions>+=
  public :: gamma_g, k_g

<SM physics: subroutines>+=
  elemental function gamma_g (nf) result (gg)
    real(kind=default), intent(in) :: nf
    real(kind=default) :: gg
    gg = 11.0_default/6.0_default * CA - two/three * TR * nf
  end function gamma_g

  elemental function k_g (nf) result (kg)
    real(kind=default), intent(in) :: nf
    real(kind=default) :: kg
    kg = (67.0_default/18.0_default - pi**2/6.0_default) * CA - &
      10.0_default/9.0_default * TR * nf
  end function k_g

```

The dilogarithm. This simplified version is bound to double precision, and restricted to argument values less or equal to unity, so we do not need complex algebra. The wrapper converts it to default precision (which is, of course, a no-op if double=default).

The routine calculates the dilogarithm through mapping on the area where there is a quickly convergent series (adapted from an F77 routine by Hans Kuijf, 1988): Map x such that x is not in the neighbourhood of 1. Note that $|z| = -\ln(1-x)$ is always smaller than 1.10, but $\frac{1 \cdot 10^{19}}{19!} \text{Bernoulli}_{19} = 2.7 \times 10^{-15}$.

```

<SM physics: public functions>+=

```

```

public :: Li2
<SM physics: subroutines>+=
function Li2 (x)
    use kinds, only: double !NODEP!
    real(default), intent(in) :: x
    real(default) :: Li2
    Li2 = real( Li2_double (real(x, kind=double)), kind=default)
end function Li2

<SM physics: subroutines>+=
function Li2_double (x) result (Li2)
    use kinds, only: double !NODEP!
    real(kind=double), intent(in) :: x
    real(kind=double) :: Li2
    real(kind=double), parameter :: pi2_6 = pi**2/6
    if (abs(1-x) < 1.E-13_double) then
        Li2 = pi2_6
    else if (abs(1-x) < 0.5_double) then
        Li2 = pi2_6 - log(1-x) * log(x) - Li2_restricted (1-x)
    else if (abs(x).gt.1.d0) then
        call msg_bug (" Dilogarithm called outside of defined range.")
    !
        Li2 = -pi2_6 - 0.5_default * log(-x) * log(-x) - Li2_restricted (1/x)
    else
        Li2 = Li2_restricted (x)
    end if
contains
function Li2_restricted (x) result (Li2)
    real(kind=double), intent(in) :: x
    real(kind=double) :: Li2
    real(kind=double) :: tmp, z, z2
    z = - log (1-x)
    z2 = z**2
    ! Horner's rule for the powers z^3 through z^19
    tmp = 43867._double/798._double
    tmp = tmp * z2 /342._double - 3617._double/510._double
    tmp = tmp * z2 /272._double + 7._double/6._double
    tmp = tmp * z2 /210._double - 691._double/2730._double
    tmp = tmp * z2 /156._double + 5._double/66._double
    tmp = tmp * z2 /110._double - 1._double/30._double
    tmp = tmp * z2 / 72._double + 1._double/42._double
    tmp = tmp * z2 / 42._double - 1._double/30._double
    tmp = tmp * z2 / 20._double + 1._double/6._double
    ! The first three terms of the power series
    Li2 = z2 * z * tmp / 6._double - 0.25_double * z2 + z
end function Li2_restricted
end function Li2_double

<SM physics: public functions>+=
public :: faux

<SM physics: subroutines>+=
elemental function faux (x) result (y)
    real(default), intent(in) :: x

```

```

complex(default) :: y
if (1 <= x) then
  y = asin(sqrt(1/x))**2
else
  y = - 1/4.0_default * (log((1 + sqrt(1 - x))/ &
    (1 - sqrt(1 - x))) - cmplx (0.0_default, pi, kind=default))**2
end if
end function faux

```

<SM physics: public functions>+≡
 public :: fonehalf

<SM physics: subroutines>+≡
 elemental function fonehalf (x) result (y)
 real(default), intent(in) :: x
 complex(default) :: y
 if (x==0) then
 y = 0
 else
 y = - 2.0_default * x * (1 + (1 - x) * faux(x))
 end if
end function fonehalf

<SM physics: public functions>+≡
 public :: fonehalf_pseudo

<SM physics: subroutines>+≡
 function fonehalf_pseudo (x) result (y)
 real(default), intent(in) :: x
 complex(default) :: y
 if (x==0) then
 y = 0
 else
 y = - 2.0_default * x * faux(x)
 end if
end function fonehalf_pseudo

<SM physics: public functions>+≡
 public :: fone

<SM physics: subroutines>+≡
 elemental function fone (x) result (y)
 real(default), intent(in) :: x
 complex(default) :: y
 if (x==0) then
 y = 2.0_default
 else
 y = 2.0_default + 3.0_default * x + &
 3.0_default * x * (2.0_default - x) * &
 faux(x)
 end if
end function fone

```

⟨SM physics: public functions⟩+≡
  public :: gauX

⟨SM physics: subroutines⟩+≡
  elemental function gauX (x) result (y)
    real(default), intent(in) :: x
    complex(default) :: y
    if (1 <= x) then
      y = sqrt(x - 1) * asin(sqrt(1/x))
    else
      y = sqrt(1 - x) * (log((1 + sqrt(1 - x)) / &
        (1 - sqrt(1 - x))) - cmplx (0.0_default, pi, kind=default)) / 2
    end if
  end function gauX

```

```

⟨SM physics: public functions⟩+≡
  public :: tri_i1

⟨SM physics: subroutines⟩+≡
  elemental function tri_i1 (a,b) result (y)
    real(default), intent(in) :: a,b
    complex(default) :: y
    y = a*b/2.0_default/(a-b) + a**2 * b**2/2.0_default/(a-b)**2 * &
      (faux(a) - faux(b)) + &
      a**2 * b/(a-b)**2 * (gauX(a) - gauX(b))
  end function tri_i1

```

```

⟨SM physics: public functions⟩+≡
  public :: tri_i2

⟨SM physics: subroutines⟩+≡
  elemental function tri_i2 (a,b) result (y)
    real(default), intent(in) :: a,b
    complex(default) :: y
    y = - a * b / 2.0_default / (a-b) * (faux(a) - faux(b))
  end function tri_i2

```

These functions are for the running of the strong coupling constants, α_s .

```

⟨SM physics: public functions⟩+≡
  public :: run_b0

⟨SM physics: subroutines⟩+≡
  elemental function run_b0 (nf) result (bnull)
    integer, intent(in) :: nf
    real(default) :: bnull
    bnull = 33.0_default - 2.0_default * nf
  end function run_b0

```

```

⟨SM physics: public functions⟩+≡
  public :: run_b1

```

```

<SM physics: subroutines>+≡
  elemental function run_b1 (nf) result (bone)
    integer, intent(in) :: nf
    real(default) :: bone
    bone = 6.0_default * (153.0_default - 19.0_default * nf)/run_b0(nf)**2
  end function run_b1

<SM physics: public functions>+≡
  public :: run_aa

<SM physics: subroutines>+≡
  elemental function run_aa (nf) result (aaa)
    integer, intent(in) :: nf
    real(default) :: aaa
    aaa = 12.0_default * PI / run_b0(nf)
  end function run_aa

<SM physics: public functions>≡
  public :: run_bb

<SM physics: subroutines>+≡
  elemental function run_bb (nf) result (bbb)
    integer, intent(in) :: nf
    real(default) :: bbb
    bbb = run_b1(nf) / run_aa(nf)
  end function run_bb

```

4.2.1 Functions for Catani-Seymour dipoles

For the automated Catani-Seymour dipole subtraction, we need the following functions.

```

<SM physics: public functions>+≡
  public :: ff_dipole

<SM physics: subroutines>+≡
  pure subroutine ff_dipole (v_ijk,y_ijk,p_ij,pp_k,p_i,p_j,p_k)
    type(vector4_t), intent(in) :: p_i, p_j, p_k
    type(vector4_t), intent(out) :: p_ij, pp_k
    real(kind=default), intent(out) :: y_ijk
    real(kind=default) :: z_i
    real(kind=default), intent(out) :: v_ijk
    z_i = (p_i*p_k) / ((p_k*p_j) + (p_k*p_i))
    y_ijk = (p_i*p_j) / ((p_i*p_j) + (p_i*p_k) + (p_j*p_k))
    p_ij = p_i + p_j - y_ijk/(1.0_default - y_ijk) * p_k
    pp_k = (1.0/(1.0_default - y_ijk)) * p_k
    !!! We don't multiply by alpha_s right here:
    v_ijk = 8.0_default * PI * CF * &
      (2.0 / (1.0 - z_i*(1.0 - y_ijk)) - (1.0 + z_i))
  end subroutine ff_dipole

<SM physics: public functions>+≡
  public :: fi_dipole

```

```

<SM physics: subroutines>+≡
pure subroutine fi_dipole (v_ija,x_ija,p_ij,pp_a,p_i,p_j,p_a)
  type(vector4_t), intent(in) :: p_i, p_j, p_a
  type(vector4_t), intent(out) :: p_ij, pp_a
  real(kind=default), intent(out) :: x_ija
  real(kind=default) :: z_i
  real(kind=default), intent(out) :: v_ija
  z_i = (p_i*p_a) / ((p_a*p_j) + (p_a*p_i))
  x_ija = ((p_i*p_a) + (p_j*p_a) - (p_i*p_j)) &
    / ((p_i*p_a) + (p_j*p_a))
  p_ij = p_i + p_j - (1.0_default - x_ija) * p_a
  pp_a = x_ija * p_a
  !!! We don't not multiply by alpha_s right here:
  v_ija = 8.0_default * PI * CF * &
    (2.0 / (1.0 - z_i + (1.0 - x_ija)) - (1.0 + z_i)) / x_ija
end subroutine fi_dipole

```

```

<SM physics: public functions>+≡
public :: if_dipole

```

```

<SM physics: subroutines>+≡
pure subroutine if_dipole (v_kja,u_j,p_aj,pp_k,p_k,p_j,p_a)
  type(vector4_t), intent(in) :: p_k, p_j, p_a
  type(vector4_t), intent(out) :: p_aj, pp_k
  real(kind=default), intent(out) :: u_j
  real(kind=default) :: x_kja
  real(kind=default), intent(out) :: v_kja
  u_j = (p_a*p_j) / ((p_a*p_j) + (p_a*p_k))
  x_kja = ((p_a*p_k) + (p_a*p_j) - (p_j*p_k)) &
    / ((p_a*p_j) + (p_a*p_k))
  p_aj = x_kja * p_a
  pp_k = p_k + p_j - (1.0_default - x_kja) * p_a
  v_kja = 8.0_default * PI * CF * &
    (2.0 / (1.0 - x_kja + u_j) - (1.0 + x_kja)) / x_kja
end subroutine if_dipole

```

This function depends on a variable number of final state particles whose kinematics all get changed by the initial-initial dipole insertion.

```

<SM physics: public functions>+≡
public :: ii_dipole

```

```

<SM physics: subroutines>+≡
pure subroutine ii_dipole (v_jab,v_j,p_in,p_out,flag_1or2)
  type(vector4_t), dimension(:), intent(in) :: p_in
  type(vector4_t), dimension(size(p_in)-1), intent(out) :: p_out
  logical, intent(in) :: flag_1or2
  real(kind=default), intent(out) :: v_j
  real(kind=default), intent(out) :: v_jab
  type(vector4_t) :: p_a, p_b, p_j
  type(vector4_t) :: k, kk
  type(vector4_t) :: p_aj
  real(kind=default) :: x_jab
  integer :: i
  !!! flag_1or2 decides whether this a 12 or 21 dipole

```

```

if (flag_1or2) then
  p_a = p_in(1)
  p_b = p_in(2)
else
  p_b = p_in(1)
  p_a = p_in(2)
end if
!!! We assume that the unresolved particle has always the last
!!! momentum
p_j = p_in(size(p_in))
x_jab = ((p_a*p_b) - (p_a*p_j) - (p_b*p_j)) / (p_a*p_b)
v_j = (p_a*p_j) / (p_a * p_b)
p_aj = x_jab * p_a
k      = p_a + p_b - p_j
kk     = p_aj + p_b
do i = 3, size(p_in)-1
  p_out(i) = p_in(i) - 2.0*((k+kk)*p_in(i))/((k+kk)*(k+kk)) * (k+kk) + &
    (2.0 * (k*p_in(i)) / (k*k)) * kk
end do
if (flag_1or2) then
  p_out(1) = p_aj
  p_out(2) = p_b
else
  p_out(1) = p_b
  p_out(2) = p_aj
end if
v_jab = 8.0_default * PI * CF * &
  (2.0 / (1.0 - x_jab) - (1.0 + x_jab)) / x_jab
end subroutine ii_dipole

```

4.2.2 Distributions for integrated dipoles and such

The Dirac delta distribution, modified for Monte-Carlo sampling:

```

<SM physics: public functions>+≡
  public :: delta

<SM physics: subroutines>+≡
  elemental function delta (x,eps) result (z)
    real(kind=default), intent(in) :: x, eps
    real(kind=default) :: z
    if (x > 1.0_default - eps) then
      z = 1.0_default/eps
    else
      z = 0
    end if
  end function delta

```

The $+$ -distribution, $P_+(x) = \left(\frac{1}{1-x}\right)_+$, for the regularization of soft-collinear singularities. The constant part for the Monte-Carlo sampling is the integral over the splitting function divided by the weight for the WHIZARD numerical integration over the interval.

```

<SM physics: public functions>+≡
  public :: plus_distr

```

```

⟨SM physics: subroutines⟩+≡
  elemental function plus_distr (x,eps) result (plusd)
    real(kind=default), intent(in) :: x, eps
    real(kind=default) :: plusd
    if (x > (1.0_default - eps)) then
      plusd = log(eps)/eps
    else
      plusd = one/(one-x)
    end if
  end function plus_distr

```

The splitting function in $D = 4$ dimensions, regularized as $+$ -distributions if necessary:

$$P^{qq}(x) = P^{\bar{q}q}(x) = C_F \cdot \left(\frac{1+x^2}{1-x} \right)_+ \quad (4.13)$$

$$P^{qg}(x) = P^{\bar{q}g}(x) = C_F \cdot \frac{1+(1-x)^2}{x} \quad (4.14)$$

$$P^{gq}(x) = P^{g\bar{q}}(x) = T_R \cdot [x^2 + (1-x)^2] \quad (4.15)$$

$$P^{gg}(x) = 2C_A \left[\left(\frac{1}{1-x} \right)_+ + \frac{1-x}{x} - 1 + x(1-x) \right] + \delta(1-x) \left(\frac{11}{6}C_A - \frac{2}{3}N_f T_R \right) \quad (4.16)$$

Since the number of flavors summed over in the gluon splitting function might depend on the physics case under consideration it is implemented as an input variable.

```

⟨SM physics: public functions⟩+≡
  public :: pqq

⟨SM physics: subroutines⟩+≡
  elemental function pqq (x,eps) result (pqqx)
    real(kind=default), intent(in) :: x, eps
    real(kind=default) :: pqqx
    if (x > (1.0_default - eps)) then
      pqqx = (eps-one)/two + two*log(eps)/eps - three*(eps-one)/eps/two
    else
      pqqx = (one + x**2)/(one-x)
    end if
    pqqx = CF * pqqx
  end function pqq

⟨SM physics: public functions⟩+≡
  public :: pgq

⟨SM physics: subroutines⟩+≡
  elemental function pgq (x) result (pgqx)
    real(kind=default), intent(in) :: x
    real(kind=default) :: pgqx
    pgqx = TR * (x**2 + (one - x)**2)
  end function pgq

```

```

<SM physics: public functions>+≡
  public :: pqg

<SM physics: subroutines>+≡
  elemental function pqg (x) result (pqgx)
    real(kind=default), intent(in) :: x
    real(kind=default) :: pqgx
    pqgx = CF * (one + (one - x)**2) / x
  end function pqg

<SM physics: public functions>+≡
  public :: pgg

<SM physics: subroutines>+≡
  elemental function pgg (x, nf, eps) result (pggx)
    real(kind=default), intent(in) :: x, nf, eps
    real(kind=default) :: pggx
    pggx = two * CA * ( plus_distr (x, eps) + (one-x)/x - one + &
                        x*(one-x)) + delta (x, eps) * gamma_g(nf)
  end function pgg

```

For the qq and gg cases, there exist “regularized” versions of the splitting functions:

$$P_{\text{reg}}^{qq}(x) = -C_F \cdot (1 + x) \quad (4.17)$$

$$P_{\text{reg}}^{gg}(x) = 2C_A \left[\frac{1-x}{x} - 1 + x(1-x) \right] \quad (4.18)$$

$$(4.19)$$

```

<SM physics: public functions>+≡
  public :: pqq_reg

<SM physics: subroutines>+≡
  elemental function pqq_reg (x) result (pqqregx)
    real(kind=default), intent(in) :: x
    real(kind=default) :: pqqregx
    pqqregx = - CF * (one + x)
  end function pqq_reg

<SM physics: public functions>+≡
  public :: pgg_reg

<SM physics: subroutines>+≡
  elemental function pgg_reg (x) result (pggregx)
    real(kind=default), intent(in) :: x
    real(kind=default) :: pggregx
    pggregx = two * CA * ((one - x)/x - one + x*(one - x))
  end function pgg_reg

```

Here, we collect the expressions needed for integrated Catani-Seymour dipoles, and the so-called flavor kernels. We always distinguish between the “ordinary” Catani-Seymour version, and the one including a phase-space slicing parameter, α .

The standard flavor kernels \overline{K}^{ab} are:

$$\overline{K}^{qg}(x) = \overline{K}^{\bar{q}g}(x) = P^{qg}(x) \log((1-x)/x) + CF \times x \quad (4.20)$$

$$\overline{K}^{gq}(x) = \overline{K}^{g\bar{q}}(x) = P^{gq}(x) \log((1-x)/x) + TR \times 2x(1-x) \quad (4.21)$$

$$\overline{K}^{qq} = C_F \left[\left(\frac{2}{1-x} \log \frac{1-x}{x} \right)_+ - (1+x) \log((1-x)/x) + (1-x) \right] - (5 - \pi^2) \cdot C_F \cdot \delta(1-x) \quad (4.22)$$

$$\overline{K}^{gg} = 2C_A \left[\left(\frac{1}{1-x} \log \frac{1-x}{x} \right)_+ + \left(\frac{1-x}{x} - 1 + x(1-x) \right) \log((1-x)/x) \right] - \delta(1-x) \left[(f \right. \quad (4.23)$$

<SM physics: public functions>+≡
public :: kbarqg

<SM physics: subroutines>+≡
function kbarqg (x) result (kbarqgx)
 real(kind=default), intent(in) :: x
 real(kind=default) :: kbarqgx
 kbarqgx = pqg(x) * log((one-x)/x) + CF * x
end function kbarqg

<SM physics: public functions>+≡
public :: kbargq

<SM physics: subroutines>+≡
function kbargq (x) result (kbargqx)
 real(kind=default), intent(in) :: x
 real(kind=default) :: kbargqx
 kbargqx = pgq(x) * log((one-x)/x) + two * TR * x * (one - x)
end function kbargq

<SM physics: public functions>+≡
public :: kbarqq

<SM physics: subroutines>+≡
function kbarqq (x,eps) result (kbarqqx)
 real(kind=default), intent(in) :: x, eps
 real(kind=default) :: kbarqqx
 kbarqqx = CF*(log_plus_distr(x,eps) - (one+x) * log((one-x)/x) + (one - &
 x) - (five - pi**2) * delta(x,eps))
end function kbarqq

<SM physics: public functions>+≡
public :: kbargg

<SM physics: subroutines>+≡
function kbargg (x,eps,nf) result (kbarggx)
 real(kind=default), intent(in) :: x, eps, nf
 real(kind=default) :: kbarggx
 kbarggx = CA * (log_plus_distr(x,eps) + two * ((one-x)/x - one + &
 x*(one-x) * log((1-x)/x))) - delta(x,eps) * &
 ((50.0_default/9.0_default - pi**2) * CA - &

```

16.0_default/9.0_default * TR * nf)
end function kbargg

```

The \tilde{K} are used when two identified hadrons participate:

$$\tilde{K}^{ab}(x) = P_{\text{reg}}^{ab}(x) \cdot \log(1-x) + \delta^{ab} \mathbf{T}_a^2 \left[\left(\frac{2}{1-x} \log(1-x) \right)_+ - \frac{\pi^2}{3} \delta(1-x) \right] \quad (4.24)$$

```

⟨SM physics: public functions⟩+≡
  public :: ktildeqq

⟨SM physics: subroutines⟩+≡
  function ktildeqq (x,eps) result (ktildeqqx)
    real(kind=default), intent(in) :: x, eps
    real(kind=default) :: ktildeqqx
    ktildeqqx = pqq_reg (x) * log(one-x) + CF * ( - log2_plus_distr (x,eps) &
      - pi**2/three * delta(x,eps))
  end function ktildeqq

⟨SM physics: public functions⟩+≡
  public :: ktildeqg

⟨SM physics: subroutines⟩+≡
  function ktildeqg (x,eps) result (ktildeqgx)
    real(kind=default), intent(in) :: x, eps
    real(kind=default) :: ktildeqgx
    ktildeqgx = pqg (x) * log(one-x)
  end function ktildeqg

⟨SM physics: public functions⟩+≡
  public :: ktildegq

⟨SM physics: subroutines⟩+≡
  function ktildegq (x,eps) result (ktildegqx)
    real(kind=default), intent(in) :: x, eps
    real(kind=default) :: ktildegqx
    ktildegqx = pgq (x) * log(one-x)
  end function ktildegq

⟨SM physics: public functions⟩+≡
  public :: ktildegg

⟨SM physics: subroutines⟩+≡
  function ktildegg (x,eps) result (ktildeggx)
    real(kind=default), intent(in) :: x, eps
    real(kind=default) :: ktildeggx
    ktildeggx = pgg_reg (x) * log(one-x) + CA * ( - &
      log2_plus_distr (x,eps) - pi**2/three * delta(x,eps))
  end function ktildegg

```

The insertion operator might not be necessary for a GOLEM interface but is demanded by the Les Houches NLO accord. It is a three-dimensional array, where the index always gives the inverse power of the DREG expansion parameter, ϵ .

```

⟨SM physics: public functions⟩+≡
  public :: insert_q

```

```

⟨SM physics: subroutines⟩+=≡
  pure function insert_q ()
    real(kind=default), dimension(0:2) :: insert_q
    insert_q(0) = gamma_q + k_q - pi**2/three * CF
    insert_q(1) = gamma_q
    insert_q(2) = CF
  end function insert_q

⟨SM physics: public functions⟩+=≡
  public :: insert_g

⟨SM physics: subroutines⟩+=≡
  pure function insert_g (nf)
    real(kind=default), intent(in) :: nf
    real(kind=default), dimension(0:2) :: insert_g
    insert_g(0) = gamma_g (nf) + k_g (nf) - pi**2/three * CA
    insert_g(1) = gamma_g (nf)
    insert_g(2) = CA
  end function insert_g

```

For better convergence, one can exclude regions of phase space with a slicing parameter from the dipole subtraction procedure. First of all, the K functions get modified:

$$K_i(\alpha) = K_i - \mathbf{T}_i^2 \log^2 \alpha + \gamma_i(\alpha - 1 - \log \alpha) \quad (4.25)$$

```

⟨SM physics: public functions⟩+=≡
  public :: k_q_al, k_g_al

⟨SM physics: subroutines⟩+=≡
  pure function k_q_al (alpha)
    real(kind=default), intent(in) :: alpha
    real(kind=default) :: k_q_al
    k_q_al = k_q - CF * (log(alpha))**2 + gamma_q * &
      (alpha - one - log(alpha))
  end function k_q_al

  pure function k_g_al (alpha, nf)
    real(kind=default), intent(in) :: alpha, nf
    real(kind=default) :: k_g_al
    k_g_al = k_g (nf) - CA * (log(alpha))**2 + gamma_g (nf) * &
      (alpha - one - log(alpha))
  end function k_g_al

```

The $+$ -distribution, but with a phase-space slicing parameter, α , $P_{1-\alpha}(x) = \left(\frac{1}{1-x}\right)_{1-x}$. Since we need the fatal error message here, this function cannot be elemental.

```

⟨SM physics: public functions⟩+=≡
  public :: plus_distr_al

⟨SM physics: subroutines⟩+=≡
  function plus_distr_al (x,alpha,eps) result (plusd_al)
    real(kind=default), intent(in) :: x, eps, alpha
    real(kind=default) :: plusd_al

```

```

if ((1.0_default - alpha) .ge. (1.0_default - eps)) then
  call msg_fatal ('sm_physics, plus_distr_al: alpha and epsilon chosen wrongly')
elseif (x < (1.0_default - alpha)) then
  plusd_al = 0
else if (x > (1.0_default - eps)) then
  plusd_al = log(eps/alpha)/eps
else
  plusd_al = one/(one-x)
end if
end function plus_distr_al

```

Introducing phase-space slicing parameters, these flavor kernels become: The standard flavor kernels \overline{K}^{ab} are:

$$\overline{K}_\alpha^{qg}(x) = \overline{K}_\alpha^{\bar{q}g}(x) = P^{qg}(x) \log(\alpha(1-x)/x) + C_F \times x \quad (4.26)$$

$$\overline{K}_\alpha^{gq}(x) = \overline{K}_\alpha^{g\bar{q}}(x) = P^{gq}(x) \log(\alpha(1-x)/x) + TR \times 2x(1-x) \quad (4.27)$$

$$\overline{K}_\alpha^{qq} = C_F(1-x) + P_{\text{reg}}^{qq}(x) \log \frac{\alpha(1-x)}{x} + C_F \delta(1-x) \log^2 \alpha + C_F \left(\frac{2}{1-x} \log \frac{1-x}{x} \right)_+ - \left(\gamma_q - \right) \quad (4.28)$$

<SM physics: public functions>+≡
 public :: kbarqg_al

<SM physics: subroutines>+≡
 function kbarqg_al (x,alpha,eps) result (kbarqgx)
 real(kind=default), intent(in) :: x, alpha, eps
 real(kind=default) :: kbarqgx
 kbarqgx = pqg (x) * log(alpha*(one-x)/x) + CF * x
 end function kbarqg_al

<SM physics: public functions>+≡
 public :: kbargq_al

<SM physics: subroutines>+≡
 function kbargq_al (x,alpha,eps) result (kbargqx)
 real(kind=default), intent(in) :: x, alpha, eps
 real(kind=default) :: kbargqx
 kbargqx = pgq (x) * log(alpha*(one-x)/x) + two * TR * x * (one-x)
 end function kbargq_al

<SM physics: public functions>+≡
 public :: kbarqq_al

<SM physics: subroutines>+≡
 function kbarqq_al (x,alpha,eps) result (kbarqqx)
 real(kind=default), intent(in) :: x, alpha, eps
 real(kind=default) :: kbarqqx
 kbarqqx = CF * (one - x) + pqq_reg(x) * log(alpha*(one-x)/x) &
 + CF * log_plus_distr(x,eps) &
 - (gamma_q + k_q_al(alpha) - CF * &
 five/6.0_default * pi**2 - CF * (log(alpha))**2) * &
 delta(x,eps) + &
 CF * two/(one -x)*log(alpha*(two-x)/(one+alpha-x))
 if (x < (one-alpha)) then

```

        kbarqqx = kbarqqx - CF * two/(one-x) * log((two-x)/(one-x))
    end if
end function kbarqq_al

<SM physics: public functions>+≡
public :: kbargg_al

<SM physics: subroutines>+≡
function kbargg_al (x,alpha,eps,nf) result (kbarggx)
    real(kind=default), intent(in) :: x, alpha, eps, nf
    real(kind=default) :: kbarggx
    kbarggx = pgg_reg(x) * log(alpha*(one-x)/x) &
        + CA * log_plus_distr(x,eps) &
        - (gamma_g(nf) + k_g_al(alpha,nf) - CA * &
        five/6.0_default * pi**2 - CA * (log(alpha))**2) * &
        delta(x,eps) + &
        CA * two/(one-x)*log(alpha*(two-x)/(one+alpha-x))
    if (x < (one-alpha)) then
        kbarggx = kbarggx - CA * two/(one-x) * log((two-x)/(one-x))
    end if
end function kbargg_al

```

The \tilde{K} flavor kernels in the presence of a phase-space slicing parameter, are:

$$\tilde{K}^{ab}(x, \alpha) = P^{qq, \text{reg}}(x) \log \frac{1-x}{\alpha} + \dots \quad (4.29)$$

```

<SM physics: public functions>+≡
public :: ktildeqq_al

<SM physics: subroutines>+≡
function ktildeqq_al (x,alpha,eps) result (ktildeqqx)
    real(kind=default), intent(in) :: x, eps, alpha
    real(kind=default) :: ktildeqqx
    ktildeqqx = pqq_reg(x) * log((one-x)/alpha) + CF*( &
        - log2_plus_distr_al(x,alpha,eps) - Pi**2/three * delta(x,eps) &
        + (one+x**2)/(one-x) * log(min(one,(alpha/(one-x)))) &
        + two/(one-x) * log((one+alpha-x)/alpha))
    if (x > (one-alpha)) then
        ktildeqqx = ktildeqqx - CF*two/(one-x)*log(two-x)
    end if
end function ktildeqq_al

```

This is a logarithmic +-distribution, $\left(\frac{\log((1-x)/x)}{1-x}\right)_+$. For the sampling, we need the integral over this function over the incomplete sampling interval $[0, 1 - \epsilon]$, which is $\log^2(x) + 2Li_2(x) - \frac{\pi^2}{3}$. As this function is negative definite for $\epsilon > 0.1816$, we take a hard upper limit for that sampling parameter, irrespective of the fact what the user chooses.

```

<SM physics: public functions>+≡
public :: log_plus_distr

<SM physics: subroutines>+≡
function log_plus_distr (x,eps) result (lpd)
    real(kind=default), intent(in) :: x, eps

```

```

real(kind=default) :: lpd, eps2
eps2 = min (eps, 0.1816_default)
if (x > (1.0_default - eps2)) then
    lpd = ((log(eps2))**2 + two*Li2(eps2) - pi**2/three)/eps2
else
    lpd = two*log((one-x)/x)/(one-x)
end if
end function log_plus_distr

```

Logarithmic +-distribution, $2 \left(\frac{\log(1/(1-x))}{1-x} \right)_+$.

<SM physics: public functions>+≡
public :: log2_plus_distr

<SM physics: subroutines>+≡
function log2_plus_distr (x,eps) result (lpd)
 real(kind=default), intent(in) :: x, eps
 real(kind=default) :: lpd
 if (x > (1.0_default - eps)) then
 lpd = - (log(eps))**2/eps
 else
 lpd = two*log(one/(one-x))/(one-x)
 end if
end function log2_plus_distr

Logarithmic +-distribution with phase-space slicing parameter, $2 \left(\frac{\log(1/(1-x))}{1-x} \right)_{1-\alpha}$.

<SM physics: public functions>+≡
public :: log2_plus_distr_al

<SM physics: subroutines>+≡
function log2_plus_distr_al (x,alpha,eps) result (lpd_al)
 real(kind=default), intent(in) :: x, eps, alpha
 real(kind=default) :: lpd_al
 if ((1.0_default - alpha) .ge. (1.0_default - eps)) then
 call msg_fatal ('alpha and epsilon chosen wrongly')
 elseif (x < (one - alpha)) then
 lpd_al = 0
 elseif (x > (1.0_default - eps)) then
 lpd_al = - ((log(eps))**2 - (log(alpha))**2)/eps
 else
 lpd_al = two*log(one/(one-x))/(one-x)
 end if
end function log2_plus_distr_al

Chapter 5

Physics Analysis

This part contains the structures and tools that are necessary for defining parameters, particle sets, analysis objects such as histograms, and expressions that deal with them.

These are the modules:

analysis Observables, histograms, and plots.

pdg_arrays Useful for particle aliases (e.g., 'quark' for u, d, s etc.)

prt_lists Particle lists/arrays used for analyzing events.

variables Store values of various kind, used by expressions and accessed by the command interface.

expressions Expressions of values of all kinds. Includes the API for recording analysis data.

5.1 Analysis tools

This module defines structures useful for data analysis. These include observables, histograms, and plots.

Observables are quantities that are calculated and summed up event by event. At the end, one can compute the average and error.

Histograms have their bins in addition to the observable properties. Histograms are usually written out in tables and displayed graphically.

In plots, each record creates its own entry in a table. This can be used for scatter plots if called event by event, or for plotting dependencies on parameters if called once per integration run.

```
<analysis.f90>≡  
  <File header>  
  
  module analysis  
  
    <Use kinds>  
    <Use strings>  
    use limits, only: HISTOGRAM_HEAD_FORMAT, HISTOGRAM_DATA_FORMAT !NODEP!  
    use limits, only: HISTOGRAM_INTG_FORMAT !NODEP!  
    <Use file utils>  
    use file_utils, only: tex_format !NODEP!  
    use diagnostics !NODEP!  
    use os_interface  
  
    <Standard module head>  
  
    <Analysis: public>  
  
    <Analysis: parameters>  
  
    <Analysis: types>  
  
    <Analysis: interfaces>  
  
    <Analysis: variables>  
  
    contains  
  
    <Analysis: procedures>  
  
  end module analysis
```

5.1.1 Output formats

These formats share a common field width (alignment).

```
<Limits: public parameters>+≡  
  character(*), parameter, public :: HISTOGRAM_HEAD_FORMAT = "1x,A13,1x"  
  character(*), parameter, public :: HISTOGRAM_INTG_FORMAT = "3x,I9,3x"  
  character(*), parameter, public :: HISTOGRAM_DATA_FORMAT = "1PG15.8"
```

5.1.2 Labels

These parameters are used for displaying data. They can be defined or reset when the driver file for the display is written.

```
<Analysis: public>≡
    public :: plot_labels_t

<Analysis: types>≡
    type :: plot_labels_t
    private
        type(string_t) :: title
        type(string_t) :: description
        type(string_t) :: xlabel
        type(string_t) :: ylabel
        integer :: width_mm = 130
        integer :: height_mm = 90
    end type plot_labels_t
```

Initialize all components that can be set by the user.

```
<Analysis: public>+≡
    public :: plot_labels_init

<Analysis: procedures>≡
    subroutine plot_labels_init (plot_labels, &
        title, description, xlabel, ylabel, width_mm, height_mm)
        type(plot_labels_t), intent(out) :: plot_labels
        type(string_t), intent(in) :: title
        type(string_t), intent(in), optional :: description
        type(string_t), intent(in), optional :: xlabel, ylabel
        integer, intent(in), optional :: width_mm, height_mm
        plot_labels%title = title
        if (present (description)) then
            plot_labels%description = description
        else
            plot_labels%description = ""
        end if
        if (present (xlabel)) then
            plot_labels%xlabel = xlabel
        else
            plot_labels%xlabel = ""
        end if
        if (present (ylabel)) then
            plot_labels%ylabel = ylabel
        else
            plot_labels%ylabel = ""
        end if
        if (present (width_mm)) plot_labels%width_mm = width_mm
        if (present (height_mm)) plot_labels%height_mm = height_mm
    end subroutine plot_labels_init
```

5.1.3 Observables

The observable type holds the accumulated observable values and weight sums which are necessary for proper averaging.

<Analysis: types>+≡

```
type :: observable_t
  private
  real(default) :: sum_values = 0
  real(default) :: sum_squared_values = 0
  real(default) :: sum_weights = 0
  real(default) :: sum_squared_weights = 0
  integer :: count = 0
  type(string_t) :: label
  type(string_t) :: physical_unit
  type(plot_labels_t) :: plot_labels
end type observable_t
```

Initialize with defined properties

<Analysis: procedures>+≡

```
subroutine observable_init (obs, label, physical_unit, plot_labels)
  type(observable_t), intent(out) :: obs
  type(string_t), intent(in), optional :: label, physical_unit
  type(plot_labels_t), intent(in), optional :: plot_labels
  if (present (label)) then
    obs%label = label
  else
    obs%label = ""
  end if
  if (present (physical_unit)) then
    obs%physical_unit = physical_unit
  else
    obs%physical_unit = ""
  end if
  if (present (plot_labels)) then
    obs%plot_labels = plot_labels
  else
    call plot_labels_init (obs%plot_labels, title = var_str ("Observable"))
  end if
end subroutine observable_init
```

Reset all numeric entries.

<Analysis: procedures>+≡

```
subroutine observable_clear (obs)
  type(observable_t), intent(inout) :: obs
  obs%sum_values = 0
  obs%sum_squared_values = 0
  obs%sum_weights = 0
  obs%sum_squared_weights = 0
  obs%count = 0
end subroutine observable_clear
```

Record a a value. Always successful for observables.

<Analysis: interfaces>≡

```

interface observable_record_value
  module procedure observable_record_value_unweighted
  module procedure observable_record_value_weighted
end interface

```

<Analysis: procedures>+≡

```

subroutine observable_record_value_unweighted (obs, value, success)
  type(observable_t), intent(inout) :: obs
  real(default), intent(in) :: value
  logical, intent(out), optional :: success
  obs%sum_values = obs%sum_values + value
  obs%sum_squared_values = obs%sum_squared_values + value**2
  obs%sum_weights = obs%sum_weights + 1
  obs%sum_squared_weights = obs%sum_squared_weights + 1
  obs%count = obs%count + 1
  if (present (success)) success = .true.
end subroutine observable_record_value_unweighted

subroutine observable_record_value_weighted (obs, value, weight, success)
  type(observable_t), intent(inout) :: obs
  real(default), intent(in) :: value, weight
  logical, intent(out), optional :: success
  obs%sum_values = obs%sum_values + value * weight
  obs%sum_squared_values = obs%sum_squared_values + (value * weight) ** 2
  obs%sum_weights = obs%sum_weights + abs (weight)
  obs%sum_squared_weights = obs%sum_squared_weights + weight**2
  obs%count = obs%count + 1
  if (present (success)) success = .true.
end subroutine observable_record_value_weighted

```

<Analysis: procedures>+≡

```

function observable_get_n_entries (obs) result (n)
  integer :: n
  type(observable_t), intent(in) :: obs
  n = obs%count
end function observable_get_n_entries

function observable_get_average (obs) result (avg)
  real(default) :: avg
  type(observable_t), intent(in) :: obs
  if (obs%sum_weights /= 0) then
    avg = obs%sum_values / obs%sum_weights
  else
    avg = 0
  end if
end function observable_get_average

function observable_get_error (obs) result (err)
  real(default) :: err
  type(observable_t), intent(in) :: obs
  if (obs%sum_squared_weights /= 0) then
    select case (obs%count)
      case (0:1)

```

```

        err = 0

        case default
            err = sqrt (obs%sum_squared_values / obs%sum_squared_weights) &
                / sqrt (real (obs%count - 1, default))
        end select
    else
        err = 0
    end if
end function observable_get_error

```

Write label and/or physical unit to a string.

<Analysis: procedures>+≡

```

function observable_get_label (obs, wl, wu) result (string)
    type(string_t) :: string
    type(observable_t), intent(in) :: obs
    logical, intent(in) :: wl, wu
    type(string_t) :: label, physical_unit
    if (wl) then
        if (obs%label /= "") then
            label = obs%label
        else
            label = "\mathcal{0}"
        end if
    else
        label = ""
    end if
    if (wu) then
        if (obs%physical_unit /= "") then
            if (wl) then
                physical_unit = ";" // obs%physical_unit // " "
            else
                physical_unit = obs%physical_unit
            end if
        else
            physical_unit = ""
        end if
    else
        physical_unit = ""
    end if
    string = label // physical_unit
end function observable_get_label

```

5.1.4 Output

<Analysis: procedures>+≡

```

subroutine observable_write (obs, unit)
    type(observable_t), intent(in) :: obs
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write (u, "(A,1x," // HISTOGRAM_DATA_FORMAT // ")") &

```

```

        "average      =", observable_get_average (obs)
write (u, "(A,1x," // HISTOGRAM_DATA_FORMAT // ")") &
        "error        =", observable_get_error (obs)
write (u, "(A,1x," // HISTOGRAM_INTG_FORMAT // ")") &
        "n_entries    =", observable_get_n_entries (obs)
end subroutine observable_write

```

LaTeX output.

(Analysis: procedures)+≡

```

subroutine observable_write_driver (obs, unit, write_heading)
  type(observable_t), intent(in) :: obs
  integer, intent(in), optional :: unit
  logical, intent(in), optional :: write_heading
  real(default) :: avg, err
  integer :: n_digits
  logical :: heading
  integer :: u
  u = output_unit (unit); if (u < 0) return
  heading = .true.; if (present (write_heading)) heading = write_heading
  avg = observable_get_average (obs)
  err = observable_get_error (obs)
  if (avg /= 0 .and. err /= 0) then
    n_digits = max (2, 2 - int (log10 (abs (err / real (avg, default)))))
  else if (avg /= 0) then
    n_digits = 100
  else
    n_digits = 1
  end if
  if (heading) then
    write (u, "(A)")
    if (obs%plot_labels%title /= "") then
      write (u, "(A)") "\section{" // char (obs%plot_labels%title) &
        // "}"
    else
      write (u, "(A)") "\section{Observable}"
    end if
    if (obs%plot_labels%description /= "") then
      write (u, "(A)") char (obs%plot_labels%description)
      write (u, *)
    end if
    write (u, "(A)") "\begin{flushleft}"
  end if
  write (u, "(A)", advance="no") "  $\langle$ ! $ sign
  write (u, "(A)", advance="no") char (observable_get_label (obs, wl=.true., wu=.false.))
  write (u, "(A)", advance="no") " \rangle = "
  write (u, "(A)", advance="no") char (tex_format (avg, n_digits))
  write (u, "(A)", advance="no") "\pm"
  write (u, "(A)", advance="no") char (tex_format (err, 2))
  write (u, "(A)", advance="no") "\;{"
  write (u, "(A)", advance="no") char (observable_get_label (obs, wl=.false., wu=.true.))
  write (u, "(A)") "}"
  write (u, "(A)", advance="no") "      \quad[n_{\text{entries}}] = "
  write (u, "(IO)", advance="no") observable_get_n_entries (obs)

```

```

write (u, "(A)") "]"$
if (heading) then
  write (u, "(A)") "\end{flushleft}"
end if
end subroutine observable_write_driver

```

5.1.5 Histograms

Bins

<Analysis: types>+≡

```

type :: bin_t
  private
  real(default) :: midpoint = 0
  real(default) :: width = 0
  real(default) :: sum_weights = 0
  real(default) :: sum_squared_weights = 0
  real(default) :: sum_excess_weights = 0
  integer :: count = 0
end type bin_t

```

<Analysis: procedures>+≡

```

subroutine bin_init (bin, midpoint, width)
  type(bin_t), intent(out) :: bin
  real(default), intent(in) :: midpoint, width
  bin%midpoint = midpoint
  bin%width = width
end subroutine bin_init

```

<Analysis: procedures>+≡

```

elemental subroutine bin_clear (bin)
  type(bin_t), intent(inout) :: bin
  bin%sum_weights = 0
  bin%sum_squared_weights = 0
  bin%sum_excess_weights = 0
  bin%count = 0
end subroutine bin_clear

```

<Analysis: procedures>+≡

```

subroutine bin_record_value (bin, weight, excess)
  type(bin_t), intent(inout) :: bin
  real(default), intent(in) :: weight
  real(default), intent(in), optional :: excess
  bin%sum_weights = bin%sum_weights + abs (weight)
  bin%sum_squared_weights = bin%sum_squared_weights + weight ** 2
  if (present (excess)) &
    bin%sum_excess_weights = bin%sum_excess_weights + abs (excess)
  bin%count = bin%count + 1
end subroutine bin_record_value

```

<Analysis: procedures>+≡

```
function bin_get_midpoint (bin) result (x)
  real(default) :: x
  type(bin_t), intent(in) :: bin
  x = bin%midpoint
end function bin_get_midpoint
```

```
function bin_get_width (bin) result (w)
  real(default) :: w
  type(bin_t), intent(in) :: bin
  w = bin%width
end function bin_get_width
```

```
function bin_get_n_entries (bin) result (n)
  integer :: n
  type(bin_t), intent(in) :: bin
  n = bin%count
end function bin_get_n_entries
```

```
function bin_get_sum (bin) result (s)
  real(default) :: s
  type(bin_t), intent(in) :: bin
  s = bin%sum_weights
end function bin_get_sum
```

```
function bin_get_error (bin) result (err)
  real(default) :: err
  type(bin_t), intent(in) :: bin
  err = sqrt (bin%sum_squared_weights)
end function bin_get_error
```

```
function bin_get_excess (bin) result (excess)
  real(default) :: excess
  type(bin_t), intent(in) :: bin
  excess = bin%sum_excess_weights
end function bin_get_excess
```

<Analysis: procedures>+≡

```
subroutine bin_write_header (unit)
  integer, intent(in), optional :: unit
  character(120) :: buffer
  integer :: u
  u = output_unit (unit); if (u < 0) return
  write (buffer, "(A,5(1x," // HISTOGRAM_HEAD_FORMAT // "))" &
    & "#", "bin midpoint", "value", "error", &
    & "n_entries", "excess"
  write (u, "(A)") trim (buffer)
end subroutine bin_write_header
```

```
subroutine bin_write (bin, unit)
  type(bin_t), intent(in) :: bin
  integer, intent(in), optional :: unit
  integer :: u
  u = output_unit (unit); if (u < 0) return
```

```

write (u, "(1x,3(1x," // HISTOGRAM_DATA_FORMAT // "), " &
      // HISTOGRAM_INTG_FORMAT // ", " &
      // HISTOGRAM_DATA_FORMAT // ")") &
      bin_get_midpoint (bin), &
      bin_get_sum (bin), &
      bin_get_error (bin), &
      bin_get_n_entries (bin), &
      bin_get_excess (bin)
end subroutine bin_write

```

Histograms

<Analysis: types>+≡

```

type :: histogram_t
  private
  real(default) :: lower_bound = 0
  real(default) :: upper_bound = 0
  real(default) :: width = 0
  integer :: n_bins = 0
  type(observable_t) :: obs
  type(observable_t) :: obs_within_bounds
  type(bin_t) :: underflow
  type(bin_t), dimension(:), allocatable :: bin
  type(bin_t) :: overflow
  type(plot_labels_t) :: plot_labels
end type histogram_t

```

Initializer/finalizer

Initialize a histogram. We may provide either the bin width or the number of bins.

<Analysis: interfaces>+≡

```

interface histogram_init
  module procedure histogram_init_n_bins
  module procedure histogram_init_bin_width
end interface

```

<Analysis: procedures>+≡

```

subroutine histogram_init_n_bins (h, &
  lower_bound, upper_bound, n_bins, obs_label, physical_unit, plot_labels)
  type(histogram_t), intent(out) :: h
  real(default), intent(in) :: lower_bound, upper_bound
  integer, intent(in) :: n_bins
  type(string_t), intent(in), optional :: obs_label, physical_unit
  type(plot_labels_t), intent(in), optional :: plot_labels
  real(default) :: bin_width
  integer :: i
  call observable_init (h%obs_within_bounds, obs_label, physical_unit)
  call observable_init (h%obs, obs_label, physical_unit)
  h%lower_bound = lower_bound

```

```

h%upper_bound = upper_bound
h%n_bins = max (n_bins, 1)
h%width = h%upper_bound - h%lower_bound
bin_width = h%width / h%n_bins
allocate (h%bin (h%n_bins))
call bin_init (h%underflow, h%lower_bound, 0._default)
do i = 1, h%n_bins
  call bin_init (h%bin(i), &
    h%lower_bound - bin_width/2 + i * bin_width, bin_width)
end do
call bin_init (h%overflow, h%upper_bound, 0._default)
if (present (plot_labels)) then
  h%plot_labels = plot_labels
else
  call plot_labels_init (h%plot_labels, &
    title = var_str (""), xlabel = var_str (""), ylabel = var_str (""))
end if
end subroutine histogram_init_n_bins

subroutine histogram_init_bin_width (h, &
  lower_bound, upper_bound, bin_width, &
  obs_label, physical_unit, plot_labels)
type(histogram_t), intent(out) :: h
real(default), intent(in) :: lower_bound, upper_bound, bin_width
type(string_t), intent(in), optional :: obs_label, physical_unit
type(plot_labels_t), intent(in), optional :: plot_labels
integer :: n_bins
if (bin_width /= 0) then
  n_bins = nint ((upper_bound - lower_bound) / bin_width)
else
  n_bins = 1
end if
call histogram_init_n_bins (h, &
  lower_bound, upper_bound, n_bins, &
  obs_label, physical_unit, plot_labels)
end subroutine histogram_init_bin_width

```

Fill histograms

Clear the histogram contents, but do not modify the structure.

(Analysis: procedures)+≡

```

subroutine histogram_clear (h)
type(histogram_t), intent(inout) :: h
call observable_clear (h%obs)
call observable_clear (h%obs_within_bounds)
call bin_clear (h%underflow)
if (allocated (h%bin)) call bin_clear (h%bin)
call bin_clear (h%overflow)
end subroutine histogram_clear

```

Record a value. Successful if the value is within bounds, otherwise it is recorded as under-/overflow. Optionally, we may provide an excess weight that could be

returned by the unweighting procedure.

<Analysis: procedures>+≡

```
subroutine histogram_record_value_unweighted (h, value, excess, success)
  type(histogram_t), intent(inout) :: h
  real(default), intent(in) :: value
  real(default), intent(in), optional :: excess
  logical, intent(out), optional :: success
  integer :: i_bin
  call observable_record_value (h%obs, value)
  if (h%width /= 0) then
    i_bin = floor (((value - h%lower_bound) / h%width) * h%n_bins) + 1
  else
    i_bin = 0
  end if
  if (i_bin <= 0) then
    call bin_record_value (h%underflow, 1._default, excess)
    if (present (success)) success = .false.
  else if (i_bin <= h%n_bins) then
    call observable_record_value (h%obs_within_bounds, value)
    call bin_record_value (h%bin(i_bin), 1._default, excess)
    if (present (success)) success = .true.
  else
    call bin_record_value (h%overflow, 1._default, excess)
    if (present (success)) success = .false.
  end if
end subroutine histogram_record_value_unweighted
```

Weighted events: analogous, but no excess weight.

<Analysis: procedures>+≡

```
subroutine histogram_record_value_weighted (h, value, weight, success)
  type(histogram_t), intent(inout) :: h
  real(default), intent(in) :: value, weight
  logical, intent(out), optional :: success
  integer :: i_bin
  call observable_record_value (h%obs, value, weight)
  if (h%width /= 0) then
    i_bin = floor (((value - h%lower_bound) / h%width) * h%n_bins) + 1
  else
    i_bin = 0
  end if
  if (i_bin <= 0) then
    call bin_record_value (h%underflow, weight)
    if (present (success)) success = .false.
  else if (i_bin <= h%n_bins) then
    call observable_record_value (h%obs_within_bounds, weight)
    call bin_record_value (h%bin(i_bin), value)
    if (present (success)) success = .true.
  else
    call bin_record_value (h%overflow, weight)
    if (present (success)) success = .false.
  end if
end subroutine histogram_record_value_weighted
```

Access contents

Inherited from the observable component (all-over average etc.)

<Analysis: procedures>+≡

```
function histogram_get_n_entries (h) result (n)
  integer :: n
  type(histogram_t), intent(in) :: h
  n = observable_get_n_entries (h%obs)
end function histogram_get_n_entries

function histogram_get_average (h) result (avg)
  real(default) :: avg
  type(histogram_t), intent(in) :: h
  avg = observable_get_average (h%obs)
end function histogram_get_average

function histogram_get_error (h) result (err)
  real(default) :: err
  type(histogram_t), intent(in) :: h
  err = observable_get_error (h%obs)
end function histogram_get_error
```

Analogous, but applied only to events within bounds.

<Analysis: procedures>+≡

```
function histogram_get_n_entries_within_bounds (h) result (n)
  integer :: n
  type(histogram_t), intent(in) :: h
  n = observable_get_n_entries (h%obs_within_bounds)
end function histogram_get_n_entries_within_bounds

function histogram_get_average_within_bounds (h) result (avg)
  real(default) :: avg
  type(histogram_t), intent(in) :: h
  avg = observable_get_average (h%obs_within_bounds)
end function histogram_get_average_within_bounds

function histogram_get_error_within_bounds (h) result (err)
  real(default) :: err
  type(histogram_t), intent(in) :: h
  err = observable_get_error (h%obs_within_bounds)
end function histogram_get_error_within_bounds
```

Check bins. If the index is zero or above the limit, return the results for underflow or overflow, respectively.

<Analysis: procedures>+≡

```
function histogram_get_n_entries_for_bin (h, i) result (n)
  integer :: n
  type(histogram_t), intent(in) :: h
  integer, intent(in) :: i
  if (i <= 0) then
    n = bin_get_n_entries (h%underflow)
  else if (i <= h%n_bins) then
    n = bin_get_n_entries (h%bin(i))
  end if
end function histogram_get_n_entries_for_bin
```

```

        else
            n = bin_get_n_entries (h%overflow)
        end if
    end function histogram_get_n_entries_for_bin

function histogram_get_sum_for_bin (h, i) result (avg)
    real(default) :: avg
    type(histogram_t), intent(in) :: h
    integer, intent(in) :: i
    if (i <= 0) then
        avg = bin_get_sum (h%underflow)
    else if (i <= h%n_bins) then
        avg = bin_get_sum (h%bin(i))
    else
        avg = bin_get_sum (h%overflow)
    end if
end function histogram_get_sum_for_bin

function histogram_get_error_for_bin (h, i) result (err)
    real(default) :: err
    type(histogram_t), intent(in) :: h
    integer, intent(in) :: i
    if (i <= 0) then
        err = bin_get_error (h%underflow)
    else if (i <= h%n_bins) then
        err = bin_get_error (h%bin(i))
    else
        err = bin_get_error (h%overflow)
    end if
end function histogram_get_error_for_bin

function histogram_get_excess_for_bin (h, i) result (err)
    real(default) :: err
    type(histogram_t), intent(in) :: h
    integer, intent(in) :: i
    if (i <= 0) then
        err = bin_get_excess (h%underflow)
    else if (i <= h%n_bins) then
        err = bin_get_excess (h%bin(i))
    else
        err = bin_get_excess (h%overflow)
    end if
end function histogram_get_excess_for_bin

```

Output

(Analysis: procedures)+≡

```

subroutine histogram_write (h, unit)
    type(histogram_t), intent(in) :: h
    integer, intent(in), optional :: unit
    integer :: u, i
    u = output_unit (unit); if (u < 0) return
    call bin_write_header (u)

```

```

if (allocated (h%bin)) then
  do i = 1, h%n_bins
    call bin_write (h%bin(i), u)
  end do
end if
write (u, *)
write (u, "(A,1x,A)" "#", "Underflow:")
call bin_write (h%underflow, u)
write (u, *)
write (u, "(A,1x,A)" "#", "Overflow:")
call bin_write (h%overflow, u)
write (u, *)
write (u, "(A,1x,A)" "#", "Summary: data within bounds")
call observable_write (h%obs_within_bounds, u)
write (u, *)
write (u, "(A,1x,A)" "#", "Summary: all data")
call observable_write (h%obs, u)
write (u, *)
end subroutine histogram_write

```

L^AT_EX output.

⟨Analysis: procedures⟩+≡

```

subroutine histogram_write_driver (h, filename, unit, write_heading)
  type(histogram_t), intent(in) :: h
  type(string_t), intent(in) :: filename
  integer, intent(in), optional :: unit
  logical, intent(in), optional :: write_heading
  logical :: heading
  character(len=32) :: lower_bound_str, upper_bound_str, bin_half_width_str
  logical, parameter :: log_plot = .false.
  integer :: u
  u = output_unit (unit); if (u < 0) return
  heading = .true.; if (present (write_heading)) heading = write_heading
  if (heading) then
    write (u, "(A)")
    if (h%plot_labels%title /= "") then
      write (u, "(A)") "\section{" // char (h%plot_labels%title) // "}"
    else
      write (u, "(A)") "\section{Histogram}"
    end if
  end if
  if (h%plot_labels%description /= "") then
    write (u, "(A)") char (h%plot_labels%description)
    write (u, *)
    write (u, "(A)") "\vspace*{\baselineskip}"
  end if
  lower_bound_str = ""
  upper_bound_str = ""
  bin_half_width_str = ""
1 format (G10.3)
  write (lower_bound_str, 1) h%lower_bound
  write (upper_bound_str, 1) h%upper_bound
  write (bin_half_width_str, 1) h%width / h%n_bins / 2

```

```

lower_bound_str = adjustl (lower_bound_str)
upper_bound_str = adjustl (upper_bound_str)
bin_half_width_str = adjustl (bin_half_width_str)
write (u, "(A)") "\vspace*{\baselineskip}"
write (u, "(A)") "\unitlength 1mm"
write (u, "(A,IO,',',IO,A)") &
    "\begin{gmlgraph*}(", &
    h%plot_labels%width_mm, h%plot_labels%height_mm, &
    ")[dat]"
if (log_plot) then
    write (u, "(2x,A)") "setup (linear,log); "
    write (u, "(2x,A)") &
        "graphrange (#" // trim (lower_bound_str) // ", ??), " &
        //"      "(#" // trim (upper_bound_str) // ", ??);"
else
    write (u, "(2x,A)") "setup (linear,linear); "
    write (u, "(2x,A)") &
        "graphrange (#" // trim (lower_bound_str) // ", #0), " &
        //"      "(#" // trim (upper_bound_str) // ", ??);"
end if
write (u, "(2x,A)") 'fromfile "' // char (filename) // ":'
write (u, "(4x,A)") 'key "# Histogram:";'
write (u, "(4x,A)") 'dx := #' // trim (bin_half_width_str) // ' ';
write (u, "(4x,A)") 'for i within block:'
write (u, "(6x,A)") 'get x, y, y.d, n, y.e;'
write (u, "(6x,A)") 'plot (dat) (x,y) hbar dx;'
!   write (u, "(6x,A)") 'if show_excess: ' // &
!       & 'plot(dat.e)(x, y plus y.e) hbar dx; fi'
write (u, "(4x,A)") 'endfor'
write (u, "(4x,A)") 'calculate dat.base (dat) (x,#0);'
write (u, "(2x,A)") 'endfrom'
write (u, "(2x,A)") 'fill piecewise from (dat, dat.base/\) ' &
    // 'withcolor col.default outlined;'
!   write (u, "(2x,A)") 'if show_excess: ' // &
!       & 'fill piecewise from(dat.e, dat/\) ' // &
!       & 'withcolor col.excess outlined; fi'
!   if (mcs%normalize_weight) then
if (h%plot_labels%ylabel /= "") then
    write (u, "(2x,A)") 'label.ulft (< ' // '<' &
        // char (h%plot_labels%ylabel) // '>' // '>', out);'
else
    write (u, "(2x,A)") 'label.ulft (< ' // '<\#evt/bin>' // '>', out);'
end if
!   else
!       write (u, '(2x,A)') 'label.ulft(< ' // '<\$d\sigma\,[\rm fb]\$/bin>' // '>', out);'
!   end if
if (h%plot_labels%xlabel /= "") then
    write (u, "(2x,A)", advance="no") 'label.bot (< ' // '<' &
        // char (h%plot_labels%xlabel) // '>' &
        // '>', out);'
else
    write (u, "(2x,A)", advance="no") 'label.bot (< ' // '<${'
    write (u, "(A)", advance="no") &
        char (observable_get_label (h%obs, wl=.true., wu=.true.))

```

```

        write (u, "(A)" '}$>' // '>', out);'
    end if
    write (u, "(A)" "\end{gmlgraph*}")
    write (u, "(A)" "\vspace*{2\baselineskip}")
    write (u, "(A)" "\begin{flushleft}")
    write (u, "(A)" "\textbf{Data within bounds:} \\")
    call observable_write_driver (h%obs_within_bounds, unit, &
                                write_heading=.false.)
    write (u, "(A)" "\\[0.5\baselineskip]")
    write (u, "(A)" "\textbf{All data:} \\")
    call observable_write_driver (h%obs, unit, write_heading=.false.)
    write (u, "(A)" "\end{flushleft}")
end subroutine histogram_write_driver

```

5.1.6 Plots

Points

(Analysis: types)+≡

```

type :: point_t
private
real(default) :: x = 0
real(default) :: y = 0
real(default) :: xerr = 0
real(default) :: yerr = 0
type(point_t), pointer :: next => null ()
end type point_t

```

(Analysis: procedures)+≡

```

subroutine point_init (point, x, y, xerr, yerr)
type(point_t), intent(out) :: point
real(default), intent(in) :: x, y
real(default), intent(in), optional :: xerr, yerr
point%x = x
point%y = y
if (present (xerr)) point%xerr = xerr
if (present (yerr)) point%yerr = yerr
end subroutine point_init

```

(Analysis: procedures)+≡

```

function point_get_x (point) result (x)
real(default) :: x
type(point_t), intent(in) :: point
x = point%x
end function point_get_x

function point_get_y (point) result (y)
real(default) :: y
type(point_t), intent(in) :: point
y = point%y
end function point_get_y

```

```

function point_get_xerr (point) result (xerr)
  real(default) :: xerr
  type(point_t), intent(in) :: point
  xerr = point%xerr
end function point_get_xerr

```

```

function point_get_yerr (point) result (yerr)
  real(default) :: yerr
  type(point_t), intent(in) :: point
  yerr = point%yerr
end function point_get_yerr

```

<Analysis: procedures>+≡

```

subroutine point_write_header (unit)
  integer, intent(in) :: unit
  character(120) :: buffer
  integer :: u
  u = output_unit (unit); if (u < 0) return
  write (buffer, "(A,4(1x," // HISTOGRAM_HEAD_FORMAT // "))" ) &
    "#", "x", "y", "xerr", "yerr"
  write (u, "(A)") trim (buffer)
end subroutine point_write_header

```

```

subroutine point_write (point, unit)
  type(point_t), intent(in) :: point
  integer, intent(in), optional :: unit
  integer :: u
  u = output_unit (unit); if (u < 0) return
  write (u, "(1x,4(1x," // HISTOGRAM_DATA_FORMAT // "))",) &
    point_get_x (point), &
    point_get_y (point), &
    point_get_xerr (point), &
    point_get_yerr (point)
end subroutine point_write

```

Histograms

<Analysis: types>+≡

```

type :: plot_t
  private
  real(default) :: lower_bound = 0
  real(default) :: upper_bound = 0
  real(default) :: width = 0
  type(bin_t) :: underflow
  type(point_t), pointer :: first => null ()
  type(point_t), pointer :: last => null ()
  type(bin_t) :: overflow
  integer :: count = 0
  integer :: count_within_bounds = 0
  type(plot_labels_t) :: plot_labels
end type plot_t

```

Initializer/finalizer

Initialize a plot. We provide the lower and upper bound in the x direction.

<Analysis: procedures>+≡

```
subroutine plot_init (plot, lower_bound, upper_bound, plot_labels)
  type(plot_t), intent(out) :: plot
  real(default), intent(in) :: lower_bound, upper_bound
  type(plot_labels_t), intent(in), optional :: plot_labels
  plot%lower_bound = lower_bound
  plot%upper_bound = upper_bound
  plot%width = plot%upper_bound - plot%lower_bound
  call bin_init (plot%underflow, plot%lower_bound, 0._default)
  call bin_init (plot%overflow, plot%upper_bound, 0._default)
  if (present (plot_labels)) then
    plot%plot_labels = plot_labels
  else
    call plot_labels_init (plot%plot_labels, &
      title = var_str (""), xlabel = var_str (""), ylabel = var_str (""))
  end if
end subroutine plot_init
```

Finalize the plot by deallocating the list of points.

<Analysis: procedures>+≡

```
subroutine plot_final (plot)
  type(plot_t), intent(inout) :: plot
  type(point_t), pointer :: current
  do while (associated (plot%first))
    current => plot%first
    plot%first => current%next
    deallocate (current)
  end do
  plot%last => null ()
end subroutine plot_final
```

Fill plots

Clear the plot contents, but do not modify the structure.

<Analysis: procedures>+≡

```
subroutine plot_clear (plot)
  type(plot_t), intent(inout) :: plot
  call bin_clear (plot%underflow)
  call bin_clear (plot%overflow)
  plot%count = 0
  plot%count_within_bounds = 0
  call plot_final (plot)
end subroutine plot_clear
```

Record a value. Successful if the value is within bounds, otherwise it is recorded as under-/overflow.

<Analysis: procedures>+≡

```
subroutine plot_record_value (plot, x, y, xerr, yerr, success)
```

```

type(plot_t), intent(inout) :: plot
real(default), intent(in) :: x, y
real(default), intent(in), optional :: xerr, yerr
logical, intent(out), optional :: success
type(point_t), pointer :: point
plot%count = plot%count + 1
if (x < plot%lower_bound) then
    call bin_record_value (plot%underflow, 1._default)
    if (present (success)) success = .false.
else if (x <= plot%upper_bound) then
    plot%count_within_bounds = plot%count_within_bounds + 1
    allocate (point)
    call point_init (point, x, y, xerr, yerr)
    if (associated (plot%first)) then
        plot%last%next => point
    else
        plot%first => point
    end if
    plot%last => point
    if (present (success)) success = .true.
else
    call bin_record_value (plot%overflow, 1._default)
    if (present (success)) success = .false.
end if
end subroutine plot_record_value

```

Access contents

The number of entries total, and the number of entries that have been recorded:

<Analysis: procedures>+≡

```

function plot_get_n_entries (plot) result (n)
    integer :: n
    type(plot_t), intent(in) :: plot
    n = plot%count
end function plot_get_n_entries

```

Analogous, but applied only to events within bounds.

<Analysis: procedures>+≡

```

function plot_get_n_entries_within_bounds (plot) result (n)
    integer :: n
    type(plot_t), intent(in) :: plot
    n = plot%count_within_bounds
end function plot_get_n_entries_within_bounds

```

Output

<Analysis: procedures>+≡

```

subroutine plot_write (plot, unit)
    type(plot_t), intent(in) :: plot
    integer, intent(in), optional :: unit
    type(point_t), pointer :: point

```

```

integer :: u
u = output_unit (unit); if (u < 0) return
call point_write_header (u)
point => plot%first
do while (associated (point))
    call point_write (point, unit)
    point => point%next
end do
write (u, *)
call bin_write_header (u)
write (u, "(A,1x,A)" "#", "Underflow:")
call bin_write (plot%underflow, u)
write (u, *)
write (u, "(A,1x,A)" "#", "Overflow:")
call bin_write (plot%overflow, u)
write (u, *)
write (u, "(A,1x,A)" "#", "Summary: points within bounds")
write (u, "(A," // HISTOGRAM_INTG_FORMAT // ")") &
    "n_entries = ", plot_get_n_entries_within_bounds (plot)
write (u, *)
write (u, "(A,1x,A)" "#", "Summary: all points")
write (u, "(A," // HISTOGRAM_INTG_FORMAT // ")") &
    "n_entries = ", plot_get_n_entries (plot)
write (u, *)
end subroutine plot_write

```

L^AT_EX output.

<Analysis: procedures>+≡

```

subroutine plot_write_driver (plot, filename, unit, write_heading)
    type(plot_t), intent(in) :: plot
    type(string_t), intent(in) :: filename
    integer, intent(in), optional :: unit
    logical, intent(in), optional :: write_heading
    logical :: heading
    character(len=32) :: lower_bound_str, upper_bound_str
    logical, parameter :: log_plot = .false.
    integer :: u
    u = output_unit (unit); if (u < 0) return
    heading = .true.; if (present (write_heading)) heading = write_heading
    if (heading) then
        write (u, "(A)")
        if (plot%plot_labels%title /= "") then
            write (u, "(A)" "\section{" // char (plot%plot_labels%title) // ")")
        else
            write (u, "(A)" "\section{Plot}")
        end if
    end if
    if (plot%plot_labels%description /= "") then
        write (u, "(A)" char (plot%plot_labels%description))
        write (u, *)
        write (u, "(A)" "\vspace*{\baselineskip}")
    end if
    lower_bound_str = ""

```

```

upper_bound_str = ""
1 format (G10.3)
write (lower_bound_str, 1) plot%lower_bound
write (upper_bound_str, 1) plot%upper_bound
lower_bound_str = adjustl (lower_bound_str)
upper_bound_str = adjustl (upper_bound_str)
write (u, "(A)") "\vspace*{\baselineskip}"
write (u, "(A)") "\unitlength 1mm"
write (u, "(A,I0,',',I0,A)") &
    "\begin{gmlgraph*}(", &
        plot%plot_labels%width_mm, plot%plot_labels%height_mm, &
        ")[dat]"
if (log_plot) then
    write (u, "(2x,A)") "setup (linear,log); "
    write (u, "(2x,A)") &
        "graphrange (#" // trim (lower_bound_str) // ", ??), " &
        //" "("#" // trim (upper_bound_str) // ", ??);"
else
    write (u, "(2x,A)") "setup (linear,linear); "
    write (u, "(2x,A)") &
        "graphrange (#" // trim (lower_bound_str) // ", #0), " &
        //" "("#" // trim (upper_bound_str) // ", ??);"
end if
write (u, "(2x,A)") 'fromfile "' // char (filename) // '":'
write (u, "(4x,A)") 'key "# Plot:";'
write (u, "(4x,A)") 'for i within block:'
write (u, "(6x,A)") 'get x, y, x.err, y.err;'
write (u, "(6x,A)") 'plot (dat) (x,y);'
write (u, "(4x,A)") 'endfor'
write (u, "(2x,A)") 'endfrom'
write (u, "(2x,A)") 'draw from (dat); '
if (plot%plot_labels%ylabel /= "") then
    write (u, "(2x,A)") 'label.ulft (< ' // '<' &
        // char (plot%plot_labels%ylabel) // '>' // '>', out);'
else
    write (u, "(2x,A)") 'label.ulft (< ' // '<y>' // '>', out);'
end if
if (plot%plot_labels%xlabel /= "") then
    write (u, "(2x,A)", advance="no") 'label.bot (< ' // '<' &
        // char (plot%plot_labels%xlabel) // '>' &
        // '>', out);'
else
    write (u, "(2x,A)") 'label.ulft (< ' // '<x>' // '>', out);'
end if
write (u, "(A)") "\end{gmlgraph*}"
write (u, "(A)") "\vspace*{2\baselineskip}"
write (u, "(A)") "\begin{flushleft}"
write (u, "(A)") "\textbf{Data within bounds:} \\"
write (u, "(A)", advance="no") "$n_{\text{entries}} = "
write (u, "(I0,A)", advance="no") plot%count_within_bounds, "$"
write (u, "(A)") "\\\[0.5\baselineskip]"
write (u, "(A)") "\textbf{All data:} \\"
write (u, "(A)", advance="no") "$n_{\text{entries}} = "
write (u, "(I0,A)") plot%count, "$"

```

```

        write (u, "(A)") "\end{flushleft}"
    end subroutine plot_write_driver

```

5.1.7 Analysis objects

This data structure holds all observables, histograms and such that are currently active. We have one global store; individual items are identified by their ID strings.

(This should rather be coded by type extension.)

```

<Analysis: parameters>≡
    integer, parameter :: AN_UNDEFINED = 0
    integer, parameter :: AN_OBSERVABLE = 1
    integer, parameter :: AN_HISTOGRAM = 2
    integer, parameter :: AN_PLOT = 3

<Analysis: types>+≡
    type :: analysis_object_t
    private
    type(string_t) :: id
    integer :: type = AN_UNDEFINED
    type(observable_t), pointer :: obs => null ()
    type(histogram_t), pointer :: h => null ()
    type(plot_t), pointer :: plot => null ()
    type(analysis_object_t), pointer :: next => null ()
end type analysis_object_t

```

Initializer/finalizer

Allocate with the correct type but do not fill initial values.

```

<Analysis: procedures>+≡
    subroutine analysis_object_init (obj, id, type)
        type(analysis_object_t), intent(out) :: obj
        type(string_t), intent(in) :: id
        integer, intent(in) :: type
        obj%id = id
        obj%type = type
        select case (obj%type)
            case (AN_OBSERVABLE); allocate (obj%obs)
            case (AN_HISTOGRAM); allocate (obj%h)
            case (AN_PLOT); allocate (obj%plot)
        end select
    end subroutine analysis_object_init

<Analysis: procedures>+≡
    subroutine analysis_object_final (obj)
        type(analysis_object_t), intent(inout) :: obj
        select case (obj%type)
            case (AN_OBSERVABLE)
                deallocate (obj%obs)
            case (AN_HISTOGRAM)

```

```

        deallocate (obj%h)
    case (AN_PLOT)
        call plot_final (obj%plot)
        deallocate (obj%plot)
    end select
    obj%type = AN_UNDEFINED
end subroutine analysis_object_final

```

Clear the analysis object, i.e., reset it to its initial state.

```

<Analysis: procedures>+≡
subroutine analysis_object_clear (obj)
    type(analysis_object_t), intent(inout) :: obj
    select case (obj%type)
    case (AN_OBSERVABLE)
        call observable_clear (obj%obs)
    case (AN_HISTOGRAM)
        call histogram_clear (obj%h)
    case (AN_PLOT)
        call plot_clear (obj%plot)
    end select
end subroutine analysis_object_clear

```

Fill with data

Record data. The effect depends on the type of analysis object.

```

<Analysis: procedures>+≡
subroutine analysis_object_record_data (obj, &
    x, y, xerr, yerr, weight, excess, success)
    type(analysis_object_t), intent(inout) :: obj
    real(default), intent(in) :: x
    real(default), intent(in), optional :: y, xerr, yerr, weight, excess
    logical, intent(out), optional :: success
    select case (obj%type)
    case (AN_OBSERVABLE)
        if (present (weight)) then
            call observable_record_value_weighted (obj%obs, x, weight, success)
        else
            call observable_record_value_unweighted (obj%obs, x, success)
        end if
    case (AN_HISTOGRAM)
        if (present (weight)) then
            call histogram_record_value_weighted (obj%h, x, weight, success)
        else
            call histogram_record_value_unweighted (obj%h, x, excess, success)
        end if
    case (AN_PLOT)
        if (present (y)) then
            call plot_record_value (obj%plot, x, y, xerr, yerr, success)
        else
            if (present (success)) success = .false.
        end if
    case default

```

```

        if (present (success)) success = .false.
    end select
end subroutine analysis_object_record_data

```

Explicitly set the pointer to the next object in the list.

```

<Analysis: procedures>+≡
subroutine analysis_object_set_next_ptr (obj, next)
    type(analysis_object_t), intent(inout) :: obj
    type(analysis_object_t), pointer :: next
    obj%next => next
end subroutine analysis_object_set_next_ptr

```

Access contents

Return a pointer to the next object in the list.

```

<Analysis: procedures>+≡
function analysis_object_get_next_ptr (obj) result (next)
    type(analysis_object_t), pointer :: next
    type(analysis_object_t), intent(in) :: obj
    next => obj%next
end function analysis_object_get_next_ptr

```

Return generic entries.

```

<Analysis: procedures>+≡
function analysis_object_get_n_entries (obj, within_bounds) result (n)
    integer :: n
    type(analysis_object_t), intent(in) :: obj
    logical, intent(in), optional :: within_bounds
    logical :: wb
    select case (obj%type)
    case (AN_OBSERVABLE)
        n = observable_get_n_entries (obj%obs)
    case (AN_HISTOGRAM)
        wb = .false.; if (present (within_bounds)) wb = within_bounds
        if (wb) then
            n = histogram_get_n_entries_within_bounds (obj%h)
        else
            n = histogram_get_n_entries (obj%h)
        end if
    case (AN_PLOT)
        wb = .false.; if (present (within_bounds)) wb = within_bounds
        if (wb) then
            n = plot_get_n_entries_within_bounds (obj%plot)
        else
            n = plot_get_n_entries (obj%plot)
        end if
    case default
        n = 0
    end select
end function analysis_object_get_n_entries

```

```

function analysis_object_get_average (obj, within_bounds) result (avg)
  real(default) :: avg
  type(analysis_object_t), intent(in) :: obj
  logical, intent(in), optional :: within_bounds
  logical :: wb
  select case (obj%type)
  case (AN_OBSERVABLE)
    avg = observable_get_average (obj%obs)
  case (AN_HISTOGRAM)
    wb = .false.; if (present (within_bounds)) wb = within_bounds
    if (wb) then
      avg = histogram_get_average_within_bounds (obj%h)
    else
      avg = histogram_get_average (obj%h)
    end if
  case default
    avg = 0
  end select
end function analysis_object_get_average

function analysis_object_get_error (obj, within_bounds) result (err)
  real(default) :: err
  type(analysis_object_t), intent(in) :: obj
  logical, intent(in), optional :: within_bounds
  logical :: wb
  select case (obj%type)
  case (AN_OBSERVABLE)
    err = observable_get_error (obj%obs)
  case (AN_HISTOGRAM)
    wb = .false.; if (present (within_bounds)) wb = within_bounds
    if (wb) then
      err = histogram_get_error_within_bounds (obj%h)
    else
      err = histogram_get_error (obj%h)
    end if
  case default
    err = 0
  end select
end function analysis_object_get_error

```

Return pointers to the actual contents:

(Analysis: procedures)+≡

```

function analysis_object_get_observable_ptr (obj) result (obs)
  type(observable_t), pointer :: obs
  type(analysis_object_t), intent(in) :: obj
  select case (obj%type)
  case (AN_OBSERVABLE); obs => obj%obs
  case default;         obs => null ()
  end select
end function analysis_object_get_observable_ptr

function analysis_object_get_histogram_ptr (obj) result (h)
  type(histogram_t), pointer :: h
  type(analysis_object_t), intent(in) :: obj

```

```

        select case (obj%type)
        case (AN_HISTOGRAM); h => obj%h
        case default;       h => null ()
        end select
    end function analysis_object_get_histogram_ptr

function analysis_object_get_plot_ptr (obj) result (plot)
    type(plot_t), pointer :: plot
    type(analysis_object_t), intent(in) :: obj
    select case (obj%type)
    case (AN_PLOT); plot => obj%plot
    case default;   plot => null ()
    end select
end function analysis_object_get_plot_ptr

```

Return true if the object has a graphical representation:

```

<Analysis: procedures>+≡
function analysis_object_has_plot (obj) result (flag)
    logical :: flag
    type(analysis_object_t), intent(in) :: obj
    select case (obj%type)
    case (AN_HISTOGRAM); flag = .true.
    case (AN_PLOT);     flag = .true.
    case default;       flag = .false.
    end select
end function analysis_object_has_plot

```

Output

```

<Analysis: procedures>+≡
subroutine analysis_object_write (obj, unit)
    type(analysis_object_t), intent(in) :: obj
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write (u, "(A)") repeat ("#", 79)
    select case (obj%type)
    case (AN_OBSERVABLE)
        write (u, "(A)", advance="no") "# Observable:"
    case (AN_HISTOGRAM)
        write (u, "(A)", advance="no") "# Histogram: "
    case (AN_PLOT)
        write (u, "(A)", advance="no") "# Plot: "
    case default
        write (u, "(A)") "# [undefined analysis object]"
    return
end select
write (u, "(1x,A)") char (obj%id)
select case (obj%type)
case (AN_OBSERVABLE); call observable_write (obj%obs, unit)
case (AN_HISTOGRAM); call histogram_write (obj%h, unit)
case (AN_PLOT);      call plot_write (obj%plot, unit)

```

```

        end select
    end subroutine analysis_object_write

```

Write the object part of the L^AT_EX driver file.

```

<Analysis: procedures>+≡
    subroutine analysis_object_write_driver (obj, filename, unit)
        type(analysis_object_t), intent(in) :: obj
        type(string_t), intent(in) :: filename
        integer, intent(in), optional :: unit
        select case (obj%type)
            case (AN_OBSERVABLE); call observable_write_driver (obj%obs, unit)
            case (AN_HISTOGRAM);  call histogram_write_driver (obj%h, filename, unit)
            case (AN_PLOT);       call plot_write_driver (obj%plot, filename, unit)
        end select
    end subroutine analysis_object_write_driver

```

5.1.8 Analysis store

This data structure holds all observables, histograms and such that are currently active. We have one global store; individual items are identified by their ID strings and types.

```

<Analysis: variables>≡
    type(analysis_store_t), save :: analysis_store

<Analysis: types>+≡
    type :: analysis_store_t
    private
        type(analysis_object_t), pointer :: first => null ()
        type(analysis_object_t), pointer :: last => null ()
    end type analysis_store_t

```

Delete the analysis store

```

<Analysis: public>+≡
    public :: analysis_final

<Analysis: procedures>+≡
    subroutine analysis_final ()
        type(analysis_object_t), pointer :: current
        do while (associated (analysis_store%first))
            current => analysis_store%first
            analysis_store%first => current%next
            call analysis_object_final (current)
        end do
        analysis_store%last => null ()
    end subroutine analysis_final

```

Append a new analysis object

```

<Analysis: procedures>+≡
    subroutine analysis_store_append_object (id, type)
        type(string_t), intent(in) :: id

```

```

integer, intent(in) :: type
type(analysis_object_t), pointer :: obj
allocate (obj)
call analysis_object_init (obj, id, type)
if (associated (analysis_store%last)) then
    analysis_store%last%next => obj
else
    analysis_store%first => obj
end if
analysis_store%last => obj
end subroutine analysis_store_append_object

```

Return a pointer to the analysis object with given ID.

```

<Analysis: procedures>+≡
function analysis_store_get_object_ptr (id) result (obj)
    type(string_t), intent(in) :: id
    type(analysis_object_t), pointer :: obj
    obj => analysis_store%first
    do while (associated (obj))
        if (obj%id == id) return
        obj => obj%next
    end do
end function analysis_store_get_object_ptr

```

Initialize an analysis object: either reset it if present, or append a new entry.

```

<Analysis: procedures>+≡
subroutine analysis_store_init_object (id, type, obj)
    type(string_t), intent(in) :: id
    integer, intent(in) :: type
    type(analysis_object_t), pointer :: obj, next
    obj => analysis_store_get_object_ptr (id)
    if (associated (obj)) then
        next => analysis_object_get_next_ptr (obj)
        call analysis_object_final (obj)
        call analysis_object_init (obj, id, type)
        call analysis_object_set_next_ptr (obj, next)
    else
        call analysis_store_append_object (id, type)
        obj => analysis_store%last
    end if
end subroutine analysis_store_init_object

```

5.1.9 L^AT_EX driver file

Write a driver file for all objects in the store.

```

<Analysis: procedures>+≡
subroutine analysis_store_write_driver_all (filename_data, unit)
    type(string_t), intent(in) :: filename_data
    integer, intent(in), optional :: unit
    type(analysis_object_t), pointer :: obj
    call analysis_store_write_driver_header (unit)

```

```

obj => analysis_store%first
do while (associated (obj))
    call analysis_object_write_driver (obj, filename_data, unit)
    obj => obj%next
end do
call analysis_store_write_driver_footer (unit)
end subroutine analysis_store_write_driver_all

```

Write a driver file for an array of objects.

<Analysis: procedures>+≡

```

subroutine analysis_store_write_driver_obj (filename_data, id, unit)
    type(string_t), intent(in) :: filename_data
    type(string_t), dimension(:), intent(in) :: id
    integer, intent(in), optional :: unit
    type(analysis_object_t), pointer :: obj
    integer :: i
    call analysis_store_write_driver_header (unit)
    do i = 1, size (id)
        obj => analysis_store_get_object_ptr (id(i))
        if (associated (obj)) &
            call analysis_object_write_driver (obj, filename_data, unit)
    end do
    call analysis_store_write_driver_footer (unit)
end subroutine analysis_store_write_driver_obj

```

The beginning of the driver file.

<Analysis: procedures>+≡

```

subroutine analysis_store_write_driver_header (unit)
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write(u, '(A)') "\documentclass[12pt]{article}"
    write(u, *)
    write(u, '(A)') "\usepackage{gamelan}"
    write(u, '(A)') "\usepackage{amsmath}"
    write(u, *)
    write(u, '(A)') "\begin{document}"
    write(u, '(A)') "\begin{gmlfile}"
    write(u, *)
    write(u, '(A)') "\begin{gmlcode}"
    write(u, '(A)') " color col.default, col.excess;"
    write(u, '(A)') " col.default = 0.9white;"
    write(u, '(A)') " col.excess = red;"
    write(u, '(A)') " boolean show_excess;"
!   if (mcs(1)%plot_excess .and. mcs(1)%unweighted) then
!       write(u, '(A)') " show_excess = true;"
!   else
    write(u, '(A)') " show_excess = false;"
!   end if
    write(u, '(A)') "\end{gmlcode}"
    write(u, *)
end subroutine analysis_store_write_driver_header

```

The end of the driver file.

```
<Analysis: procedures>+≡
subroutine analysis_store_write_driver_footer (unit)
  integer, intent(in), optional :: unit
  integer :: u
  u = output_unit (unit); if (u < 0) return
  write(u, *)
  write(u, '(A)') "\end{gmlfile}"
  write(u, '(A)') "\end{document}"
end subroutine analysis_store_write_driver_footer
```

5.1.10 API

Creating new objects

The specific versions below:

```
<Analysis: public>+≡
public :: analysis_init_observable

<Analysis: procedures>+≡
subroutine analysis_init_observable (id, label, physical_unit, plot_labels)
  type(string_t), intent(in) :: id
  type(string_t), intent(in), optional :: label, physical_unit
  type(plot_labels_t), intent(in), optional :: plot_labels
  type(analysis_object_t), pointer :: obj
  type(observable_t), pointer :: obs
  call analysis_store_init_object (id, AN_OBSERVABLE, obj)
  obs => analysis_object_get_observable_ptr (obj)
  call observable_init (obs, label, physical_unit, plot_labels)
end subroutine analysis_init_observable

<Analysis: public>+≡
public :: analysis_init_histogram

<Analysis: interfaces>+≡
interface analysis_init_histogram
  module procedure analysis_init_histogram_n_bins
  module procedure analysis_init_histogram_bin_width
end interface

<Analysis: procedures>+≡
subroutine analysis_init_histogram_n_bins &
  (id, lower_bound, upper_bound, n_bins, &
   label, physical_unit, plot_labels)
  type(string_t), intent(in) :: id
  real(default), intent(in) :: lower_bound, upper_bound
  integer, intent(in) :: n_bins
  type(string_t), intent(in), optional :: label, physical_unit
  type(plot_labels_t), intent(in), optional :: plot_labels
  type(analysis_object_t), pointer :: obj
  type(histogram_t), pointer :: h
  call analysis_store_init_object (id, AN_HISTOGRAM, obj)
  h => analysis_object_get_histogram_ptr (obj)
```

```

    call histogram_init (h, &
        lower_bound, upper_bound, n_bins, &
        label, physical_unit, plot_labels)
end subroutine analysis_init_histogram_n_bins

subroutine analysis_init_histogram_bin_width &
    (id, lower_bound, upper_bound, bin_width, &
    label, physical_unit, plot_labels)
type(string_t), intent(in) :: id
real(default), intent(in) :: lower_bound, upper_bound, bin_width
type(string_t), intent(in), optional :: label, physical_unit
type(plot_labels_t), intent(in), optional :: plot_labels
type(analysis_object_t), pointer :: obj
type(histogram_t), pointer :: h
call analysis_store_init_object (id, AN_HISTOGRAM, obj)
h => analysis_object_get_histogram_ptr (obj)
call histogram_init (h, &
    lower_bound, upper_bound, bin_width, &
    label, physical_unit, plot_labels)
end subroutine analysis_init_histogram_bin_width

```

<Analysis: public>+≡

```
public :: analysis_init_plot
```

<Analysis: procedures>+≡

```

subroutine analysis_init_plot (id, lower_bound, upper_bound, plot_labels)
    type(string_t), intent(in) :: id
    real(default), intent(in) :: lower_bound, upper_bound
    type(plot_labels_t), intent(in), optional :: plot_labels
    type(analysis_object_t), pointer :: obj
    type(plot_t), pointer :: plot
    call analysis_store_init_object (id, AN_PLOT, obj)
    plot => analysis_object_get_plot_ptr (obj)
    call plot_init (plot, &
        lower_bound, upper_bound, plot_labels)
end subroutine analysis_init_plot

```

Recording data

This procedure resets an object or the whole store to its initial state.

<Analysis: public>+≡

```
public :: analysis_clear
```

<Analysis: interfaces>+≡

```

interface analysis_clear
    module procedure analysis_store_clear_obj
    module procedure analysis_store_clear_all
end interface

```

<Analysis: procedures>+≡

```

subroutine analysis_store_clear_obj (id)
    type(string_t), intent(in) :: id
    type(analysis_object_t), pointer :: obj

```

```

obj => analysis_store_get_object_ptr (id)
if (associated (obj)) then
  call analysis_object_clear (obj)
end if
end subroutine analysis_store_clear_obj

subroutine analysis_store_clear_all ()
  type(analysis_object_t), pointer :: obj
  obj => analysis_store%first
  do while (associated (obj))
    call analysis_object_clear (obj)
    obj => obj%next
  end do
end subroutine analysis_store_clear_all

```

There is one generic recording function whose behavior depends on the type of analysis object.

```

<Analysis: public>+≡
  public :: analysis_record_data

<Analysis: procedures>+≡
  subroutine analysis_record_data (id, x, y, xerr, yerr, &
    weight, excess, success, exist)
    type(string_t), intent(in) :: id
    real(default), intent(in) :: x
    real(default), intent(in), optional :: y, xerr, yerr, weight, excess
    logical, intent(out), optional :: success, exist
    type(analysis_object_t), pointer :: obj
    obj => analysis_store_get_object_ptr (id)
    if (associated (obj)) then
      call analysis_object_record_data (obj, x, y, xerr, yerr, &
        weight, excess, success)
      if (present (exist)) exist = .true.
    else
      if (present (success)) success = .false.
      if (present (exist)) exist = .false.
    end if
  end subroutine analysis_record_data

```

Retrieve generic results

The following functions should work for all kinds of analysis object:

```

<Analysis: public>+≡
  public :: analysis_get_n_entries
  public :: analysis_get_average
  public :: analysis_get_error

<Analysis: procedures>+≡
  function analysis_get_n_entries (id, within_bounds) result (n)
    integer :: n
    type(string_t), intent(in) :: id
    logical, intent(in), optional :: within_bounds
    type(analysis_object_t), pointer :: obj

```

```

obj => analysis_store_get_object_ptr (id)
if (associated (obj)) then
  n = analysis_object_get_n_entries (obj, within_bounds)
else
  n = 0
end if
end function analysis_get_n_entries

function analysis_get_average (id, within_bounds) result (avg)
  real(default) :: avg
  type(string_t), intent(in) :: id
  type(analysis_object_t), pointer :: obj
  logical, intent(in), optional :: within_bounds
  obj => analysis_store_get_object_ptr (id)
  if (associated (obj)) then
    avg = analysis_object_get_average (obj, within_bounds)
  else
    avg = 0
  end if
end function analysis_get_average

function analysis_get_error (id, within_bounds) result (err)
  real(default) :: err
  type(string_t), intent(in) :: id
  type(analysis_object_t), pointer :: obj
  logical, intent(in), optional :: within_bounds
  obj => analysis_store_get_object_ptr (id)
  if (associated (obj)) then
    err = analysis_object_get_error (obj, within_bounds)
  else
    err = 0
  end if
end function analysis_get_error

```

Return true if any analysis object is graphical

<Analysis: public>+≡

```
public :: analysis_has_plots
```

<Analysis: interfaces>+≡

```
interface analysis_has_plots
  module procedure analysis_has_plots_any
  module procedure analysis_has_plots_obj
end interface

```

<Analysis: procedures>+≡

```
function analysis_has_plots_any () result (flag)
  logical :: flag
  type(analysis_object_t), pointer :: obj
  flag = .false.
  obj => analysis_store%first
  do while (associated (obj))
    flag = analysis_object_has_plot (obj)
    if (flag) return
  end do

```

```

end function analysis_has_plots_any

function analysis_has_plots_obj (id) result (flag)
  logical :: flag
  type(string_t), dimension(:), intent(in) :: id
  type(analysis_object_t), pointer :: obj
  integer :: i
  flag = .false.
  do i = 1, size (id)
    obj => analysis_store_get_object_ptr (id(i))
    if (associated (obj)) then
      flag = analysis_object_has_plot (obj)
      if (flag) return
    end if
  end do
end function analysis_has_plots_obj

```

Output

```

<Analysis: public>+≡
  public :: analysis_write

<Analysis: interfaces>+≡
  interface analysis_write
    module procedure analysis_write_object
    module procedure analysis_write_all
  end interface

<Analysis: procedures>+≡
  subroutine analysis_write_object (id, unit)
    type(string_t), intent(in) :: id
    integer, intent(in), optional :: unit
    type(analysis_object_t), pointer :: obj
    obj => analysis_store_get_object_ptr (id)
    if (associated (obj)) then
      call analysis_object_write (obj, unit)
    else
      call msg_error ("Analysis object '" // char (id) // "' not found")
    end if
  end subroutine analysis_write_object

  subroutine analysis_write_all (unit)
    integer, intent(in), optional :: unit
    type(analysis_object_t), pointer :: obj
    integer :: u
    u = output_unit (unit); if (u < 0) return
    obj => analysis_store%first
    do while (associated (obj))
      call analysis_object_write (obj, unit)
      obj => obj%next
    end do
  end subroutine analysis_write_all

```

```

<Analysis: public>+≡
public :: analysis_write_driver

<Analysis: procedures>+≡
subroutine analysis_write_driver (filename_data, id, unit)
  type(string_t), intent(in) :: filename_data
  type(string_t), dimension(:), intent(in), optional :: id
  integer, intent(in), optional :: unit
  if (present(id)) then
    call analysis_store_write_driver_obj (filename_data, id, unit)
  else
    call analysis_store_write_driver_all (filename_data, unit)
  end if
end subroutine analysis_write_driver

<Analysis: public>+≡
public :: analysis_compile_tex

<Analysis: procedures>+≡
subroutine analysis_compile_tex (file, has_gmlcode, os_data)
  type(string_t), intent(in) :: file
  logical, intent(in) :: has_gmlcode
  type(os_data_t), intent(in) :: os_data
  type(string_t) :: setenv
  integer :: status
  if (os_data%event_analysis_ps) then
    BLOCK: do
      if (os_data%whizard_texpath /= "") then
        setenv = "TEXINPUTS=" // os_data%whizard_texpath // ":$TEXINPUTS "
      else
        setenv = ""
      end if
      call os_system_call (setenv // os_data%latex // " " // file, status)
      if (status /= 0) exit BLOCK
      if (has_gmlcode) then
        call os_system_call (os_data%gml // " " // file, status)
        if (status /= 0) exit BLOCK
        call os_system_call (setenv // os_data%latex // " " // file, &
          status)
        if (status /= 0) exit BLOCK
      end if
      call os_system_call (os_data%dvips // " " // file, status)
      if (status /= 0) exit BLOCK
      if (os_data%event_analysis_pdf) then
        call os_system_call (os_data%ps2pdf // " " // file // ".ps", &
          status)
        if (status /= 0) exit BLOCK
      end if
      exit BLOCK
    end do BLOCK
    if (status /= 0) then
      call msg_error ("Unable to compile analysis output file")
    end if
  end if
end subroutine analysis_compile_tex

```

5.1.11 Test

```
<Analysis: public>+≡
public :: analysis_test

<Analysis: procedures>+≡
subroutine analysis_test ()
  call analysis_test1 ()
  call analysis_final ()
end subroutine analysis_test

<Analysis: procedures>+≡
subroutine analysis_test1 ()
  type(string_t) :: id1, id2, id3, id4
  integer :: i
  id1 = "foo"
  id2 = "bar"
  id3 = "hist"
  id4 = "plot"
  call analysis_init_observable (id1)
  call analysis_init_observable (id2)
  call analysis_init_histogram_bin_width &
    (id3, 0.5_default, 5.5_default, 1._default)
  call analysis_init_plot (id4, 0.5_default, 5.5_default)
  do i = 1, 3
    print *, "data = ", real(i,default)
    call analysis_record_data (id1, real(i,default))
    call analysis_record_data (id2, real(i,default), &
      weight=real(i,default))
    call analysis_record_data (id3, real(i,default))
    call analysis_record_data (id4, real(i,default), real(i,default)**2)
  end do
1  format (A,10(1x,I5))
2  format (A,10(1x,F5.3))
  print 1, "n_entries = ", &
    analysis_get_n_entries (id1), &
    analysis_get_n_entries (id2), &
    analysis_get_n_entries (id3), &
    analysis_get_n_entries (id3, within_bounds = .true.), &
    analysis_get_n_entries (id4), &
    analysis_get_n_entries (id4, within_bounds = .true.)
  print 2, "average   = ", &
    analysis_get_average (id1), &
    analysis_get_average (id2), &
    analysis_get_average (id3), &
    analysis_get_average (id3, within_bounds = .true.)
  print 2, "error     = ", &
    analysis_get_error (id1), &
    analysis_get_error (id2), &
    analysis_get_error (id3), &
    analysis_get_error (id3, within_bounds = .true.)
  print *, "clear #2"
```

```

call analysis_clear (id2)
do i = 4, 6
  print *, "data = ", real(i,default)
  call analysis_record_data (id1, real(i,default))
  call analysis_record_data (id2, real(i,default), &
                             weight=real(i,default))
  call analysis_record_data (id3, real(i,default))
  call analysis_record_data (id4, real(i,default), real(i,default)**2)
end do
print 1, "n_entries = ", &
  analysis_get_n_entries (id1), &
  analysis_get_n_entries (id2), &
  analysis_get_n_entries (id3), &
  analysis_get_n_entries (id3, within_bounds = .true.), &
  analysis_get_n_entries (id4), &
  analysis_get_n_entries (id4, within_bounds = .true.)
print 2, "average   = ", &
  analysis_get_average (id1), &
  analysis_get_average (id2), &
  analysis_get_average (id3), &
  analysis_get_average (id3, within_bounds = .true.)
print 2, "error     = ", &
  analysis_get_error (id1), &
  analysis_get_error (id2), &
  analysis_get_error (id3), &
  analysis_get_error (id3, within_bounds = .true.)
print *
call analysis_write ()
call analysis_clear ()
end subroutine analysis_test1

```

5.2 PDG arrays

For defining aliases, we introduce a special type which holds a set of (integer) PDG codes.

```
<pdg_arrays.f90>≡  
<File header>  
  
module pdg_arrays  
  
<Use file utils>  
  
<Standard module head>  
  
<PDG arrays: public>  
  
<PDG arrays: parameters>  
  
<PDG arrays: types>  
  
<PDG arrays: interfaces>  
  
contains  
  
<PDG arrays: procedures>  
  
end module pdg_arrays
```

5.2.1 Type definition

Using an allocatable array eliminates the need for initializer and/or finalizer.

```
<PDG arrays: public>≡  
public :: pdg_array_t  
  
<PDG arrays: types>≡  
type :: pdg_array_t  
private  
integer, dimension(:), allocatable :: pdg  
end type pdg_array_t
```

Output

```
<PDG arrays: public>+≡  
public :: pdg_array_write  
  
<PDG arrays: procedures>≡  
subroutine pdg_array_write (aval, unit)  
type(pdg_array_t), intent(in) :: aval  
integer, intent(in), optional :: unit  
integer :: u, i  
u = output_unit (unit); if (u < 0) return  
write (u, "(A)", advance="no") "PDG("  
if (allocated (aval%pdg)) then  
do i = 1, size (aval%pdg)  
if (i > 1) write (u, "(A)", advance="no") " , "
```

```

        write (u, "(I0)", advance="no")  aval%pdg(i)
    end do
end if
write (u, "(A)", advance="no")  ""
end subroutine pdg_array_write

```

5.2.2 Parameters

We need an UNDEFINED value:

```

(PDG arrays: parameters)≡
    integer, parameter, public :: UNDEFINED = 0

```

5.2.3 Basic operations

Assignment. We define assignment from and to an integer array. Note that the integer array, if it is the l.h.s., must be declared allocatable by the caller.

```

(PDG arrays: public)+≡
    public :: assignment(=)

(PDG arrays: interfaces)≡
    interface assignment(=)
        module procedure pdg_array_from_int_array
        module procedure pdg_array_from_int
        module procedure int_array_from_pdg_array
    end interface

(PDG arrays: procedures)+≡
    subroutine pdg_array_from_int_array (aval, iarray)
        type(pdg_array_t), intent(out) :: aval
        integer, dimension(:), intent(in) :: iarray
        allocate (aval%pdg (size (iarray)))
        aval%pdg = iarray
    end subroutine pdg_array_from_int_array

    elemental subroutine pdg_array_from_int (aval, int)
        type(pdg_array_t), intent(out) :: aval
        integer, intent(in) :: int
        allocate (aval%pdg (1))
        aval%pdg = int
    end subroutine pdg_array_from_int

    subroutine int_array_from_pdg_array (iarray, aval)
        integer, dimension(:), allocatable, intent(out) :: iarray
        type(pdg_array_t), intent(in) :: aval
        if (allocated (aval%pdg)) then
            allocate (iarray (size (aval%pdg)))
            iarray = aval%pdg
        else
            allocate (iarray (0))
        end if
    end subroutine int_array_from_pdg_array

```

The only nontrivial operation: concatenate two PDG arrays

```

(PDG arrays: public)+≡
    public :: operator(//)

(PDG arrays: interfaces)+≡
    interface operator(//)
        module procedure concat_pdg_arrays
    end interface

(PDG arrays: procedures)+≡
    function concat_pdg_arrays (aval1, aval2) result (aval)
        type(pdg_array_t) :: aval
        type(pdg_array_t), intent(in) :: aval1, aval2
        integer :: n1, n2
        if (allocated (aval1%pdg) .and. allocated (aval2%pdg)) then
            n1 = size (aval1%pdg)
            n2 = size (aval2%pdg)
            allocate (aval%pdg (n1 + n2))
            aval%pdg(:n1) = aval1%pdg
            aval%pdg(n1+1:) = aval2%pdg
        else if (allocated (aval1%pdg)) then
            aval = aval1
        else if (allocated (aval2%pdg)) then
            aval = aval2
        end if
    end function concat_pdg_arrays

```

5.2.4 Matching

A PDG array matches a given PDG code if the code is present within the array. If either one is zero (UNDEFINED), the match also succeeds.

```

(PDG arrays: public)+≡
    public :: operator(.match.)

(PDG arrays: interfaces)+≡
    interface operator(.match.)
        module procedure pdg_array_match_integer
    end interface

(PDG arrays: procedures)+≡
    elemental function pdg_array_match_integer (aval, pdg) result (flag)
        logical :: flag
        type(pdg_array_t), intent(in) :: aval
        integer, intent(in) :: pdg
        if (allocated (aval%pdg)) then
            flag = pdg == UNDEFINED &
                .or. any (aval%pdg == UNDEFINED) &
                .or. any (aval%pdg == pdg)
        else
            flag = .false.
        end if
    end function pdg_array_match_integer

```

Equivalence. Two PDG arrays are equivalent if either both contain UNDEFINED or each element of array 1 is present in array 2, and vice versa.

```

(PDG arrays: public)+≡
    public :: operator(.eqv.)
    public :: operator(.neqv.)

(PDG arrays: interfaces)+≡
    interface operator(.eqv.)
        module procedure pdg_array_equivalent
    end interface
    interface operator(.neqv.)
        module procedure pdg_array_inequivalent
    end interface

(PDG arrays: procedures)+≡
    function pdg_array_equivalent (aval1, aval2) result (eq)
        logical :: eq
        type(pdg_array_t), intent(in) :: aval1, aval2
        logical, dimension(:), allocatable :: match1, match2
        integer :: i
        if (allocated (aval1%pdg) .and. allocated (aval2%pdg)) then
            eq = any (aval1%pdg == UNDEFINED) &
                .and. any (aval2%pdg == UNDEFINED)
            if (.not. eq) then
                allocate (match1 (size (aval1%pdg)))
                allocate (match2 (size (aval2%pdg)))
                match1 = .false.
                match2 = .false.
                do i = 1, size (aval1%pdg)
                    match2 = match2 .or. aval1%pdg(i) == aval2%pdg
                end do
                do i = 1, size (aval2%pdg)
                    match1 = match1 .or. aval2%pdg(i) == aval1%pdg
                end do
                eq = all (match1) .and. all (match2)
            end if
        else
            eq = .false.
        end if
    end function pdg_array_equivalent

    function pdg_array_inequivalent (aval1, aval2) result (neq)
        logical :: neq
        type(pdg_array_t), intent(in) :: aval1, aval2
        neq = .not. pdg_array_equivalent (aval1, aval2)
    end function pdg_array_inequivalent

```

5.3 Particle lists

Within expressions (see below), we need a representation for particle lists, which is independent from other particle representations within WHIZARD. This is provided here.

```
<prt_lists.f90>≡  
<File header>  
  
module prt_lists  
  
  <Use kinds>  
  <Use file utils>  
  use lorentz !NODEP!  
  use sorting  
  use pdg_arrays  
  
  <Standard module head>  
  
  <Prt lists: public>  
  
  <Prt lists: parameters>  
  
  <Prt lists: types>  
  
  <Prt lists: interfaces>  
  
contains  
  
  <Prt lists: procedures>  
  
end module prt_lists
```

5.3.1 Particles

For the purpose of this module, a particle has a type which can indicate an incoming, outgoing, or composite particle, flavor and helicity codes (integer, undefined for composite), four-momentum and invariant mass squared. Furthermore, each particle has an allocatable array of ancestors – particle indices which indicate the building blocks of a composite particle. For an incoming/outgoing particle, the array contains only the index of the particle itself.

For incoming particles, the momentum is inverted before storing it in the particle object.

```
<Prt lists: parameters>≡  
  integer, parameter, public :: PRT_UNDEFINED = 0  
  integer, parameter, public :: PRT_INCOMING = 1  
  integer, parameter, public :: PRT_OUTGOING = 2  
  integer, parameter, public :: PRT_COMPOSITE = 3  
  integer, parameter, public :: PRT_VIRTUAL = 3  
  integer, parameter, public :: PRT_RESONANT = 4
```

The type

We initialize only the type here and mark as unpolarized. The initializers below do the rest.

```
<Prt lists: public>≡
    public :: prt_t

<Prt lists: types>≡
    type :: prt_t
    private
        integer :: type = PRT_UNDEFINED
        integer :: pdg
        logical :: polarized = .false.
        integer :: h
        type(vector4_t) :: p
        real(default) :: p2
        integer, dimension(:), allocatable :: src
    end type prt_t
```

Initializers. Polarization is set separately. Finalizers are not needed.

```
<Prt lists: procedures>≡
    subroutine prt_init_incoming (prt, pdg, p, p2, src)
        type(prt_t), intent(out) :: prt
        integer, intent(in) :: pdg
        type(vector4_t), intent(in) :: p
        real(default), intent(in) :: p2
        integer, dimension(:), intent(in) :: src
        prt%type = PRT_INCOMING
        call prt_set (prt, pdg, - p, p2, src)
    end subroutine prt_init_incoming

    subroutine prt_init_outgoing (prt, pdg, p, p2, src)
        type(prt_t), intent(out) :: prt
        integer, intent(in) :: pdg
        type(vector4_t), intent(in) :: p
        real(default), intent(in) :: p2
        integer, dimension(:), intent(in) :: src
        prt%type = PRT_OUTGOING
        call prt_set (prt, pdg, p, p2, src)
    end subroutine prt_init_outgoing

    subroutine prt_init_composite (prt, p, src)
        type(prt_t), intent(out) :: prt
        type(vector4_t), intent(in) :: p
        integer, dimension(:), intent(in) :: src
        prt%type = PRT_COMPOSITE
        call prt_set (prt, 0, p, p**2, src)
    end subroutine prt_init_composite
```

This version is for temporary particle objects, so the `src` array is not set.

```
<Prt lists: public>+≡
    public :: prt_init_combine
```

```

<Prt lists: procedures>+≡
subroutine prt_init_combine (prt, prt1, prt2)
  type(prt_t), intent(out) :: prt
  type(prt_t), intent(in) :: prt1, prt2
  type(vector4_t) :: p
  integer, dimension(0) :: src
  prt%type = PRT_COMPOSITE
  p = prt1%p + prt2%p
  call prt_set (prt, 0, p, p**2, src)
end subroutine prt_init_combine

```

Accessing contents

```

<Prt lists: public>+≡
public :: prt_get_pdg

<Prt lists: procedures>+≡
elemental function prt_get_pdg (prt) result (pdg)
  integer :: pdg
  type(prt_t), intent(in) :: prt
  pdg = prt%pdg
end function prt_get_pdg

<Prt lists: public>+≡
public :: prt_get_momentum

<Prt lists: procedures>+≡
elemental function prt_get_momentum (prt) result (p)
  type(vector4_t) :: p
  type(prt_t), intent(in) :: prt
  p = prt%p
end function prt_get_momentum

<Prt lists: public>+≡
public :: prt_get_msq

<Prt lists: procedures>+≡
elemental function prt_get_msq (prt) result (msq)
  real(default) :: msq
  type(prt_t), intent(in) :: prt
  msq = prt%p2
end function prt_get_msq

<Prt lists: public>+≡
public :: prt_is_polarized

<Prt lists: procedures>+≡
elemental function prt_is_polarized (prt) result (flag)
  logical :: flag
  type(prt_t), intent(in) :: prt
  flag = prt%polarized
end function prt_is_polarized

```

```

<Prt lists: public>+≡
  public :: prt_get_helicity

<Prt lists: procedures>+≡
  elemental function prt_get_helicity (prt) result (h)
    integer :: h
    type(prt_t), intent(in) :: prt
    h = prt%h
  end function prt_get_helicity

```

Setting data

Set the PDG, momentum and momentum squared, and ancestors. If allocate-on-assignment is available, this can be simplified.

```

<Prt lists: procedures>+≡
  subroutine prt_set (prt, pdg, p, p2, src)
    type(prt_t), intent(inout) :: prt
    integer, intent(in) :: pdg
    type(vector4_t), intent(in) :: p
    real(default), intent(in) :: p2
    integer, dimension(:), intent(in) :: src
    prt%pdg = pdg
    prt%p = p
    prt%p2 = p2
    if (allocated (prt%src)) then
      if (size (src) /= size (prt%src)) then
        deallocate (prt%src)
        allocate (prt%src (size (src)))
      end if
    else
      allocate (prt%src (size (src)))
    end if
    prt%src = src
  end subroutine prt_set

```

Set the momentum separately.

```

<Prt lists: procedures>+≡
  elemental subroutine prt_set_p (prt, p)
    type(prt_t), intent(inout) :: prt
    type(vector4_t), intent(in) :: p
    prt%p = p
  end subroutine prt_set_p

```

Set helicity (optional).

```

<Prt lists: procedures>+≡
  subroutine prt_polarize (prt, h)
    type(prt_t), intent(inout) :: prt
    integer, intent(in) :: h
    prt%polarized = .true.
    prt%h = h
  end subroutine prt_polarize

```

Output

<Prt lists: public>+≡

```
public :: prt_write
```

<Prt lists: procedures>+≡

```
subroutine prt_write (prt, unit)
  type(prt_t), intent(in) :: prt
  integer, intent(in), optional :: unit
  integer :: u, i
  u = output_unit (unit); if (u < 0) return
  write (u, "(1x,A)", advance="no") "prt("
  select case (prt%type)
    case (PRT_UNDEFINED); write (u, "('')", advance="no")
    case (PRT_INCOMING); write (u, "('i:')", advance="no")
    case (PRT_OUTGOING); write (u, "('o:~')", advance="no")
    case (PRT_COMPOSITE); write (u, "('c:~')", advance="no")
  end select
  select case (prt%type)
    case (PRT_INCOMING, PRT_OUTGOING)
      if (prt%polarized) then
        write (u, "(IO,'/',IO,'|')", advance="no") prt%pdg, prt%h
      else
        write (u, "(IO,'|')", advance="no") prt%pdg
      end if
    end select
  select case (prt%type)
    case (PRT_INCOMING, PRT_OUTGOING, PRT_COMPOSITE)
      write (u, "(1PE12.5,';',1PE12.5,';',1PE12.5,';',1PE12.5)", advance="no") &
        array_from_vector4 (prt%p)
      write (u, "('|',1PE12.5)", advance="no") prt%p2
    end select
  if (allocated (prt%src)) then
    write (u, "('|')", advance="no")
    do i = 1, size (prt%src)
      write (u, "(1x,IO)", advance="no") prt%src(i)
    end do
  end if
  write (u, "(A)" ) ")"
end subroutine prt_write
```

Tools

Two particles match if their src arrays are the same.

<Prt lists: interfaces>≡

```
interface operator(.match.)
  module procedure prt_match
end interface
```

<Prt lists: procedures>+≡

```
elemental function prt_match (prt1, prt2) result (match)
  logical :: match
  type(prt_t), intent(in) :: prt1, prt2
```

```

    if (size (prt1%src) == size (prt2%src)) then
        match = all (prt1%src == prt2%src)
    else
        match = .false.
    end if
end function prt_match

```

The combine operation makes a pseudoparticle whose momentum is the result of adding (the momenta of) the pair of input particles. We trace the particles from which a particle is built by storing a `src` array. Each particle entry in the `src` list contains a list of indices which indicates its building blocks. The indices refer to an original list of particles. Index lists are sorted, and they contain no element more than once.

We thus require that in a given pseudoparticle, each original particle occurs at most once.

The result is intent(inout), so it will not be initialized when the subroutine is entered.

```

<Prt lists: procedures>+≡
subroutine prt_combine (prt, prt_in1, prt_in2, ok)
    type(prt_t), intent(inout) :: prt
    type(prt_t), intent(in) :: prt_in1, prt_in2
    logical :: ok
    integer, dimension(:), allocatable :: src
    call combine_index_lists (src, prt_in1%src, prt_in2%src)
    ok = allocated (src)
    if (ok) call prt_init_composite (prt, prt_in1%p + prt_in2%p, src)
end subroutine prt_combine

```

This variant does not produce the combined particle, it just checks whether the combination is valid (no common `src` entry).

```

<Prt lists: public>+≡
public :: are_disjoint

<Prt lists: procedures>+≡
function are_disjoint (prt_in1, prt_in2) result (flag)
    logical :: flag
    type(prt_t), intent(in) :: prt_in1, prt_in2
    flag = index_lists_are_disjoint (prt_in1%src, prt_in2%src)
end function are_disjoint

```

`src` Lists with length > 1 are built by a `combine` operation which merges the lists in a sorted manner. If the result would have a duplicate entry, it is discarded, and the result is unallocated.

```

<Prt lists: procedures>+≡
subroutine combine_index_lists (res, src1, src2)
    integer, dimension(:), intent(in) :: src1, src2
    integer, dimension(:), allocatable :: res
    integer :: i1, i2, i
    allocate (res (size (src1) + size (src2)))
    i1 = 1
    i2 = 1

```

```

LOOP: do i = 1, size (res)
  if (src1(i1) < src2(i2)) then
    res(i) = src1(i1); i1 = i1 + 1
    if (i1 > size (src1)) then
      res(i+1:) = src2(i2:)
      exit LOOP
    end if
  else if (src1(i1) > src2(i2)) then
    res(i) = src2(i2); i2 = i2 + 1
    if (i2 > size (src2)) then
      res(i+1:) = src1(i1:)
      exit LOOP
    end if
  else
    deallocate (res)
    exit LOOP
  end if
end do LOOP
end subroutine combine_index_lists

```

This function is similar, but it does not actually merge the list, it just checks whether they are disjoint (no common src entry).

(Prt lists: procedures)+≡

```

function index_lists_are_disjoint (src1, src2) result (flag)
  logical :: flag
  integer, dimension(:), intent(in) :: src1, src2
  integer :: i1, i2, i
  flag = .true.
  i1 = 1
  i2 = 1
  LOOP: do i = 1, size (src1) + size (src2)
    if (src1(i1) < src2(i2)) then
      i1 = i1 + 1
      if (i1 > size (src1)) then
        exit LOOP
      end if
    else if (src1(i1) > src2(i2)) then
      i2 = i2 + 1
      if (i2 > size (src2)) then
        exit LOOP
      end if
    else
      flag = .false.
      exit LOOP
    end if
  end do LOOP
end function index_lists_are_disjoint

```

5.3.2 Particle lists

Particles are usually collected in lists. The list is actually implemented as a dynamically allocated array, which need not be completely filled.

Type definition

```
<Prt lists: public>+≡
  public :: prt_list_t

<Prt lists: types>+≡
  type :: prt_list_t
  private
    integer :: n = 0
    type(prt_t), dimension(:), allocatable :: prt
  end type prt_list_t
```

Initialize, allocating with size zero (default) or given size. The number of contained particles is set equal to the size.

```
<Prt lists: public>+≡
  public :: prt_list_init

<Prt lists: procedures>+≡
  subroutine prt_list_init (prt_list, n)
    type(prt_list_t), intent(out) :: prt_list
    integer, intent(in), optional :: n
    if (present (n)) then
      allocate (prt_list%prt (n))
      prt_list%n = n
    else
      allocate (prt_list%prt (0))
    end if
  end subroutine prt_list_init
```

(Re-)allocate the particle list with some given size. If the size is greater than the previous one, do a real reallocation. Otherwise, just reset the recorded size. Contents are untouched, but become invalid.

```
<Prt lists: public>+≡
  public :: prt_list_reset

<Prt lists: procedures>+≡
  subroutine prt_list_reset (prt_list, n)
    type(prt_list_t), intent(inout) :: prt_list
    integer, intent(in) :: n
    if (n > size (prt_list%prt)) then
      deallocate (prt_list%prt)
      allocate (prt_list%prt (n))
    end if
    prt_list%n = n
  end subroutine prt_list_reset
```

Output.

```
<Prt lists: public>+≡
  public :: prt_list_write

<Prt lists: procedures>+≡
  subroutine prt_list_write (prt_list, unit, prefix)
    type(prt_list_t), intent(in) :: prt_list
    integer, intent(in), optional :: unit
```

```

character(*), intent(in), optional :: prefix
integer :: u, i
u = output_unit (unit); if (u < 0) return
write (u, *) "Particle list:"
do i = 1, prt_list%n
    if (present (prefix)) write (u, "(A)", advance="no") prefix
    write (u, "(1x,I0)", advance="no") i
    call prt_write (prt_list%prt(i), unit)
end do
end subroutine prt_list_write

```

Defined assignment: transfer only meaningful entries. This is a deep copy (as would be default assignment).

```

<Prt lists: interfaces>+≡
interface assignment(=)
    module procedure prt_list_assign
end interface

<Prt lists: procedures>+≡
subroutine prt_list_assign (prt_list, prt_list_in)
    type(prt_list_t), intent(inout) :: prt_list
    type(prt_list_t), intent(in) :: prt_list_in
    integer :: i
    if (.not. allocated (prt_list%prt)) call prt_list_init (prt_list)
    call prt_list_reset (prt_list, prt_list_in%n)
    do i = 1, prt_list%n
        prt_list%prt(i) = prt_list_in%prt(i)
    end do
end subroutine prt_list_assign

```

Fill contents

Store incoming/outgoing particles which are completely defined.

```

<Prt lists: public>+≡
public :: prt_list_set_incoming
public :: prt_list_set_outgoing
public :: prt_list_set_composite

<Prt lists: procedures>+≡
subroutine prt_list_set_incoming (prt_list, i, pdg, p, p2, src)
    type(prt_list_t), intent(inout) :: prt_list
    integer, intent(in) :: i
    integer, intent(in) :: pdg
    type(vector4_t), intent(in) :: p
    real(default), intent(in) :: p2
    integer, dimension(:), intent(in), optional :: src
    if (present (src)) then
        call prt_init_incoming (prt_list%prt(i), pdg, p, p2, src)
    else
        call prt_init_incoming (prt_list%prt(i), pdg, p, p2, (/ i /))
    end if
end subroutine prt_list_set_incoming

```

```

subroutine prt_list_set_outgoing (prt_list, i, pdg, p, p2, src)
  type(prt_list_t), intent(inout) :: prt_list
  integer, intent(in) :: i
  integer, intent(in) :: pdg
  type(vector4_t), intent(in) :: p
  real(default), intent(in) :: p2
  integer, dimension(:), intent(in), optional :: src
  if (present (src)) then
    call prt_init_outgoing (prt_list%prt(i), pdg, p, p2, src)
  else
    call prt_init_outgoing (prt_list%prt(i), pdg, p, p2, (/ i /))
  end if
end subroutine prt_list_set_outgoing

subroutine prt_list_set_composite (prt_list, i, p, src)
  type(prt_list_t), intent(inout) :: prt_list
  integer, intent(in) :: i
  type(vector4_t), intent(in) :: p
  integer, dimension(:), intent(in) :: src
  call prt_init_composite (prt_list%prt(i), p, src)
end subroutine prt_list_set_composite

```

Separately assign momentum, simultaneously for all incoming/outgoing particles. We assume that the list length coincides with the array size.

```

<Prt lists: public>+=
  public :: prt_list_set_p_incoming
  public :: prt_list_set_p_outgoing

<Prt lists: procedures>+=
  subroutine prt_list_set_p_incoming (prt_list, p)
    type(prt_list_t), intent(inout) :: prt_list
    type(vector4_t), dimension(:), intent(in) :: p
    integer :: n_in
    n_in = size (p)
    call prt_set_p (prt_list%prt(:n_in), p)
  end subroutine prt_list_set_p_incoming

  subroutine prt_list_set_p_outgoing (prt_list, p)
    type(prt_list_t), intent(inout) :: prt_list
    type(vector4_t), dimension(:), intent(in) :: p
    integer :: n_in, n_out
    n_out = size (p)
    n_in = prt_list%n - n_out
    call prt_set_p (prt_list%prt(n_in+1:), p)
  end subroutine prt_list_set_p_outgoing

```

Set polarization for an entry

```

<Prt lists: public>+=
  public :: prt_list_polarize

<Prt lists: procedures>+=
  subroutine prt_list_polarize (prt_list, i, h)

```

```

    type(prt_list_t), intent(inout) :: prt_list
    integer, intent(in) :: i, h
    call prt_polarize (prt_list%prt(i), h)
end subroutine prt_list_polarize

```

Accessing contents

Return true if the particle list has entries.

```

<Prt lists: public>+≡
    public :: prt_list_is_nonempty

<Prt lists: procedures>+≡
    function prt_list_is_nonempty (prt_list) result (flag)
        logical :: flag
        type(prt_list_t), intent(in) :: prt_list
        flag = prt_list%n /= 0
    end function prt_list_is_nonempty

```

Return the number of entries

```

<Prt lists: public>+≡
    public :: prt_list_get_length

<Prt lists: procedures>+≡
    function prt_list_get_length (prt_list) result (length)
        integer :: length
        type(prt_list_t), intent(in) :: prt_list
        length = prt_list%n
    end function prt_list_get_length

```

Return a specific particle. The index is not checked for validity.

```

<Prt lists: public>+≡
    public :: prt_list_get_prt

<Prt lists: procedures>+≡
    function prt_list_get_prt (prt_list, i) result (prt)
        type(prt_t) :: prt
        type(prt_list_t), intent(in) :: prt_list
        integer, intent(in) :: i
        prt = prt_list%prt(i)
    end function prt_list_get_prt

```

Operations with particle lists

The join operation joins two particle lists. When appending the elements of the second list, we check for each particle whether it is already in the first list. If yes, it is discarded. The result list should be initialized already.

If a mask is present, it refers to the second particle list. Particles where the mask is not set are discarded.

```

<Prt lists: public>+≡
    public :: prt_list_join

```

```

<Prt lists: procedures>+≡
subroutine prt_list_join (prt_list, pl1, pl2, mask2)
  type(prt_list_t), intent(inout) :: prt_list
  type(prt_list_t), intent(in) :: pl1, pl2
  logical, dimension(:), intent(in) :: mask2
  integer :: n1, n2, i, n
  n1 = pl1%n
  n2 = pl2%n
  call prt_list_reset (prt_list, n1 + n2)
  prt_list%prt(:n1) = pl1%prt(:n1)
  n = n1
  do i = 1, pl2%n
    if (mask2(i) .and. .not. any (pl2%prt(i) .match. pl1%prt(:pl1%n))) then
      n = n + 1
      prt_list%prt(n) = pl2%prt(i)
    end if
  end do
  prt_list%n = n
end subroutine prt_list_join

```

The combine operation makes a particle list whose entries are the result of adding (the momenta of) each pair of particles in the input lists. We trace the particles from which a particles is built by storing a **src** array. Each particle entry in the **src** list contains a list of indices which indicates its building blocks. The indices refer to an original list of particles. Index lists are sorted, and they contain no element more than once.

We thus require that in a given pseudoparticle, each original particle occurs at most once.

```

<Prt lists: public>+≡
public :: prt_list_combine

<Prt lists: procedures>+≡
subroutine prt_list_combine (prt_list, pl1, pl2, mask12)
  type(prt_list_t), intent(inout) :: prt_list
  type(prt_list_t), intent(in) :: pl1, pl2
  logical, dimension(:,:), intent(in), optional :: mask12
  integer :: n1, n2, i1, i2, n, j
  logical :: ok
  n1 = pl1%n
  n2 = pl2%n
  call prt_list_reset (prt_list, n1 * n2)
  n = 1
  do i1 = 1, n1
    do i2 = 1, n2
      if (present (mask12)) then
        ok = mask12(i1,i2)
      else
        ok = .true.
      end if
      if (ok) call prt_combine &
        (prt_list%prt(n), pl1%prt(i1), pl2%prt(i2), ok)
      if (ok) then
        CHECK_DOUBLES: do j = 1, n - 1

```

```

        if (prt_list%prt(n) .match. prt_list%prt(j)) then
            ok = .false.; exit CHECK_DOUBLES
        end if
    end do CHECK_DOUBLES
    if (ok) n = n + 1
end if
end do
end do
prt_list%n = n - 1
end subroutine prt_list_combine

```

The collect operation makes a single-entry particle list which results from combining (the momenta of) all particles in the input list. As above, the result does not contain an original particle more than once; this is checked for each particle when it is collected. Furthermore, each entry has a mask; where the mask is false, the entry is dropped.

(Thus, if the input particles are already composite, there is some chance that the result depends on the order of the input list and is not as expected. This situation should be avoided.)

```

<Prt lists: public>+≡
    public :: prt_list_collect

<Prt lists: procedures>+≡
    subroutine prt_list_collect (prt_list, pl1, mask1)
        type(prt_list_t), intent(inout) :: prt_list
        type(prt_list_t), intent(in) :: pl1
        logical, dimension(:), intent(in) :: mask1
        type(prt_t) :: prt
        integer :: i
        logical :: ok
        call prt_list_reset (prt_list, 1)
        prt_list%n = 0
        do i = 1, pl1%n
            if (mask1(i)) then
                if (prt_list%n == 0) then
                    prt_list%n = 1
                    prt_list%prt(1) = pl1%prt(i)
                else
                    call prt_combine (prt, prt_list%prt(1), pl1%prt(i), ok)
                    if (ok) prt_list%prt(1) = prt
                end if
            end if
        end do
    end subroutine prt_list_collect

```

Return a list of all particles for which the mask is true.

```

<Prt lists: public>+≡
    public :: prt_list_select

<Prt lists: procedures>+≡
    subroutine prt_list_select (prt_list, pl, mask1)
        type(prt_list_t), intent(inout) :: prt_list
        type(prt_list_t), intent(in) :: pl

```

```

logical, dimension(:), intent(in) :: mask1
integer :: i, n
call prt_list_reset (prt_list, pl%n)
n = 0
do i = 1, pl%n
  if (mask1(i)) then
    n = n + 1
    prt_list%prt(n) = pl%prt(i)
  end if
end do
prt_list%n = n
end subroutine prt_list_select

```

Return a particle list which consists of the single particle with specified `index`. If `index` is negative, count from the end. If it is out of bounds, return an empty list.

```

<Prt lists: public>+≡
public :: prt_list_extract

<Prt lists: procedures>+≡
subroutine prt_list_extract (prt_list, pl, index)
  type(prt_list_t), intent(inout) :: prt_list
  type(prt_list_t), intent(in) :: pl
  integer, intent(in) :: index
  if (index > 0) then
    if (index <= pl%n) then
      call prt_list_reset (prt_list, 1)
      prt_list%prt(1) = pl%prt(index)
    else
      call prt_list_reset (prt_list, 0)
    end if
  else if (index < 0) then
    if (abs (index) <= pl%n) then
      call prt_list_reset (prt_list, 1)
      prt_list%prt(1) = pl%prt(pl%n + 1 + index)
    else
      call prt_list_reset (prt_list, 0)
    end if
  else
    call prt_list_reset (prt_list, 0)
  end if
end subroutine prt_list_extract

```

Return the list of particles sorted according to increasing values of the provided integer or real array. If no array is given, sort by PDG value.

```

<Prt lists: public>+≡
public :: prt_list_sort

<Prt lists: interfaces>+≡
interface prt_list_sort
  module procedure prt_list_sort_pdg
  module procedure prt_list_sort_int
  module procedure prt_list_sort_real
end interface

```

```

<Prt lists: procedures>+≡
subroutine prt_list_sort_pdg (prt_list, pl)
  type(prt_list_t), intent(inout) :: prt_list
  type(prt_list_t), intent(in) :: pl
  integer :: n
  n = prt_list%n
  call prt_list_sort_int (prt_list, pl, abs (3 * prt_list%prt(:n)%pdg - 1))
end subroutine prt_list_sort_pdg

subroutine prt_list_sort_int (prt_list, pl, ival)
  type(prt_list_t), intent(inout) :: prt_list
  type(prt_list_t), intent(in) :: pl
  integer, dimension(:), intent(in) :: ival
  call prt_list_reset (prt_list, pl%n)
  prt_list%n = pl%n
  prt_list%prt = pl%prt( order (ival) )
end subroutine prt_list_sort_int

subroutine prt_list_sort_real (prt_list, pl, rval)
  type(prt_list_t), intent(inout) :: prt_list
  type(prt_list_t), intent(in) :: pl
  real(default), dimension(:), intent(in) :: rval
  call prt_list_reset (prt_list, pl%n)
  prt_list%n = pl%n
  prt_list%prt = pl%prt( order (rval) )
end subroutine prt_list_sort_real

```

Return the list of particles which have any of the specified PDG codes.

The `pack` command was buggy in some gfortran versions, therefore it is unrolled. The unrolled version may be more efficient, actually.

```

<Prt lists: public>+≡
public :: prt_list_select_pdg_code

<Prt lists: procedures>+≡
subroutine prt_list_select_pdg_code (prt_list, aval, prt_list_in, prt_type)
  type(prt_list_t), intent(inout) :: prt_list
  type(pdg_array_t), intent(in) :: aval
  type(prt_list_t), intent(in) :: prt_list_in
  integer, intent(in), optional :: prt_type
  integer :: n_tot, n_match
  logical, dimension(:), allocatable :: mask
  integer :: i, j
  n_tot = prt_list_in%n
  allocate (mask (n_tot))
  forall (i = 1:n_tot) &
    mask(i) = aval .match. prt_list_in%prt(i)%pdg
  if (present (prt_type)) &
    mask = mask .and. prt_list_in%prt(:n_tot)%type == prt_type
  n_match = count (mask)
  call prt_list_reset (prt_list, n_match)
!   prt_list%prt(:n_match) = pack (prt_list_in%prt(:n_tot), mask)
  j = 0

```

```

do i = 1, n_tot
  if (mask(i)) then
    j = j + 1
    prt_list%prt(j) = prt_list_in%prt(i)
  end if
end do
end subroutine prt_list_select_pdg_code

```

5.4 Variables

The user interface deals with variables that are handled similar to full-fledged programming languages. The system will add a lot of predefined variables (model parameters, flags, etc.) that are accessible to the user by the same methods.

Variables can be of various type: logical (boolean/flag), integer, real (default precision), particle lists (used in cut expressions), arrays of PDG codes (aliases for particles), strings. Furthermore, in cut expressions we have unary and binary observables, which are used like real parameters but behave like functions.

`<variables.f90>`≡
<File header>

```

module variables

```

<Use kinds>

<Use strings>

<Use file utils>

```

  use diagnostics !NODEP!

```

```

  use lorentz !NODEP!

```

```

  use pdg_arrays

```

```

  use prt_lists

```

<Standard module head>

<Variables: public>

<Variables: parameters>

<Variables: types>

<Variables: interfaces>

```

contains

```

<Variables: procedures>

```

end module variables

```

5.4.1 Variable list entries

The expressions that we are considering here can contain not just constants, but also variables. We collect them in lists which are associated to particular

nodes in the evaluation tree.

The variables itself can be initialized, but they actually cannot be altered. However, we can initialize them with a pointer to some value elsewhere, so the value changes whenever this target is modified.

Observables are also recorded in the variable list. They are not associated to a value pointer, but to a procedure pointer. The procedure takes one or two evaluation nodes as arguments and produces an integer or a real value, so there are four types and associated procedure-pointer types.

Variable (and constant) values can be of one of the following types:

```

<Variables: parameters>≡
  integer, parameter, public :: V_NONE = 0, V_LOG = 1, V_INT = 2, V_REAL = 3
  integer, parameter, public :: V_CMPLX = 4, V_PTL = 5, V_PDG = 6, V_STR = 7
  integer, parameter, public :: V_OBS1_INT = 11, V_OBS2_INT = 12
  integer, parameter, public :: V_OBS1_REAL = 21, V_OBS2_REAL = 22

```

The type

This is an entry in the variable list. It can be of any type; in each case only one value is allocated. It may be physically allocated upon creation, in which case `is_allocated` is true, or it may contain just a pointer to a value somewhere else, in which case `is_allocated` is false.

The flag `is_known` is also a pointer which parallels the use of the value pointer.

The pointer `model_var` is relevant for the parameters of physics models. The global variable list contains copies of all independent parameters, which hold a pointer to the actual variable entry in the model record. The first implementation used direct pointers to this record. However, this induces a problem when during compilation of the variable list the model is undefined. This could happen if the model definition is inside a conditional. The current implementation allows for cleanly switching the underlying model when the command list is executed.

```

<Variables: public>≡
  public :: var_entry_t

<Variables: types>≡
  type :: var_entry_t
  private
    integer :: type = V_NONE
    type(string_t) :: name
    logical :: is_allocated = .false.
    logical :: is_locked = .false.
    logical :: is_copy = .false.
    logical :: is_intrinsic = .false.
    type(var_entry_t), pointer :: original => null ()
    logical, pointer :: is_known => null ()
    logical, pointer :: lval => null ()
    integer, pointer :: ival => null ()
    real(default), pointer :: rval => null ()
    complex(default), pointer :: cval => null ()
    type(prt_list_t), pointer :: pval => null ()
    type(pdg_array_t), pointer :: aval => null ()

```

```

type(string_t),    pointer :: sval => null ()
procedure(obs_unary_int),    nopass, pointer :: obs1_int  => null ()
procedure(obs_unary_real),    nopass, pointer :: obs1_real => null ()
procedure(obs_binary_int),    nopass, pointer :: obs2_int  => null ()
procedure(obs_binary_real),    nopass, pointer :: obs2_real => null ()
type(prt_t), pointer :: prt1 => null ()
type(prt_t), pointer :: prt2 => null ()
type(var_entry_t), pointer :: next => null ()
end type var_entry_t

```

Interfaces for the observable functions

```

<Variables: public>+≡
public :: obs_unary_int
public :: obs_unary_real
public :: obs_binary_int
public :: obs_binary_real

<Variables: interfaces>≡
abstract interface
  function obs_unary_int (prt1) result (ival)
    import
    integer :: ival
    type(prt_t), intent(in) :: prt1
  end function obs_unary_int
end interface
abstract interface
  function obs_unary_real (prt1) result (rval)
    import
    real(default) :: rval
    type(prt_t), intent(in) :: prt1
  end function obs_unary_real
end interface
abstract interface
  function obs_binary_int (prt1, prt2) result (ival)
    import
    integer :: ival
    type(prt_t), intent(in) :: prt1, prt2
  end function obs_binary_int
end interface
abstract interface
  function obs_binary_real (prt1, prt2) result (rval)
    import
    real(default) :: rval
    type(prt_t), intent(in) :: prt1, prt2
  end function obs_binary_real
end interface

```

Initialization

Initialize an entry, optionally with a physical value. We also allocate the `is_known` flag and set it if the value is set.

```

{Variables: procedures}≡
subroutine var_entry_init_log (var, name, lval, intrinsic)
  type(var_entry_t), intent(out) :: var
  type(string_t), intent(in) :: name
  logical, intent(in), optional :: lval
  logical, intent(in), optional :: intrinsic
  var%name = name
  var%type = V_LOG
  allocate (var%lval, var%is_known)
  if (present (lval)) then
    var%lval = lval
    var%is_known = .true.
  else
    var%is_known = .false.
  end if
  if (present (intrinsic)) var%is_intrinsic = intrinsic
  var%is_allocated = .true.
end subroutine var_entry_init_log

subroutine var_entry_init_int (var, name, ival, intrinsic)
  type(var_entry_t), intent(out) :: var
  type(string_t), intent(in) :: name
  integer, intent(in), optional :: ival
  logical, intent(in), optional :: intrinsic
  var%name = name
  var%type = V_INT
  allocate (var%ival, var%is_known)
  if (present (ival)) then
    var%ival = ival
    var%is_known = .true.
  else
    var%is_known = .false.
  end if
  if (present (intrinsic)) var%is_intrinsic = intrinsic
  var%is_allocated = .true.
end subroutine var_entry_init_int

subroutine var_entry_init_real (var, name, rval, intrinsic)
  type(var_entry_t), intent(out) :: var
  type(string_t), intent(in) :: name
  real(default), intent(in), optional :: rval
  logical, intent(in), optional :: intrinsic
  var%name = name
  var%type = V_REAL
  allocate (var%rval, var%is_known)
  if (present (rval)) then
    var%rval = rval
    var%is_known = .true.
  else
    var%is_known = .false.
  end if
  if (present (intrinsic)) var%is_intrinsic = intrinsic
  var%is_allocated = .true.
end subroutine var_entry_init_real

```

```

subroutine var_entry_init_cmplx (var, name, cval, intrinsic)
  type(var_entry_t), intent(out) :: var
  type(string_t), intent(in) :: name
  complex(default), intent(in), optional :: cval
  logical, intent(in), optional :: intrinsic
  var%name = name
  var%type = V_CMPLX
  allocate (var%cval, var%is_known)
  if (present (cval)) then
    var%cval = cval
    var%is_known = .true.
  else
    var%is_known = .false.
  end if
  if (present (intrinsic)) var%is_intrinsic = intrinsic
  var%is_allocated = .true.
end subroutine var_entry_init_cmplx

subroutine var_entry_init_prt_list (var, name, pval, intrinsic)
  type(var_entry_t), intent(out) :: var
  type(string_t), intent(in) :: name
  type(prt_list_t), intent(in), optional :: pval
  logical, intent(in), optional :: intrinsic
  var%name = name
  var%type = V_PTL
  allocate (var%pval, var%is_known)
  if (present (pval)) then
    var%pval = pval
    var%is_known = .true.
  else
    var%is_known = .false.
  end if
  if (present (intrinsic)) var%is_intrinsic = intrinsic
  var%is_allocated = .true.
end subroutine var_entry_init_prt_list

subroutine var_entry_init_pdg_array (var, name, aval, intrinsic)
  type(var_entry_t), intent(out) :: var
  type(string_t), intent(in) :: name
  type(pdg_array_t), intent(in), optional :: aval
  logical, intent(in), optional :: intrinsic
  var%name = name
  var%type = V_PDG
  allocate (var%aval, var%is_known)
  if (present (aval)) then
    var%aval = aval
    var%is_known = .true.
  else
    var%is_known = .false.
  end if
  if (present (intrinsic)) var%is_intrinsic = intrinsic
  var%is_allocated = .true.
end subroutine var_entry_init_pdg_array

```

```

subroutine var_entry_init_string (var, name, sval, intrinsic)
  type(var_entry_t), intent(out) :: var
  type(string_t), intent(in) :: name
  type(string_t), intent(in), optional :: sval
  logical, intent(in), optional :: intrinsic
  var%name = name
  var%type = V_STR
  allocate (var%sval, var%is_known)
  if (present (sval)) then
    var%sval = sval
    var%is_known = .true.
  else
    var%is_known = .false.
  end if
  if (present (intrinsic)) var%is_intrinsic = intrinsic
  var%is_allocated = .true.
end subroutine var_entry_init_string

```

Initialize an entry with a pointer to the value and, for numeric/logical values, a pointer to the is_known flag.

(Variables: public)+≡

```

public :: var_entry_init_log_ptr
public :: var_entry_init_int_ptr
public :: var_entry_init_real_ptr
public :: var_entry_init_cmplx_ptr
public :: var_entry_init_pdg_array_ptr
public :: var_entry_init_prt_list_ptr
public :: var_entry_init_string_ptr

```

(Variables: procedures)+≡

```

subroutine var_entry_init_log_ptr (var, name, lval, is_known, intrinsic)
  type(var_entry_t), intent(out) :: var
  type(string_t), intent(in) :: name
  logical, intent(in), target :: lval
  logical, intent(in), target :: is_known
  logical, intent(in), optional :: intrinsic
  var%name = name
  var%type = V_LOG
  var%lval => lval
  var%is_known => is_known
  if (present (intrinsic)) var%is_intrinsic = intrinsic
end subroutine var_entry_init_log_ptr

```

```

subroutine var_entry_init_int_ptr (var, name, ival, is_known, intrinsic)
  type(var_entry_t), intent(out) :: var
  type(string_t), intent(in) :: name
  integer, intent(in), target :: ival
  logical, intent(in), target :: is_known
  logical, intent(in), optional :: intrinsic
  var%name = name
  var%type = V_INT
  var%ival => ival
  var%is_known => is_known

```

```

        if (present (intrinsic)) var%is_intrinsic = intrinsic
    end subroutine var_entry_init_int_ptr

subroutine var_entry_init_real_ptr (var, name, rval, is_known, intrinsic)
    type(var_entry_t), intent(out) :: var
    type(string_t), intent(in) :: name
    real(default), intent(in), target :: rval
    logical, intent(in), target :: is_known
    logical, intent(in), optional :: intrinsic
    var%name = name
    var%type = V_REAL
    var%rval => rval
    var%is_known => is_known
    if (present (intrinsic)) var%is_intrinsic = intrinsic
end subroutine var_entry_init_real_ptr

subroutine var_entry_init_cmplx_ptr (var, name, cval, is_known, intrinsic)
    type(var_entry_t), intent(out) :: var
    type(string_t), intent(in) :: name
    complex(default), intent(in), target :: cval
    logical, intent(in), target :: is_known
    logical, intent(in), optional :: intrinsic
    var%name = name
    var%type = V_CMPLX
    var%cval => cval
    var%is_known => is_known
    if (present (intrinsic)) var%is_intrinsic = intrinsic
end subroutine var_entry_init_cmplx_ptr

subroutine var_entry_init_pdg_array_ptr (var, name, aval, is_known, intrinsic)
    type(var_entry_t), intent(out) :: var
    type(string_t), intent(in) :: name
    type(pdg_array_t), intent(in), target :: aval
    logical, intent(in), target :: is_known
    logical, intent(in), optional :: intrinsic
    var%name = name
    var%type = V_PDG
    var%aval => aval
    var%is_known => is_known
    if (present (intrinsic)) var%is_intrinsic = intrinsic
end subroutine var_entry_init_pdg_array_ptr

subroutine var_entry_init_prt_list_ptr (var, name, pval, is_known, intrinsic)
    type(var_entry_t), intent(out) :: var
    type(string_t), intent(in) :: name
    type(prt_list_t), intent(in), target :: pval
    logical, intent(in), target :: is_known
    logical, intent(in), optional :: intrinsic
    var%name = name
    var%type = V_PTL
    var%pval => pval
    var%is_known => is_known
    if (present (intrinsic)) var%is_intrinsic = intrinsic
end subroutine var_entry_init_prt_list_ptr

```

```

subroutine var_entry_init_string_ptr (var, name, sval, is_known, intrinsic)
  type(var_entry_t), intent(out) :: var
  type(string_t), intent(in) :: name
  type(string_t), intent(in), target :: sval
  logical, intent(in), target :: is_known
  logical, intent(in), optional :: intrinsic
  var%name = name
  var%type = V_STR
  var%sval => sval
  var%is_known => is_known
  if (present (intrinsic)) var%is_intrinsic = intrinsic
end subroutine var_entry_init_string_ptr

```

Initialize an entry with an observable. The procedure pointer is not yet set.

```

<Variables: procedures>+≡
subroutine var_entry_init_obs (var, name, type, prt1, prt2)
  type(var_entry_t), intent(out) :: var
  type(string_t), intent(in) :: name
  integer, intent(in) :: type
  type(prt_t), intent(in), target :: prt1
  type(prt_t), intent(in), optional, target :: prt2
  var%type = type
  var%name = name
  var%prt1 => prt1
  if (present (prt2)) var%prt2 => prt2
end subroutine var_entry_init_obs

```

Lock an entry: forbid resetting the entry after initialization.

```

<Variables: procedures>+≡
subroutine var_entry_lock (var, locked)
  type(var_entry_t), intent(inout) :: var
  logical, intent(in), optional :: locked
  if (present (locked)) then
    var%is_locked = locked
  else
    var%is_locked = .true.
  end if
end subroutine var_entry_lock

```

Finalizer

```

<Variables: public>+≡
public :: var_entry_final

<Variables: procedures>+≡
subroutine var_entry_final (var)
  type(var_entry_t), intent(inout) :: var
  if (var%is_allocated) then
    select case (var%type)
      case (V_LOG); deallocate (var%lval)
      case (V_INT); deallocate (var%ival)
    end select
  end if
end subroutine var_entry_final

```

```

        case (V_REAL); deallocate (var%rval)
        case (V_CMPLX); deallocate (var%cval)
        case (V_PTL); deallocate (var%pval)
        case (V_PDG); deallocate (var%aval)
        case (V_STR); deallocate (var%sval)
    end select
    deallocate (var%is_known)
    var%is_allocated = .false.
end if
end subroutine var_entry_final

```

Output

```

<Variables: public>+=
    public :: var_entry_write

<Variables: procedures>+=
    recursive subroutine var_entry_write (var, unit, model_name, show_ptr, &
        intrinsic)
        type(var_entry_t), intent(in) :: var
        integer, intent(in), optional :: unit
        type(string_t), intent(in), optional :: model_name
        logical, intent(in), optional :: show_ptr
        logical, intent(in), optional :: intrinsic
        integer :: u
        u = output_unit (unit); if (u < 0) return
        if (present (intrinsic)) then
            if (var%is_intrinsic .neqv. intrinsic) return
        end if
        if (.not. var%is_intrinsic) then
            write (u, "(A,1x)", advance="no") "[user variable]"
        end if
        if (associated (var%original)) then
            if (present (model_name)) then
                write (u, "(A,A)", advance="no") char(model_name), "."
            end if
        end if
        write (u, "(A)", advance="no") char (var%name)
        if (var%is_locked) write (u, "(A)", advance="no") "*"
        if (var%is_allocated) then
            write (u, "(A)", advance="no") " = "
        else if (var%type /= V_NONE) then
            write (u, "(A)", advance="no") " -> "
        end if
        select case (var%type)
        case (V_NONE); write (u, *)
        case (V_LOG)
            if (var%is_known) then
                if (var%lval) then
                    write (u, "(A)") "true"
                else
                    write (u, "(A)") "false"
                end if
            end if

```

```

        else
            write (u, "(A)") "[unknown logical]"
        end if
    case (V_INT)
        if (var%is_known) then
            write (u, *) var%ival
        else
            write (u, "(A)") "[unknown integer]"
        end if
    case (V_REAL)
        if (var%is_known) then
            write (u, *) var%rval
        else
            write (u, "(A)") "[unknown real]"
        end if
    case (V_CMPLX)
        if (var%is_known) then
            write (u, *) var%cval
        else
            write (u, "(A)") "[unknown complex]"
        end if
    case (V_PTL)
        if (var%is_known) then
            call prt_list_write (var%pval, unit, prefix="      ")
        else
            write (u, "(A)") "[unknown particle list]"
        end if
    case (V_PDG)
        if (var%is_known) then
            call pdg_array_write (var%aval, u); write (u, *)
        else
            write (u, "(A)") "[unknown PDG array]"
        end if
    case (V_STR)
        if (var%is_known) then
            write (u, "(A)" ' "' // char (var%sval) // "'")
        else
            write (u, "(A)") "[unknown string]"
        end if
    case (V_OBS1_INT); write (u, *) "[int] = unary observable"
    case (V_OBS2_INT); write (u, *) "[int] = binary observable"
    case (V_OBS1_REAL); write (u, *) "[real] = unary observable"
    case (V_OBS2_REAL); write (u, *) "[real] = binary observable"
end select
if (present (show_ptr)) then
    if (show_ptr .and. var%is_copy .and. associated (var%original)) then
        write (u, "(' => ')", advance="no")
        call var_entry_write (var%original, unit)
    end if
end if
end subroutine var_entry_write

```

Accessing contents

```
<Variables: public>+=  
    public :: var_entry_get_name  
    public :: var_entry_get_type  
  
<Variables: procedures>+=  
    function var_entry_get_name (var) result (name)  
        type(string_t) :: name  
        type(var_entry_t), intent(in) :: var  
        name = var%name  
    end function var_entry_get_name  
  
    function var_entry_get_type (var) result (type)  
        integer :: type  
        type(var_entry_t), intent(in) :: var  
        type = var%type  
    end function var_entry_get_type
```

Return true if the variable is locked

```
<Variables: public>+=  
    public :: var_entry_is_locked  
  
<Variables: procedures>+=  
    function var_entry_is_locked (var) result (locked)  
        logical :: locked  
        type(var_entry_t), intent(in) :: var  
        locked = var%is_locked  
    end function var_entry_is_locked
```

Return true if the variable is a copy

```
<Variables: public>+=  
    public :: var_entry_is_copy  
  
<Variables: procedures>+=  
    function var_entry_is_copy (var) result (flag)  
        logical :: flag  
        type(var_entry_t), intent(in) :: var  
        flag = var%is_copy  
    end function var_entry_is_copy
```

Return components

```
<Variables: public>+=  
    public :: var_entry_is_known  
    public :: var_entry_get_lval  
    public :: var_entry_get_ival  
    public :: var_entry_get_rval  
    public :: var_entry_get_cval  
    public :: var_entry_get_aval  
    public :: var_entry_get_pval  
    public :: var_entry_get_sval
```

```

<Variables: procedures>+=
function var_entry_is_known (var) result (flag)
    logical :: flag
    type(var_entry_t), intent(in) :: var
    flag = var%is_known
end function var_entry_is_known

function var_entry_get_lval (var) result (lval)
    logical :: lval
    type(var_entry_t), intent(in) :: var
    lval = var%lval
end function var_entry_get_lval

function var_entry_get_ival (var) result (ival)
    integer :: ival
    type(var_entry_t), intent(in) :: var
    ival = var%ival
end function var_entry_get_ival

function var_entry_get_rval (var) result (rval)
    real(default) :: rval
    type(var_entry_t), intent(in) :: var
    rval = var%rval
end function var_entry_get_rval

function var_entry_get_cval (var) result (cval)
    complex(default) :: cval
    type(var_entry_t), intent(in) :: var
    cval = var%cval
end function var_entry_get_cval

function var_entry_get_aval (var) result (aval)
    type(pdg_array_t) :: aval
    type(var_entry_t), intent(in) :: var
    aval = var%aval
end function var_entry_get_aval

function var_entry_get_pval (var) result (pval)
    type(prt_list_t) :: pval
    type(var_entry_t), intent(in) :: var
    pval = var%pval
end function var_entry_get_pval

function var_entry_get_sval (var) result (sval)
    type(string_t) :: sval
    type(var_entry_t), intent(in) :: var
    sval = var%sval
end function var_entry_get_sval

```

Return pointers to components

```

<Variables: public>+=
public :: var_entry_get_known_ptr
public :: var_entry_get_lval_ptr

```

```

public :: var_entry_get_ival_ptr
public :: var_entry_get_rval_ptr
public :: var_entry_get_cval_ptr
public :: var_entry_get_aval_ptr
public :: var_entry_get_pval_ptr
public :: var_entry_get_sval_ptr

(Variables: procedures) +=
function var_entry_get_known_ptr (var) result (ptr)
    logical, pointer :: ptr
    type(var_entry_t), intent(in), target :: var
    ptr => var%is_known
end function var_entry_get_known_ptr

function var_entry_get_lval_ptr (var) result (ptr)
    logical, pointer :: ptr
    type(var_entry_t), intent(in), target :: var
    ptr => var%lval
end function var_entry_get_lval_ptr

function var_entry_get_ival_ptr (var) result (ptr)
    integer, pointer :: ptr
    type(var_entry_t), intent(in), target :: var
    ptr => var%ival
end function var_entry_get_ival_ptr

function var_entry_get_rval_ptr (var) result (ptr)
    real(default), pointer :: ptr
    type(var_entry_t), intent(in), target :: var
    ptr => var%rval
end function var_entry_get_rval_ptr

function var_entry_get_cval_ptr (var) result (ptr)
    complex(default), pointer :: ptr
    type(var_entry_t), intent(in), target :: var
    ptr => var%cval
end function var_entry_get_cval_ptr

function var_entry_get_pval_ptr (var) result (ptr)
    type(prt_list_t), pointer :: ptr
    type(var_entry_t), intent(in), target :: var
    ptr => var%pval
end function var_entry_get_pval_ptr

function var_entry_get_aval_ptr (var) result (ptr)
    type(pdg_array_t), pointer :: ptr
    type(var_entry_t), intent(in), target :: var
    ptr => var%aval
end function var_entry_get_aval_ptr

function var_entry_get_sval_ptr (var) result (ptr)
    type(string_t), pointer :: ptr
    type(var_entry_t), intent(in), target :: var
    ptr => var%sval
end function var_entry_get_sval_ptr

```

```

<Variables: public>+=
    public :: var_entry_get_prt1_ptr
    public :: var_entry_get_prt2_ptr

<Variables: procedures>+=
    function var_entry_get_prt1_ptr (var) result (ptr)
        type(prt_t), pointer :: ptr
        type(var_entry_t), intent(in), target :: var
        ptr => var%prt1
    end function var_entry_get_prt1_ptr

    function var_entry_get_prt2_ptr (var) result (ptr)
        type(prt_t), pointer :: ptr
        type(var_entry_t), intent(in), target :: var
        ptr => var%prt2
    end function var_entry_get_prt2_ptr

```

We would like to also use functions here (for consistency), but a nagfor bug temporarily forces use to use subroutines.

```

<Variables: public>+=
    public :: var_entry_assign_obs1_int_ptr
    public :: var_entry_assign_obs1_real_ptr
    public :: var_entry_assign_obs2_int_ptr
    public :: var_entry_assign_obs2_real_ptr

<Variables: procedures>+=
    subroutine var_entry_assign_obs1_int_ptr (ptr, var)
        procedure(obs_unary_int), pointer :: ptr
        type(var_entry_t), intent(in), target :: var
        ptr => var%obs1_int
    end subroutine var_entry_assign_obs1_int_ptr

    subroutine var_entry_assign_obs1_real_ptr (ptr, var)
        procedure(obs_unary_real), pointer :: ptr
        type(var_entry_t), intent(in), target :: var
        ptr => var%obs1_real
    end subroutine var_entry_assign_obs1_real_ptr

    subroutine var_entry_assign_obs2_int_ptr (ptr, var)
        procedure(obs_binary_int), pointer :: ptr
        type(var_entry_t), intent(in), target :: var
        ptr => var%obs2_int
    end subroutine var_entry_assign_obs2_int_ptr

    subroutine var_entry_assign_obs2_real_ptr (ptr, var)
        procedure(obs_binary_real), pointer :: ptr
        type(var_entry_t), intent(in), target :: var
        ptr => var%obs2_real
    end subroutine var_entry_assign_obs2_real_ptr

```

5.4.2 Setting values

Undefine the value.

(Variables: procedures)+≡

```
subroutine var_entry_undefine (var)
  type(var_entry_t), intent(inout) :: var
  var%is_known = .false.
end subroutine var_entry_undefine
```

(Variables: public)+≡

```
public :: var_entry_set_log
public :: var_entry_set_int
public :: var_entry_set_real
public :: var_entry_set_cmplx
public :: var_entry_set_pdg_array
public :: var_entry_set_prt_list
public :: var_entry_set_string
```

(Variables: procedures)+≡

```
recursive subroutine var_entry_set_log &
  (var, lval, is_known, verbose, model_name)
  type(var_entry_t), intent(inout) :: var
  logical, intent(in) :: lval
  logical, intent(in) :: is_known
  logical, intent(in), optional :: verbose
  type(string_t), intent(in), optional :: model_name
  integer :: u
  u = logfile_unit ()
  var%lval = lval
  var%is_known = is_known
  if (associated (var%original)) then
    call var_entry_set_log (var%original, lval, is_known)
  end if
  if (present (verbose)) then
    if (verbose) then
      call var_entry_write (var, model_name=model_name)
      call var_entry_write (var, model_name=model_name, unit=u)
      flush (u)
    end if
  end if
end subroutine var_entry_set_log

recursive subroutine var_entry_set_int &
  (var, ival, is_known, verbose, model_name)
  type(var_entry_t), intent(inout) :: var
  integer, intent(in) :: ival
  logical, intent(in) :: is_known
  logical, intent(in), optional :: verbose
  type(string_t), intent(in), optional :: model_name
  integer :: u
  u = logfile_unit ()
  var%ival = ival
  var%is_known = is_known
  if (associated (var%original)) then
```

```

        call var_entry_set_int (var%original, ival, is_known)
    end if
    if (present (verbose)) then
        if (verbose) then
            call var_entry_write (var, model_name=model_name)
            call var_entry_write (var, model_name=model_name, unit=u)
            flush (u)
        end if
    end if
end subroutine var_entry_set_int

recursive subroutine var_entry_set_real &
    (var, rval, is_known, verbose, model_name)
    type(var_entry_t), intent(inout) :: var
    real(default), intent(in) :: rval
    logical, intent(in) :: is_known
    logical, intent(in), optional :: verbose
    type(string_t), intent(in), optional :: model_name
    integer :: u
    u = logfile_unit ()
    var%rval = rval
    var%is_known = is_known
    if (associated (var%original)) then
        call var_entry_set_real (var%original, rval, is_known)
    end if
    if (present (verbose)) then
        if (verbose) then
            call var_entry_write (var, model_name=model_name)
            call var_entry_write (var, model_name=model_name, unit=u)
            flush (u)
        end if
    end if
end subroutine var_entry_set_real

recursive subroutine var_entry_set_cmplx &
    (var, cval, is_known, verbose, model_name)
    type(var_entry_t), intent(inout) :: var
    complex(default), intent(in) :: cval
    logical, intent(in) :: is_known
    logical, intent(in), optional :: verbose
    type(string_t), intent(in), optional :: model_name
    integer :: u
    u = logfile_unit ()
    var%cval = cval
    var%is_known = is_known
    if (associated (var%original)) then
        call var_entry_set_cmplx (var%original, cval, is_known)
    end if
    if (present (verbose)) then
        if (verbose) then
            call var_entry_write (var, model_name=model_name)
            call var_entry_write (var, model_name=model_name, unit=u)
            flush (u)
        end if
    end if
end if

```

```

        end if
    end subroutine var_entry_set_cmplx

recursive subroutine var_entry_set_pdg_array &
    (var, aval, is_known, verbose, model_name)
    type(var_entry_t), intent(inout) :: var
    type(pdg_array_t), intent(in) :: aval
    logical, intent(in) :: is_known
    logical, intent(in), optional :: verbose
    type(string_t), intent(in), optional :: model_name
    integer :: u
    u = logfile_unit ()
    var%aval = aval
    var%is_known = is_known
    if (associated (var%original)) then
        call var_entry_set_pdg_array (var%original, aval, is_known)
    end if
    if (present (verbose)) then
        if (verbose) then
            call var_entry_write (var, model_name=model_name)
            call var_entry_write (var, model_name=model_name, unit=u)
            flush (u)
        end if
    end if
end subroutine var_entry_set_pdg_array

recursive subroutine var_entry_set_prt_list &
    (var, pval, is_known, verbose, model_name)
    type(var_entry_t), intent(inout) :: var
    type(prt_list_t), intent(in) :: pval
    logical, intent(in) :: is_known
    logical, intent(in), optional :: verbose
    type(string_t), intent(in), optional :: model_name
    integer :: u
    u = logfile_unit ()
    var%pval = pval
    var%is_known = is_known
    if (associated (var%original)) then
        call var_entry_set_prt_list (var%original, pval, is_known)
    end if
    if (present (verbose)) then
        if (verbose) then
            call var_entry_write (var, model_name=model_name)
            call var_entry_write (var, model_name=model_name, unit=u)
            flush (u)
        end if
    end if
end subroutine var_entry_set_prt_list

recursive subroutine var_entry_set_string &
    (var, sval, is_known, verbose, model_name)
    type(var_entry_t), intent(inout) :: var
    type(string_t), intent(in) :: sval
    logical, intent(in) :: is_known

```

```

logical, intent(in), optional :: verbose
type(string_t), intent(in), optional :: model_name
integer :: u
u = logfile_unit ()
var%sval = sval
var%is_known = is_known
if (associated (var%original)) then
    call var_entry_set_string (var%original, sval, is_known)
end if
if (present (verbose)) then
    if (verbose) then
        call var_entry_write (var, model_name=model_name)
        call var_entry_write (var, model_name=model_name, unit=u)
        flush (u)
    end if
end if
end subroutine var_entry_set_string

```

5.4.3 Copies and pointer variables

Initialize an entry with a copy of an existing variable entry. The copy is physically allocated with the same type as the original.

(Variables: procedures) +=

```

subroutine var_entry_init_copy (var, original)
    type(var_entry_t), intent(out) :: var
    type(var_entry_t), intent(in), target :: original
    type(string_t) :: name
    logical :: intrinsic
    name = var_entry_get_name (original)
    intrinsic = original%is_intrinsic
    select case (original%type)
    case (V_LOG)
        call var_entry_init_log (var, name, intrinsic=intrinsic)
    case (V_INT)
        call var_entry_init_int (var, name, intrinsic=intrinsic)
    case (V_REAL)
        call var_entry_init_real (var, name, intrinsic=intrinsic)
    case (V_CMPLX)
        call var_entry_init_cmplx (var, name, intrinsic=intrinsic)
    case (V_PTL)
        call var_entry_init_prt_list (var, name, intrinsic=intrinsic)
    case (V_PDG)
        call var_entry_init_pdg_array (var, name, intrinsic=intrinsic)
    case (V_STR)
        call var_entry_init_string (var, name, intrinsic=intrinsic)
    end select
    var%is_copy = .true.
end subroutine var_entry_init_copy

```

Clear the pointer to the original.

(Variables: procedures) +=

```

subroutine var_entry_clear_original_pointer (var)

```

```

    type(var_entry_t), intent(inout) :: var
    var%original => null ()
end subroutine var_entry_clear_original_pointer

```

Set the pointer to the original. For a free parameter, the variable holds both the value and the pointer. For a derived parameter, we associate the pointer directly. Derived parameters thus need not be synchronized explicitly.

Update: this does not work. If locked parameters are accessed in expressions and the model is non-default, the pointers in the expression may be undefined at compile time. Reassigning the variables at runtime does not help, since the pointers in the expression are dereferenced before assignment. Hence, no special treatment for derived parameters.

(Variables: procedures) +=

```

subroutine var_entry_set_original_pointer (var, original)
    type(var_entry_t), intent(inout) :: var
    type(var_entry_t), intent(in), target :: original
    type(string_t) :: name
    type(var_entry_t), pointer :: next
    if (var_entry_is_locked (original)) then
!       next => var%next
!       name = var_entry_get_name (original)
!       select case (original%type)
!       case (V_LOG); call var_entry_init_log_ptr (var, name, &
!           original%lval, original%is_known)
!       case (V_INT); call var_entry_init_int_ptr (var, name, &
!           original%ival, original%is_known)
!       case (V_REAL); call var_entry_init_real_ptr (var, name, &
!           original%rval, original%is_known)
!       case (V_CMPLX); call var_entry_init_cmplx_ptr (var, name, &
!           original%cval, original%is_known)
!       case (V_PTL); call var_entry_init_prt_list_ptr (var, name, &
!           original%pval, original%is_known)
!       case (V_PDG); call var_entry_init_pdg_array_ptr (var, name, &
!           original%aval, original%is_known)
!       case (V_STR); call var_entry_init_string_ptr (var, name, &
!           original%sval, original%is_known)
!       end select
!       var%next => next
        call var_entry_lock (var)
    !     else
    !       var%original => original
    end if
    var%original => original
end subroutine var_entry_set_original_pointer

```

Synchronize a variable with its original: if a pointer exists, set the value to be equal to value pointed to.

(Variables: procedures) +=

```

subroutine var_entry_synchronize (var)
    type(var_entry_t), intent(inout) :: var
    if (associated (var%original)) then
        var%is_known = var%original%is_known
    end if
end subroutine var_entry_synchronize

```

```

        if (var%original%is_known) then
            select case (var%type)
            case (V_LOG); var%lval = var%original%lval
            case (V_INT); var%ival = var%original%ival
            case (V_REAL); var%rval = var%original%rval
            case (V_CMPLX); var%cval = var%original%cval
            case (V_PTL); var%pval = var%original%pval
            case (V_PDG); var%aval = var%original%aval
            case (V_STR); var%sval = var%original%sval
            end select
        end if
    end if
end subroutine var_entry_synchronize

```

Restore the previous value of the original, using the value stored in the variable. This is a side-effect operation.

```

<Variables: procedures>+≡
subroutine var_entry_restore (var)
    type(var_entry_t), intent(in) :: var
    if (associated (var%original)) then
        if (var%is_known) then
            select case (var%type)
            case (V_LOG); var%original%lval = var%lval
            case (V_INT); var%original%ival = var%ival
            case (V_REAL); var%original%rval = var%rval
            case (V_CMPLX); var%original%cval = var%cval
            case (V_PTL); var%original%pval = var%pval
            case (V_PDG); var%original%aval = var%aval
            case (V_STR); var%original%sval = var%sval
            end select
        end if
    end if
end subroutine var_entry_restore

```

5.4.4 Variable lists

The type

Variable lists can be linked together. No initializer needed. They are deleted separately.

```

<Variables: public>+≡
    public :: var_list_t

<Variables: types>+≡
    type :: var_list_t
        private
        type(var_entry_t), pointer :: first => null ()
        type(var_entry_t), pointer :: last => null ()
        type(var_list_t), pointer :: next => null ()
    end type var_list_t

```

Constructors

```
{Variables: public}+=  
    public :: var_list_link  
{Variables: procedures}+=  
    subroutine var_list_link (var_list, next)  
        type(var_list_t), intent(inout) :: var_list  
        type(var_list_t), intent(in), target :: next  
        var_list%next => next  
    end subroutine var_list_link
```

Append a new entry to an existing list.

```
{Variables: procedures}+=  
    subroutine var_list_append (var_list, var, verbose)  
        type(var_list_t), intent(inout) :: var_list  
        type(var_entry_t), intent(in), target :: var  
        logical, intent(in), optional :: verbose  
        if (associated (var_list%last)) then  
            var_list%last%next => var  
        else  
            var_list%first => var  
        end if  
        var_list%last => var  
        if (present (verbose)) then  
            if (verbose) call var_entry_write (var)  
        end if  
    end subroutine var_list_append
```

```
{Variables: public}+=  
    public :: var_list_append_log  
    public :: var_list_append_int  
    public :: var_list_append_real  
    public :: var_list_append_cmplx  
    public :: var_list_append_prt_list  
    public :: var_list_append_pdg_array  
    public :: var_list_append_string  
{Variables: procedures}+=  
    subroutine var_list_append_log &  
        (var_list, name, lval, locked, verbose, intrinsic)  
        type(var_list_t), intent(inout) :: var_list  
        type(string_t), intent(in) :: name  
        logical, intent(in), optional :: lval  
        logical, intent(in), optional :: locked, verbose, intrinsic  
        type(var_entry_t), pointer :: var  
        allocate (var)  
        call var_entry_init_log (var, name, lval, intrinsic)  
        if (present (locked)) call var_entry_lock (var, locked)  
        call var_list_append (var_list, var, verbose)  
    end subroutine var_list_append_log  
  
    subroutine var_list_append_int &  
        (var_list, name, ival, locked, verbose, intrinsic)  
        type(var_list_t), intent(inout) :: var_list
```

```

type(string_t), intent(in) :: name
integer, intent(in), optional :: ival
logical, intent(in), optional :: locked, verbose, intrinsic
type(var_entry_t), pointer :: var
allocate (var)
call var_entry_init_int (var, name, ival, intrinsic)
if (present (locked)) call var_entry_lock (var, locked)
call var_list_append (var_list, var, verbose)
end subroutine var_list_append_int

subroutine var_list_append_real &
  (var_list, name, rval, locked, verbose, intrinsic)
type(var_list_t), intent(inout) :: var_list
type(string_t), intent(in) :: name
real(default), intent(in), optional :: rval
logical, intent(in), optional :: locked, verbose, intrinsic
type(var_entry_t), pointer :: var
allocate (var)
call var_entry_init_real (var, name, rval, intrinsic)
if (present (locked)) call var_entry_lock (var, locked)
call var_list_append (var_list, var, verbose)
end subroutine var_list_append_real

subroutine var_list_append_cmplx &
  (var_list, name, cval, locked, verbose, intrinsic)
type(var_list_t), intent(inout) :: var_list
type(string_t), intent(in) :: name
complex(default), intent(in), optional :: cval
logical, intent(in), optional :: locked, verbose, intrinsic
type(var_entry_t), pointer :: var
allocate (var)
call var_entry_init_cmplx (var, name, cval, intrinsic)
if (present (locked)) call var_entry_lock (var, locked)
call var_list_append (var_list, var, verbose)
end subroutine var_list_append_cmplx

subroutine var_list_append_prt_list &
  (var_list, name, pval, locked, verbose, intrinsic)
type(var_list_t), intent(inout) :: var_list
type(string_t), intent(in) :: name
type(prt_list_t), intent(in), optional :: pval
logical, intent(in), optional :: locked, verbose, intrinsic
type(var_entry_t), pointer :: var
allocate (var)
call var_entry_init_prt_list (var, name, pval, intrinsic)
if (present (locked)) call var_entry_lock (var, locked)
call var_list_append (var_list, var, verbose)
end subroutine var_list_append_prt_list

subroutine var_list_append_pdg_array &
  (var_list, name, aval, locked, verbose, intrinsic)
type(var_list_t), intent(inout) :: var_list
type(string_t), intent(in) :: name
type(pdg_array_t), intent(in), optional :: aval

```

```

logical, intent(in), optional :: locked, verbose, intrinsic
type(var_entry_t), pointer :: var
allocate (var)
call var_entry_init_pdg_array (var, name, aval, intrinsic)
if (present (locked)) call var_entry_lock (var, locked)
call var_list_append (var_list, var, verbose)
end subroutine var_list_append_pdg_array

```

```

subroutine var_list_append_string &
  (var_list, name, sval, locked, verbose, intrinsic)
type(var_list_t), intent(inout) :: var_list
type(string_t), intent(in) :: name
type(string_t), intent(in), optional :: sval
logical, intent(in), optional :: locked, verbose, intrinsic
type(var_entry_t), pointer :: var
allocate (var)
call var_entry_init_string (var, name, sval, intrinsic)
if (present (locked)) call var_entry_lock (var, locked)
call var_list_append (var_list, var, verbose)
end subroutine var_list_append_string

```

<Variables: public>+≡

```

public :: var_list_append_log_ptr
public :: var_list_append_int_ptr
public :: var_list_append_real_ptr
public :: var_list_append_cmplx_ptr
public :: var_list_append_pdg_array_ptr
public :: var_list_append_ptr_list_ptr
public :: var_list_append_string_ptr

```

<Variables: procedures>+≡

```

subroutine var_list_append_log_ptr &
  (var_list, name, lval, is_known, locked, verbose, intrinsic)
type(var_list_t), intent(inout) :: var_list
type(string_t), intent(in) :: name
logical, intent(in), target :: lval
logical, intent(in), target :: is_known
logical, intent(in), optional :: locked, verbose, intrinsic
type(var_entry_t), pointer :: var
allocate (var)
call var_entry_init_log_ptr (var, name, lval, is_known, intrinsic)
if (present (locked)) call var_entry_lock (var, locked)
call var_list_append (var_list, var, verbose)
end subroutine var_list_append_log_ptr

```

```

subroutine var_list_append_int_ptr &
  (var_list, name, ival, is_known, locked, verbose, intrinsic)
type(var_list_t), intent(inout) :: var_list
type(string_t), intent(in) :: name
integer, intent(in), target :: ival
logical, intent(in), target :: is_known
logical, intent(in), optional :: locked, verbose, intrinsic
type(var_entry_t), pointer :: var
allocate (var)

```

```

    call var_entry_init_int_ptr (var, name, ival, is_known, intrinsic)
    if (present (locked)) call var_entry_lock (var, locked)
    call var_list_append (var_list, var, verbose)
end subroutine var_list_append_int_ptr

subroutine var_list_append_real_ptr &
    (var_list, name, rval, is_known, locked, verbose, intrinsic)
    type(var_list_t), intent(inout) :: var_list
    type(string_t), intent(in) :: name
    real(default), intent(in), target :: rval
    logical, intent(in), target :: is_known
    logical, intent(in), optional :: locked, verbose, intrinsic
    type(var_entry_t), pointer :: var
    allocate (var)
    call var_entry_init_real_ptr (var, name, rval, is_known, intrinsic)
    if (present (locked)) call var_entry_lock (var, locked)
    call var_list_append (var_list, var, verbose)
end subroutine var_list_append_real_ptr

subroutine var_list_append_cmplx_ptr &
    (var_list, name, cval, is_known, locked, verbose, intrinsic)
    type(var_list_t), intent(inout) :: var_list
    type(string_t), intent(in) :: name
    complex(default), intent(in), target :: cval
    logical, intent(in), target :: is_known
    logical, intent(in), optional :: locked, verbose, intrinsic
    type(var_entry_t), pointer :: var
    allocate (var)
    call var_entry_init_cmplx_ptr (var, name, cval, is_known, intrinsic)
    if (present (locked)) call var_entry_lock (var, locked)
    call var_list_append (var_list, var, verbose)
end subroutine var_list_append_cmplx_ptr

subroutine var_list_append_pdg_array_ptr &
    (var_list, name, aval, is_known, locked, verbose, intrinsic)
    type(var_list_t), intent(inout) :: var_list
    type(string_t), intent(in) :: name
    type(pdg_array_t), intent(in), target :: aval
    logical, intent(in), target :: is_known
    logical, intent(in), optional :: locked, verbose, intrinsic
    type(var_entry_t), pointer :: var
    allocate (var)
    call var_entry_init_pdg_array_ptr (var, name, aval, is_known, intrinsic)
    if (present (locked)) call var_entry_lock (var, locked)
    call var_list_append (var_list, var, verbose)
end subroutine var_list_append_pdg_array_ptr

subroutine var_list_append_prt_list_ptr &
    (var_list, name, pval, is_known, locked, verbose, intrinsic)
    type(var_list_t), intent(inout) :: var_list
    type(string_t), intent(in) :: name
    type(prt_list_t), intent(in), target :: pval
    logical, intent(in), target :: is_known
    logical, intent(in), optional :: locked, verbose, intrinsic

```

```

    type(var_entry_t), pointer :: var
    allocate (var)
    call var_entry_init_ptr_list_ptr (var, name, pval, is_known, intrinsic)
    if (present (locked)) call var_entry_lock (var, locked)
    call var_list_append (var_list, var, verbose)
end subroutine var_list_append_ptr_list_ptr

subroutine var_list_append_string_ptr &
    (var_list, name, sval, is_known, locked, verbose, intrinsic)
    type(var_list_t), intent(inout) :: var_list
    type(string_t), intent(in) :: name
    type(string_t), intent(in), target :: sval
    logical, intent(in), target :: is_known
    logical, intent(in), optional :: locked, verbose, intrinsic
    type(var_entry_t), pointer :: var
    allocate (var)
    call var_entry_init_string_ptr (var, name, sval, is_known, intrinsic)
    if (present (locked)) call var_entry_lock (var, locked)
    call var_list_append (var_list, var, verbose)
end subroutine var_list_append_string_ptr

```

Finalizer

<Variables: public>+≡

```
public :: var_list_final
```

Finalize, delete the list entry by entry.

<Variables: procedures>+≡

```

subroutine var_list_final (var_list)
    type(var_list_t), intent(inout) :: var_list
    type(var_entry_t), pointer :: var
    var_list%last => null ()
    do while (associated (var_list%first))
        var => var_list%first
        var_list%first => var%next
        call var_entry_final (var)
        deallocate (var)
    end do
end subroutine var_list_final

```

Output

Optionally, show only variables of a certain type.

<Variables: public>+≡

```
public :: var_list_write
```

<Variables: procedures>+≡

```

recursive subroutine var_list_write &
    (var_list, unit, follow_link, only_type, prefix, model_name, show_ptr, &
    intrinsic)
    type(var_list_t), intent(in), target :: var_list
    integer, intent(in), optional :: unit

```

```

logical, intent(in), optional :: follow_link
integer, intent(in), optional :: only_type
character(*), intent(in), optional :: prefix
type(string_t), intent(in), optional :: model_name
logical, intent(in), optional :: show_ptr
logical, intent(in), optional :: intrinsic
type(var_entry_t), pointer :: var
integer :: u, length
logical :: write_this, write_next
u = output_unit (unit); if (u < 0) return
if (present (prefix)) length = len (prefix)
var => var_list%first
if (associated (var)) then
  do while (associated (var))
    if (present (only_type)) then
      write_this = only_type == var%type
    else
      write_this = .true.
    end if
    if (write_this .and. present (prefix)) then
      if (prefix /= extract (var%name, 1, length)) &
        write_this = .false.
    end if
    if (write_this) then
      call var_entry_write &
        (var, unit, model_name = model_name, show_ptr = show_ptr, &
          intrinsic=intrinsic)
    end if
    var => var%next
  end do
end if
write_next = associated (var_list%next)
if (present (follow_link)) &
  write_next = write_next .and. follow_link
if (write_next) then
  call var_list_write (var_list%next, &
    unit, follow_link, only_type, prefix, model_name, show_ptr, &
    intrinsic)
end if
end subroutine var_list_write

```

Write only a certain variable.

{Variables: public}+≡

```
public :: var_list_write_var
```

{Variables: procedures}+≡

```

recursive subroutine var_list_write_var &
  (var_list, name, unit, type, follow_link, model_name, show_ptr)
type(var_list_t), intent(in), target :: var_list
type(string_t), intent(in) :: name
integer, intent(in), optional :: unit
integer, intent(in), optional :: type
logical, intent(in), optional :: follow_link
type(string_t), intent(in), optional :: model_name

```

```

logical, intent(in), optional :: show_ptr
type(var_entry_t), pointer :: var
integer :: u
u = output_unit (unit); if (u < 0) return
var => var_list_get_var_ptr (var_list, name, type, follow_link=follow_link)
if (associated (var)) then
    call var_entry_write &
        (var, unit, model_name = model_name, show_ptr = show_ptr)
else
    write (u, "(A)") char (name) // " = [undefined]"
end if
end subroutine var_list_write_var

```

5.4.5 Tools

Return a pointer to the variable with the requested name. If no such name exists, return a null pointer. In that case, try the next list if present.

```

<Variables: public>+≡
public :: var_list_get_var_ptr

<Variables: procedures>+≡
recursive function var_list_get_var_ptr (var_list, name, type, follow_link) &
    result (var)
    type(var_entry_t), pointer :: var
    type(var_list_t), intent(in), target :: var_list
    type(string_t), intent(in) :: name
    integer, intent(in), optional :: type
    logical, intent(in), optional :: follow_link
    logical :: search_next
    var => var_list%first
    if (present (type)) then
        do while (associated (var))
            if (var%type == type) then
                if (var%name == name) return
            end if
            var => var%next
        end do
    else
        do while (associated (var))
            if (var%name == name) return
            var => var%next
        end do
    end if
    search_next = associated (var_list%next)
    if (present (follow_link)) &
        search_next = search_next .and. follow_link
    if (search_next) &
        var => var_list_get_var_ptr (var_list%next, name, type)
end function var_list_get_var_ptr

```

Return the variable type

```

<Variables: public>+≡

```

```

    public :: var_list_get_type
  <Variables: procedures>+≡
    function var_list_get_type (var_list, name, follow_link) result (type)
      integer :: type
      type(string_t), intent(in) :: name
      type(var_list_t), intent(in), target :: var_list
      logical, intent(in), optional :: follow_link
      type(var_entry_t), pointer :: var
      var => var_list_get_var_ptr (var_list, name, follow_link=follow_link)
      if (associated (var)) then
        type = var%type
      else
        type = V_NONE
      end if
    end function var_list_get_type

```

Return true if the variable exists.

```

  <Variables: public>+≡
    public :: var_list_exists
  <Variables: procedures>+≡
    function var_list_exists (var_list, name, follow_link) result (flag)
      logical :: flag
      type(string_t), intent(in) :: name
      type(var_list_t), intent(in), target :: var_list
      logical, intent(in), optional :: follow_link
      type(var_entry_t), pointer :: var
      var => var_list_get_var_ptr (var_list, name, follow_link=follow_link)
      flag = associated (var)
    end function var_list_exists

```

Return true if the variable is declared as intrinsic.

```

  <Variables: public>+≡
    public :: var_list_is_intrinsic
  <Variables: procedures>+≡
    function var_list_is_intrinsic (var_list, name, follow_link) result (flag)
      logical :: flag
      type(string_t), intent(in) :: name
      type(var_list_t), intent(in), target :: var_list
      logical, intent(in), optional :: follow_link
      type(var_entry_t), pointer :: var
      var => var_list_get_var_ptr (var_list, name, follow_link=follow_link)
      if (associated (var)) then
        flag = var%is_intrinsic
      else
        flag = .false.
      end if
    end function var_list_is_intrinsic

```

Return true if the value is known.

```

  <Variables: public>+≡
    public :: var_list_is_known

```

```

{Variables: procedures}+=
function var_list_is_known (var_list, name, follow_link) result (flag)
    logical :: flag
    type(string_t), intent(in) :: name
    type(var_list_t), intent(in), target :: var_list
    logical, intent(in), optional :: follow_link
    type(var_entry_t), pointer :: var
    var => var_list_get_var_ptr (var_list, name, follow_link=follow_link)
    if (associated (var)) then
        flag = var%is_known
    else
        flag = .false.
    end if
end function var_list_is_known

```

Return true if the value is locked.

```

{Variables: public}+=
public :: var_list_is_locked

{Variables: procedures}+=
function var_list_is_locked (var_list, name, follow_link) result (flag)
    logical :: flag
    type(string_t), intent(in) :: name
    type(var_list_t), intent(in), target :: var_list
    logical, intent(in), optional :: follow_link
    type(var_entry_t), pointer :: var
    var => var_list_get_var_ptr (var_list, name, follow_link=follow_link)
    if (associated (var)) then
        flag = var_entry_is_locked (var)
    else
        flag = .false.
    end if
end function var_list_is_locked

```

Return the value, assuming that the type is correct:

```

{Variables: public}+=
public :: var_list_get_lval
public :: var_list_get_ival
public :: var_list_get_rval
public :: var_list_get_cval
public :: var_list_get_pval
public :: var_list_get_aval
public :: var_list_get_sval

{Variables: procedures}+=
function var_list_get_lval (var_list, name, follow_link) result (lval)
    logical :: lval
    type(string_t), intent(in) :: name
    type(var_list_t), intent(in), target :: var_list
    logical, intent(in), optional :: follow_link
    type(var_entry_t), pointer :: var
    var => var_list_get_var_ptr (var_list, name, V_LOG, follow_link)
    lval = var%lval
end function var_list_get_lval

```

```

function var_list_get_ival (var_list, name, follow_link) result (ival)
    integer :: ival
    type(string_t), intent(in) :: name
    type(var_list_t), intent(in), target :: var_list
    logical, intent(in), optional :: follow_link
    type(var_entry_t), pointer :: var
    var => var_list_get_var_ptr (var_list, name, V_INT, follow_link)
    ival = var%ival
end function var_list_get_ival

function var_list_get_rval (var_list, name, follow_link) result (rval)
    real(default) :: rval
    type(string_t), intent(in) :: name
    type(var_list_t), intent(in), target :: var_list
    logical, intent(in), optional :: follow_link
    type(var_entry_t), pointer :: var
    var => var_list_get_var_ptr (var_list, name, V_REAL, follow_link)
    rval = var%rval
end function var_list_get_rval

function var_list_get_cval (var_list, name, follow_link) result (cval)
    complex(default) :: cval
    type(string_t), intent(in) :: name
    type(var_list_t), intent(in), target :: var_list
    logical, intent(in), optional :: follow_link
    type(var_entry_t), pointer :: var
    var => var_list_get_var_ptr (var_list, name, V_CMPLX, follow_link)
    cval = var%cval
end function var_list_get_cval

function var_list_get_aval (var_list, name, follow_link) result (aval)
    type(pdg_array_t) :: aval
    type(string_t), intent(in) :: name
    type(var_list_t), intent(in), target :: var_list
    logical, intent(in), optional :: follow_link
    type(var_entry_t), pointer :: var
    var => var_list_get_var_ptr (var_list, name, V_PDG, follow_link)
    aval = var%aval
end function var_list_get_aval

function var_list_get_pval (var_list, name, follow_link) result (pval)
    type(prt_list_t) :: pval
    type(string_t), intent(in) :: name
    type(var_list_t), intent(in), target :: var_list
    logical, intent(in), optional :: follow_link
    type(var_entry_t), pointer :: var
    var => var_list_get_var_ptr (var_list, name, V_PTL, follow_link)
    pval = var%pval
end function var_list_get_pval

function var_list_get_sval (var_list, name, follow_link) result (sval)
    type(string_t) :: sval
    type(string_t), intent(in) :: name

```

```

type(var_list_t), intent(in), target :: var_list
logical, intent(in), optional :: follow_link
type(var_entry_t), pointer :: var
var => var_list_get_var_ptr (var_list, name, V_STR, follow_link)
sval = var%sval
end function var_list_get_sval

```

5.4.6 Observable initialization

Observables are formally treated as variables, which however are evaluated each time the observable is used. The arguments (pointers) to evaluate and the function are part of the variable-list entry.

The procedure pointer should be set by this subroutine. This, however, triggers a bug in nagfor 5.2(649). As a workaround, we return the variable pointer, so the pointer can be set directly.

```

<Variables: procedures>+≡
subroutine var_list_set_obs (var_list, name, type, var, prt1, prt2)
type(var_list_t), intent(inout) :: var_list
type(string_t), intent(in) :: name
integer, intent(in) :: type
type(var_entry_t), pointer :: var
type(prt_t), intent(in), target :: prt1
type(prt_t), intent(in), optional, target :: prt2
allocate (var)
call var_entry_init_obs (var, name, type, prt1, prt2)
call var_list_append (var_list, var)
end subroutine var_list_set_obs

```

Unary and binary observables are different. Most unary observables can be equally well evaluated for particle pairs. Binary observables cannot be evaluated for single particles.

```

<Variables: public>+≡
public :: var_list_set_observables_unary
public :: var_list_set_observables_binary

<Variables: procedures>+≡
subroutine var_list_set_observables_unary (var_list, prt1)
type(var_list_t), intent(inout) :: var_list
type(prt_t), intent(in), target :: prt1
type(var_entry_t), pointer :: var
call var_list_set_obs &
    (var_list, var_str ("PDG"), V_OBS1_INT, var, prt1)
var% obs1_int => obs_pdg1
call var_list_set_obs &
    (var_list, var_str ("Hel"), V_OBS1_INT, var, prt1)
var% obs1_int => obs_helicity1
call var_list_set_obs &
    (var_list, var_str ("M"), V_OBS1_REAL, var, prt1)
var% obs1_real => obs_signed_mass1
call var_list_set_obs &
    (var_list, var_str ("M2"), V_OBS1_REAL, var, prt1)
var% obs1_real => obs_mass_squared1

```

```

call var_list_set_obs &
  (var_list, var_str ("E"), V_OBS1_REAL, var, prt1)
var% obs1_real => obs_energy1
call var_list_set_obs &
  (var_list, var_str ("Px"), V_OBS1_REAL, var, prt1)
var% obs1_real => obs_px1
call var_list_set_obs &
  (var_list, var_str ("Py"), V_OBS1_REAL, var, prt1)
var% obs1_real => obs_py1
call var_list_set_obs &
  (var_list, var_str ("Pz"), V_OBS1_REAL, var, prt1)
var% obs1_real => obs_pz1
call var_list_set_obs &
  (var_list, var_str ("P"), V_OBS1_REAL, var, prt1)
var% obs1_real => obs_p1
call var_list_set_obs &
  (var_list, var_str ("Pl"), V_OBS1_REAL, var, prt1)
var% obs1_real => obs_pl1
call var_list_set_obs &
  (var_list, var_str ("Pt"), V_OBS1_REAL, var, prt1)
var% obs1_real => obs_pt1
call var_list_set_obs &
  (var_list, var_str ("Theta"), V_OBS1_REAL, var, prt1)
var% obs1_real => obs_theta1
call var_list_set_obs &
  (var_list, var_str ("Phi"), V_OBS1_REAL, var, prt1)
var% obs1_real => obs_phi1
call var_list_set_obs &
  (var_list, var_str ("Rap"), V_OBS1_REAL, var, prt1)
var% obs1_real => obs_rap1
call var_list_set_obs &
  (var_list, var_str ("Eta"), V_OBS1_REAL, var, prt1)
var% obs1_real => obs_eta1
call var_list_set_obs &
  (var_list, var_str ("Theta_RF"), V_OBS1_REAL, var, prt1)
var% obs1_real => obs_theta_rf1
call var_list_set_obs &
  (var_list, var_str ("Dist"), V_OBS1_REAL, var, prt1)
var% obs1_real => obs_dist1
end subroutine var_list_set_observables_unary

subroutine var_list_set_observables_binary (var_list, prt1, prt2)
  type(var_list_t), intent(inout) :: var_list
  type(prt_t), intent(in), target :: prt1
  type(prt_t), intent(in), optional, target :: prt2
  type(var_entry_t), pointer :: var
  call var_list_set_obs &
    (var_list, var_str ("PDG"), V_OBS2_INT, var, prt1, prt2)
  var% obs2_int => obs_pdg2
  call var_list_set_obs &
    (var_list, var_str ("Hel"), V_OBS2_INT, var, prt1, prt2)
  var% obs2_int => obs_helicity2
  call var_list_set_obs &
    (var_list, var_str ("M"), V_OBS2_REAL, var, prt1, prt2)

```

```

var% obs2_real => obs_signed_mass2
call var_list_set_obs &
    (var_list, var_str ("M2"), V_OBS2_REAL, var, prt1, prt2)
var% obs2_real => obs_mass_squared2
call var_list_set_obs &
    (var_list, var_str ("E"), V_OBS2_REAL, var, prt1, prt2)
var% obs2_real => obs_energy2
call var_list_set_obs &
    (var_list, var_str ("Px"), V_OBS2_REAL, var, prt1, prt2)
var% obs2_real => obs_px2
call var_list_set_obs &
    (var_list, var_str ("Py"), V_OBS2_REAL, var, prt1, prt2)
var% obs2_real => obs_py2
call var_list_set_obs &
    (var_list, var_str ("Pz"), V_OBS2_REAL, var, prt1, prt2)
var% obs2_real => obs_pz2
call var_list_set_obs &
    (var_list, var_str ("P"), V_OBS2_REAL, var, prt1, prt2)
var% obs2_real => obs_p2
call var_list_set_obs &
    (var_list, var_str ("Pl"), V_OBS2_REAL, var, prt1, prt2)
var% obs2_real => obs_pl2
call var_list_set_obs &
    (var_list, var_str ("Pt"), V_OBS2_REAL, var, prt1, prt2)
var% obs2_real => obs_pt2
call var_list_set_obs &
    (var_list, var_str ("Theta"), V_OBS2_REAL, var, prt1, prt2)
var% obs2_real => obs_theta2
call var_list_set_obs &
    (var_list, var_str ("Phi"), V_OBS2_REAL, var, prt1, prt2)
var% obs2_real => obs_phi2
call var_list_set_obs &
    (var_list, var_str ("Rap"), V_OBS2_REAL, var, prt1, prt2)
var% obs2_real => obs_rap2
call var_list_set_obs &
    (var_list, var_str ("Eta"), V_OBS2_REAL, var, prt1, prt2)
var% obs2_real => obs_eta2
call var_list_set_obs &
    (var_list, var_str ("Theta_RF"), V_OBS2_REAL, var, prt1, prt2)
var% obs2_real => obs_theta_rf2
call var_list_set_obs &
    (var_list, var_str ("Dist"), V_OBS2_REAL, var, prt1, prt2)
var% obs2_real => obs_dist2
end subroutine var_list_set_observables_binary

```

Check if a variable name is defined as an observable:

```

<Variables: public>+≡
    public :: string_is_observable_id

<Variables: procedures>+≡
    function string_is_observable_id (string) result (flag)
        logical :: flag
        type(string_t), intent(in) :: string
        select case (char (string))

```

```

    case ("PDG", "Hel", "M", "M2", "E", "Px", "Py", "Pz", "P", "Pl", "Pt", &
          "Theta", "Phi", "Rap", "Eta", "Theta_RF", "Dist")
        flag = .true.
    case default
        flag = .false.
    end select
end function string_is_observable_id

```

5.4.7 Observables

These are analogous to the unary and binary numeric functions listed above. An observable takes the `pval` component(s) of its one or two argument nodes and produces an integer or real value.

Integer-valued unary observables

The PDG code

```

<Variables: procedures>+=
integer function obs_pdg1 (prt1) result (pdg)
    type(prt_t), intent(in) :: prt1
    pdg = prt_get_pdg (prt1)
end function obs_pdg1

```

The helicity. The return value is meaningful only if the particle is polarized, otherwise an invalid value is returned (-9).

```

<Variables: procedures>+=
integer function obs_helicity1 (prt1) result (h)
    type(prt_t), intent(in) :: prt1
    if (prt_is_polarized (prt1)) then
        h = prt_get_helicity (prt1)
    else
        h = -9
    end if
end function obs_helicity1

```

Real-valued unary observables

The invariant mass squared, obtained from the separately stored value.

```

<Variables: procedures>+=
real(default) function obs_mass_squared1 (prt1) result (p2)
    type(prt_t), intent(in) :: prt1
    p2 = prt_get_msq (prt1)
end function obs_mass_squared1

```

The signed invariant mass, which is the signed square root of the previous observable.

```

<Variables: procedures>+=
real(default) function obs_signed_mass1 (prt1) result (m)
    type(prt_t), intent(in) :: prt1

```

```

    real(default) :: msq
    msq = prt_get_msq (prt1)
    m = sign (sqrt (abs (msq)), msq)
end function obs_signed_mass1

```

The particle energy

```

<Variables: procedures>+≡
real(default) function obs_energy1 (prt1) result (e)
    type(prt_t), intent(in) :: prt1
    e = energy (prt_get_momentum (prt1))
end function obs_energy1

```

Particle momentum (components)

```

<Variables: procedures>+≡
real(default) function obs_px1 (prt1) result (p)
    type(prt_t), intent(in) :: prt1
    p = vector4_get_component (prt_get_momentum (prt1), 1)
end function obs_px1

real(default) function obs_py1 (prt1) result (p)
    type(prt_t), intent(in) :: prt1
    p = vector4_get_component (prt_get_momentum (prt1), 2)
end function obs_py1

real(default) function obs_pz1 (prt1) result (p)
    type(prt_t), intent(in) :: prt1
    p = vector4_get_component (prt_get_momentum (prt1), 3)
end function obs_pz1

real(default) function obs_p1 (prt1) result (p)
    type(prt_t), intent(in) :: prt1
    p = space_part_norm (prt_get_momentum (prt1))
end function obs_p1

real(default) function obs_pl1 (prt1) result (p)
    type(prt_t), intent(in) :: prt1
    p = longitudinal_part (prt_get_momentum (prt1))
end function obs_pl1

real(default) function obs_pt1 (prt1) result (p)
    type(prt_t), intent(in) :: prt1
    p = transverse_part (prt_get_momentum (prt1))
end function obs_pt1

```

Polar and azimuthal angle (lab frame).

```

<Variables: procedures>+≡
real(default) function obs_theta1 (prt1) result (p)
    type(prt_t), intent(in) :: prt1
    p = polar_angle (prt_get_momentum (prt1))
end function obs_theta1

real(default) function obs_phi1 (prt1) result (p)

```

```

    type(prt_t), intent(in) :: prt1
    p = azimuthal_angle (prt_get_momentum (prt1))
end function obs_phi1

```

Rapidity and pseudorapidity

```

<Variables: procedures>+=
real(default) function obs_rap1 (prt1) result (p)
    type(prt_t), intent(in) :: prt1
    p = rapidity (prt_get_momentum (prt1))
end function obs_rap1

real(default) function obs_eta1 (prt1) result (p)
    type(prt_t), intent(in) :: prt1
    p = pseudorapidity (prt_get_momentum (prt1))
end function obs_eta1

```

Meaningless: Polar angle in the rest frame of the 2nd argument.

```

<Variables: procedures>+=
real(default) function obs_theta_rf1 (prt1) result (dist)
    type(prt_t), intent(in) :: prt1
    call msg_fatal (" 'Theta_RF' is undefined as unary observable")
    dist = 0
end function obs_theta_rf1

```

Meaningless: Distance on the η - ϕ cylinder.

```

<Variables: procedures>+=
real(default) function obs_dist1 (prt1) result (dist)
    type(prt_t), intent(in) :: prt1
    call msg_fatal (" 'Dist' is undefined as unary observable")
    dist = 0
end function obs_dist1

```

Integer-valued binary observables

These observables are meaningless as binary functions.

```

<Variables: procedures>+=
integer function obs_pdg2 (prt1, prt2) result (pdg)
    type(prt_t), intent(in) :: prt1, prt2
    call msg_fatal (" PDG_Code is undefined as binary observable")
    pdg = 0
end function obs_pdg2

integer function obs_helicity2 (prt1, prt2) result (h)
    type(prt_t), intent(in) :: prt1, prt2
    call msg_fatal (" Helicity is undefined as binary observable")
    h = 0
end function obs_helicity2

```

Real-valued binary observables

The invariant mass squared, obtained from the separately stored value.

```
< Variables: procedures >+≡
  real(default) function obs_mass_squared2 (prt1, prt2) result (p2)
    type(prt_t), intent(in) :: prt1, prt2
    type(prt_t) :: prt
    call prt_init_combine (prt, prt1, prt2)
    p2 = prt_get_msq (prt)
  end function obs_mass_squared2
```

The signed invariant mass, which is the signed square root of the previous observable.

```
< Variables: procedures >+≡
  real(default) function obs_signed_mass2 (prt1, prt2) result (m)
    type(prt_t), intent(in) :: prt1, prt2
    type(prt_t) :: prt
    real(default) :: msq
    call prt_init_combine (prt, prt1, prt2)
    msq = prt_get_msq (prt)
    m = sign (sqrt (abs (msq)), msq)
  end function obs_signed_mass2
```

The particle energy

```
< Variables: procedures >+≡
  real(default) function obs_energy2 (prt1, prt2) result (e)
    type(prt_t), intent(in) :: prt1, prt2
    type(prt_t) :: prt
    call prt_init_combine (prt, prt1, prt2)
    e = energy (prt_get_momentum (prt))
  end function obs_energy2
```

Particle momentum (components)

```
< Variables: procedures >+≡
  real(default) function obs_px2 (prt1, prt2) result (p)
    type(prt_t), intent(in) :: prt1, prt2
    type(prt_t) :: prt
    call prt_init_combine (prt, prt1, prt2)
    p = vector4_get_component (prt_get_momentum (prt), 1)
  end function obs_px2

  real(default) function obs_py2 (prt1, prt2) result (p)
    type(prt_t), intent(in) :: prt1, prt2
    type(prt_t) :: prt
    call prt_init_combine (prt, prt1, prt2)
    p = vector4_get_component (prt_get_momentum (prt), 2)
  end function obs_py2

  real(default) function obs_pz2 (prt1, prt2) result (p)
    type(prt_t), intent(in) :: prt1, prt2
    type(prt_t) :: prt
    call prt_init_combine (prt, prt1, prt2)
```

```

    p = vector4_get_component (prt_get_momentum (prt), 3)
end function obs_pz2

```

```

real(default) function obs_p2 (prt1, prt2) result (p)
    type(prt_t), intent(in) :: prt1, prt2
    type(prt_t) :: prt
    call prt_init_combine (prt, prt1, prt2)
    p = space_part_norm (prt_get_momentum (prt))
end function obs_p2

```

```

real(default) function obs_pl2 (prt1, prt2) result (p)
    type(prt_t), intent(in) :: prt1, prt2
    type(prt_t) :: prt
    call prt_init_combine (prt, prt1, prt2)
    p = longitudinal_part (prt_get_momentum (prt))
end function obs_pl2

```

```

real(default) function obs_pt2 (prt1, prt2) result (p)
    type(prt_t), intent(in) :: prt1, prt2
    type(prt_t) :: prt
    call prt_init_combine (prt, prt1, prt2)
    p = transverse_part (prt_get_momentum (prt))
end function obs_pt2

```

Enclosed angle and azimuthal distance (lab frame).

(Variables: procedures)+≡

```

real(default) function obs_theta2 (prt1, prt2) result (p)
    type(prt_t), intent(in) :: prt1, prt2
    p = enclosed_angle (prt_get_momentum (prt1), prt_get_momentum (prt2))
end function obs_theta2

```

```

real(default) function obs_phi2 (prt1, prt2) result (p)
    type(prt_t), intent(in) :: prt1, prt2
    type(prt_t) :: prt
    call prt_init_combine (prt, prt1, prt2)
    p = azimuthal_distance (prt_get_momentum (prt1), prt_get_momentum (prt2))
end function obs_phi2

```

Rapidity and pseudorapidity distance

(Variables: procedures)+≡

```

real(default) function obs_rap2 (prt1, prt2) result (p)
    type(prt_t), intent(in) :: prt1, prt2
    p = rapidity_distance &
        (prt_get_momentum (prt1), prt_get_momentum (prt2))
end function obs_rap2

```

```

real(default) function obs_eta2 (prt1, prt2) result (p)
    type(prt_t), intent(in) :: prt1, prt2
    type(prt_t) :: prt
    call prt_init_combine (prt, prt1, prt2)
    p = pseudorapidity_distance &
        (prt_get_momentum (prt1), prt_get_momentum (prt2))
end function obs_eta2

```

Polar angle in the rest frame of the 2nd argument.

```
(Variables: procedures)+≡
  real(default) function obs_theta_rf2 (prt1, prt2) result (theta)
    type(prt_t), intent(in) :: prt1, prt2
    theta = enclosed_angle_rest_frame &
      (prt_get_momentum (prt1), prt_get_momentum (prt2))
  end function obs_theta_rf2
```

Distance on the η - ϕ cylinder.

```
(Variables: procedures)+≡
  real(default) function obs_dist2 (prt1, prt2) result (dist)
    type(prt_t), intent(in) :: prt1, prt2
    dist = eta_phi_distance &
      (prt_get_momentum (prt1), prt_get_momentum (prt2))
  end function obs_dist2
```

5.4.8 API for variable lists

Set a new value. If the variable holds a pointer, this pointer is followed, e.g., a model parameter is actually set. If `ignore` is set, do nothing if the variable does not exist. If `verbose` is set, echo the new value.

```
(Variables: public)+≡
  public :: var_list_set_log
  public :: var_list_set_int
  public :: var_list_set_real
  public :: var_list_set_cmplx
  public :: var_list_set_prt_list
  public :: var_list_set_pdg_array
  public :: var_list_set_string

(Variables: procedures)+≡
  subroutine var_list_set_log &
    (var_list, name, lval, is_known, ignore, verbose, model_name)
    type(var_list_t), intent(inout), target :: var_list
    type(string_t), intent(in) :: name
    logical, intent(in) :: lval
    logical, intent(in) :: is_known
    logical, intent(in), optional :: ignore, verbose
    type(string_t), intent(in), optional :: model_name
    type(var_entry_t), pointer :: var
    var => var_list_get_var_ptr (var_list, name, V_LOG)
    if (associated (var)) then
      if (.not. var_entry_is_locked (var)) then
        select case (var%type)
          case (V_LOG)
            call var_entry_set_log (var, lval, is_known, verbose, model_name)
          case default
            call var_mismatch_error (name)
        end select
      else
        call var_locked_error (name)
      end if
    end if
```

```

        end if
    else
        call var_missing_error (name, ignore)
    end if
end subroutine var_list_set_log

subroutine var_list_set_int &
    (var_list, name, ival, is_known, ignore, verbose, model_name)
    type(var_list_t), intent(inout), target :: var_list
    type(string_t), intent(in) :: name
    integer, intent(in) :: ival
    logical, intent(in) :: is_known
    logical, intent(in), optional :: ignore, verbose
    type(string_t), intent(in), optional :: model_name
    type(var_entry_t), pointer :: var
    var => var_list_get_var_ptr (var_list, name, V_INT)
    if (associated (var)) then
        if (.not. var_entry_is_locked (var)) then
            select case (var%type)
            case (V_INT)
                call var_entry_set_int (var, ival, is_known, verbose, model_name)
            case default
                call var_mismatch_error (name)
            end select
        else
            call var_locked_error (name)
        end if
    else
        call var_missing_error (name, ignore)
    end if
end subroutine var_list_set_int

subroutine var_list_set_real &
    (var_list, name, rval, is_known, ignore, verbose, model_name)
    type(var_list_t), intent(inout), target :: var_list
    type(string_t), intent(in) :: name
    real(default), intent(in) :: rval
    logical, intent(in) :: is_known
    logical, intent(in), optional :: ignore, verbose
    type(string_t), intent(in), optional :: model_name
    type(var_entry_t), pointer :: var
    var => var_list_get_var_ptr (var_list, name, V_REAL)
    if (associated (var)) then
        if (.not. var_entry_is_locked (var)) then
            select case (var%type)
            case (V_REAL)
                call var_entry_set_real (var, rval, is_known, verbose, model_name)
            case default
                call var_mismatch_error (name)
            end select
        else
            call var_locked_error (name)
        end if
    else

```

```

        call var_missing_error (name, ignore)
    end if
end subroutine var_list_set_real

subroutine var_list_set_cmplx &
    (var_list, name, cval, is_known, ignore, verbose, model_name)
    type(var_list_t), intent(inout), target :: var_list
    type(string_t), intent(in) :: name
    complex(default), intent(in) :: cval
    logical, intent(in) :: is_known
    logical, intent(in), optional :: ignore, verbose
    type(string_t), intent(in), optional :: model_name
    type(var_entry_t), pointer :: var
    var => var_list_get_var_ptr (var_list, name, V_CMPLX)
    if (associated (var)) then
        if (.not. var_entry_is_locked (var)) then
            select case (var%type)
            case (V_CMPLX)
                call var_entry_set_cmplx (var, cval, is_known, verbose, model_name)
            case default
                call var_mismatch_error (name)
            end select
        else
            call var_locked_error (name)
        end if
    else
        call var_missing_error (name, ignore)
    end if
end subroutine var_list_set_cmplx

subroutine var_list_set_pdg_array &
    (var_list, name, aval, is_known, ignore, verbose, model_name)
    type(var_list_t), intent(inout), target :: var_list
    type(string_t), intent(in) :: name
    type(pdg_array_t), intent(in) :: aval
    logical, intent(in) :: is_known
    logical, intent(in), optional :: ignore, verbose
    type(string_t), intent(in), optional :: model_name
    type(var_entry_t), pointer :: var
    var => var_list_get_var_ptr (var_list, name, V_PDG)
    if (associated (var)) then
        if (.not. var_entry_is_locked (var)) then
            select case (var%type)
            case (V_PDG)
                call var_entry_set_pdg_array &
                    (var, aval, is_known, verbose, model_name)
            case default
                call var_mismatch_error (name)
            end select
        else
            call var_locked_error (name)
        end if
    else
        call var_missing_error (name, ignore)
    end if
end subroutine var_list_set_pdg_array

```

```

end if
end subroutine var_list_set_pdg_array

subroutine var_list_set_prt_list &
    (var_list, name, pval, is_known, ignore, verbose, model_name)
    type(var_list_t), intent(inout), target :: var_list
    type(string_t), intent(in) :: name
    type(prt_list_t), intent(in) :: pval
    logical, intent(in) :: is_known
    logical, intent(in), optional :: ignore, verbose
    type(string_t), intent(in), optional :: model_name
    type(var_entry_t), pointer :: var
    var => var_list_get_var_ptr (var_list, name, V_PTL)
    if (associated (var)) then
        if (.not. var_entry_is_locked (var)) then
            select case (var%type)
            case (V_PTL)
                call var_entry_set_prt_list &
                    (var, pval, is_known, verbose, model_name)
            case default
                call var_mismatch_error (name)
            end select
        else
            call var_locked_error (name)
        end if
    else
        call var_missing_error (name, ignore)
    end if
end subroutine var_list_set_prt_list

subroutine var_list_set_string &
    (var_list, name, sval, is_known, ignore, verbose, model_name)
    type(var_list_t), intent(inout), target :: var_list
    type(string_t), intent(in) :: name
    type(string_t), intent(in) :: sval
    logical, intent(in) :: is_known
    logical, intent(in), optional :: ignore, verbose
    type(string_t), intent(in), optional :: model_name
    type(var_entry_t), pointer :: var
    var => var_list_get_var_ptr (var_list, name, V_STR)
    if (associated (var)) then
        if (.not. var_entry_is_locked (var)) then
            select case (var%type)
            case (V_STR)
                call var_entry_set_string &
                    (var, sval, is_known, verbose, model_name)
            case default
                call var_mismatch_error (name)
            end select
        else
            call var_locked_error (name)
        end if
    else
        call var_missing_error (name, ignore)
    end if
end subroutine var_list_set_string

```

```

        end if
    end subroutine var_list_set_string

    subroutine var_mismatch_error (name)
        type(string_t), intent(in) :: name
        call msg_fatal ("Type mismatch for variable '" // char (name) // "'")
    end subroutine var_mismatch_error

    subroutine var_locked_error (name)
        type(string_t), intent(in) :: name
        call msg_error ("Variable '" // char (name) // "' is not user-definable")
    end subroutine var_locked_error

    subroutine var_missing_error (name, ignore)
        type(string_t), intent(in) :: name
        logical, intent(in), optional :: ignore
        logical :: error
        if (present (ignore)) then
            error = .not. ignore
        else
            error = .true.
        end if
        if (error) then
            call msg_fatal ("Variable '" // char (name) // "' has not been declared")
        end if
    end subroutine var_missing_error

```

5.4.9 Linking model variables

The variable list of a model can be linked to the global variable list, so the model variables become available. However, the model may change during the execution of the command list, and this is not known at compile time. So, we make a copy of all variables that can be modified by the user; this will include all variables that are present in any of the models. At runtime, the linked list and the pointers to it can be exchanged, but the global variables will stay.

Append a single model variable to the local variable list. The pointer to the original is not set (yet). Check first if it already exists; in that case, do nothing.

```

<Variables: public>+≡
    public :: var_list_init_copy

<Variables: procedures>+≡
    subroutine var_list_init_copy (var_list, model_var)
        type(var_list_t), intent(inout), target :: var_list
        type(var_entry_t), intent(in), target :: model_var
        type(var_entry_t), pointer :: var
        if (.not. var_list_exists &
            (var_list, model_var%name, follow_link = .false.)) then
            allocate (var)
            call var_entry_init_copy (var, model_var)
            call var_list_append (var_list, var)
        end if
    end subroutine var_list_init_copy

```

Append all model variables, or reuse (unset) them if they already exist. If `derived_only` is set, copy only derived parameters; these are real parameters that are locked. How should we (should we at all?) generalize this to complex parameters?

```

<Variables: public>+≡
    public :: var_list_init_copies

<Variables: procedures>+≡
    subroutine var_list_init_copies (var_list, model_vars, derived_only)
        type(var_list_t), intent(inout), target :: var_list
        type(var_list_t), intent(in) :: model_vars
        logical, intent(in), optional :: derived_only
        type(var_entry_t), pointer :: model_var, var
        type(string_t) :: name
        logical :: copy_all, locked, derived
        integer :: type
        copy_all = .true.
        if (present (derived_only)) copy_all = .not. derived_only
        model_var => model_vars%first
        do while (associated (model_var))
            name = var_entry_get_name (model_var)
            type = var_entry_get_type (model_var)
            locked = var_entry_is_locked (model_var)
            derived = type == V_REAL .and. locked
            if (copy_all .or. derived) then
                var => var_list_get_var_ptr &
                    (var_list, name, type, follow_link = .false.)
                if (associated (var)) then
                    call var_entry_undefine (var)
                else
                    allocate (var)
                    call var_entry_init_copy (var, model_var)
                    call var_list_append (var_list, var)
                end if
            end if
            model_var => model_var%next
        end do
    end subroutine var_list_init_copies

```

Clear all previously allocated pointers to some model:

```

<Variables: procedures>+≡
    subroutine var_list_clear_original_pointers (var_list)
        type(var_list_t), intent(inout) :: var_list
        type(var_entry_t), pointer :: var
        var => var_list%first
        do while (associated (var))
            call var_entry_clear_original_pointer (var)
            var => var%next
        end do
    end subroutine var_list_clear_original_pointers

```

Assign the pointer to the original for a single variable.

```

<Variables: public>+≡
    public :: var_list_set_original_pointer

<Variables: procedures>+≡
    subroutine var_list_set_original_pointer (var_list, name, model_vars)
        type(var_list_t), intent(inout) :: var_list
        type(string_t), intent(in) :: name
        type(var_list_t), intent(in), target :: model_vars
        type(var_entry_t), pointer :: var, model_var
        integer :: type
        model_var => var_list_get_var_ptr (model_vars, name)
        if (associated (model_var)) then
            type = var_entry_get_type (model_var)
            var => var_list_get_var_ptr (var_list, name, type, follow_link=.false.)
            if (associated (var)) then
                call var_entry_set_original_pointer (var, model_var)
            end if
        end if
    end subroutine var_list_set_original_pointer

```

Assign pointers to the originals for all variables in the model variable list.

```

<Variables: procedures>+≡
    subroutine var_list_set_original_pointers (var_list, model_vars)
        type(var_list_t), intent(inout) :: var_list
        type(var_list_t), intent(in), target :: model_vars
        type(var_entry_t), pointer :: var, model_var
        type(string_t) :: name
        integer :: type
        model_var => model_vars%first
        do while (associated (model_var))
            name = var_entry_get_name (model_var)
            type = var_entry_get_type (model_var)
            var => var_list_get_var_ptr (var_list, name, type, follow_link=.false.)
            if (associated (var)) then
                call var_entry_set_original_pointer (var, model_var)
            end if
            model_var => model_var%next
        end do
    end subroutine var_list_set_original_pointers

```

Synchronize the local variable list with the model variable list (which is accessed by the pointers assigned in the previous subroutine).

If `reset_pointers` is unset, do not reset pointers but just update values where a variable is a copy. Resetting pointers is done only in the local variable list.

```

<Variables: public>+≡
    public :: var_list_synchronize

<Variables: procedures>+≡
    subroutine var_list_synchronize (var_list, model_vars, reset_pointers)
        type(var_list_t), intent(inout) :: var_list
        type(var_list_t), intent(in), target :: model_vars

```

```

logical, intent(in), optional :: reset_pointers
type(var_entry_t), pointer :: var
if (present (reset_pointers)) then
  if (reset_pointers) then
    call var_list_clear_original_pointers (var_list)
    call var_list_set_original_pointers (var_list, model_vars)
  end if
end if
var => var_list%first
do while (associated (var))
  call var_entry_synchronize (var)
  var => var%next
end do
end subroutine var_list_synchronize

```

This is the inverse operation: synchronize the model variable list with the current variable list. This is necessary after discarding a local variable list.

```

<Variables: public>+≡
  public :: var_list_restore

<Variables: procedures>+≡
  recursive subroutine var_list_restore (var_list)
    type(var_list_t), intent(inout) :: var_list
    type(var_entry_t), pointer :: var
    var => var_list%first
    do while (associated (var))
      call var_entry_restore (var)
      var => var%next
    end do
  end subroutine var_list_restore

```

Make a deep copy of a variable list. The copy does not contain any pointer variables. Clear the original pointer after use, since the original may be lost when the copy is in use.

```

<Variables: public>+≡
  public :: var_list_init_snapshot

<Variables: procedures>+≡
  recursive subroutine var_list_init_snapshot (var_list, vars_in, follow_link)
    type(var_list_t), intent(out) :: var_list
    type(var_list_t), intent(in) :: vars_in
    logical, intent(in), optional :: follow_link
    type(var_entry_t), pointer :: var, var_in
    type(var_list_t), pointer :: var_list_next
    logical :: rec
    rec = .true.; if (present (follow_link)) rec = follow_link
    var_in => vars_in%first
    do while (associated (var_in))
      allocate (var)
      call var_entry_init_copy (var, var_in)
      call var_entry_set_original_pointer (var, var_in)
      call var_entry_synchronize (var)
      call var_entry_clear_original_pointer (var)
      call var_list_append (var_list, var)
    end do
  end subroutine var_list_init_snapshot

```

```

        var_in => var_in%next
    end do
    if (rec .and. associated (vars_in%next)) then
        allocate (var_list_next)
        call var_list_init_snapshot (var_list_next, vars_in%next)
        call var_list_link (var_list, var_list_next)
    end if
end subroutine var_list_init_snapshot

```

5.5 Expressions

In this module we define the structures needed to parse a user-defined expression, to compile it into an evaluation tree, and to evaluate it.

We have two flavors of expressions: one with particles and one without particles. The latter version is used for defining cut/selection criteria and for online analysis.

`<expressions.f90>`≡
<File header>

`module expressions`

<Use kinds>

<Use strings>

`use constants !NODEP!`

<Use file utils>

`use diagnostics !NODEP!`

`use lorentz !NODEP!`

`use sorting`

`use ifiles`

`use lexers`

`use syntax_rules`

`use parser`

`use analysis`

`use pdg_arrays`

`use prt_lists`

`use variables`

<Standard module head>

<Expressions: public>

<Expressions: types>

<Expressions: interfaces>

<Expressions: variables>

`contains`

<Expressions: procedures>

```
end module expressions
```

5.5.1 Tree nodes

The evaluation tree consists of branch nodes (unary and binary) and of leaf nodes, originating from a common root. The node object should be polymorphic. For the time being, polymorphism is emulated here. This means that we have to maintain all possibilities that the node may hold, including associated procedures as pointers.

The following parameter values characterize the node. Unary and binary operators have sub-nodes. The other are leaf nodes. Possible leafs are literal constants or named-parameter references.

(Expressions: types)≡

```
integer, parameter :: EN_UNKNOWN = 0, EN_UNARY = 1, EN_BINARY = 2
integer, parameter :: EN_CONSTANT = 3, EN_VARIABLE = 4
integer, parameter :: EN_CONDITIONAL = 5, EN_BLOCK = 6
integer, parameter :: EN_RECORD_CMD = 7
integer, parameter :: EN_OBS1_INT = 11, EN_OBS2_INT = 12
integer, parameter :: EN_OBS1_REAL = 21, EN_OBS2_REAL = 22
integer, parameter :: EN_PRT_FUN_UNARY = 101, EN_PRT_FUN_BINARY = 102
integer, parameter :: EN_EVAL_FUN_UNARY = 111, EN_EVAL_FUN_BINARY = 112
integer, parameter :: EN_LOG_FUN_UNARY = 121, EN_LOG_FUN_BINARY = 122
integer, parameter :: EN_INT_FUN_UNARY = 131, EN_INT_FUN_BINARY = 132
```

(Expressions: types)+≡

```
type :: eval_node_t
private
type(string_t) :: tag
integer :: type = EN_UNKNOWN
integer :: result_type = V_NONE
type(var_list_t), pointer :: var_list => null ()
type(string_t) :: var_name
logical, pointer :: value_is_known => null ()
logical,          pointer :: lval => null ()
integer,          pointer :: ival => null ()
real(default),    pointer :: rval => null ()
complex(default), pointer :: cval => null ()
type(prt_list_t), pointer :: pval => null ()
type(pdg_array_t), pointer :: aval => null ()
type(string_t),    pointer :: sval => null ()
type(eval_node_t), pointer :: arg0 => null ()
type(eval_node_t), pointer :: arg1 => null ()
type(eval_node_t), pointer :: arg2 => null ()
procedure(obs_unary_int), nopass, pointer :: obs1_int => null ()
procedure(obs_unary_real), nopass, pointer :: obs1_real => null ()
procedure(obs_binary_int), nopass, pointer :: obs2_int => null ()
procedure(obs_binary_real), nopass, pointer :: obs2_real => null ()
integer, pointer :: prt_type => null ()
integer, pointer :: index => null ()
real(default), pointer :: tolerance => null ()
type(prt_t), pointer :: prt1 => null ()
type(prt_t), pointer :: prt2 => null ()
```

```

procedure(unary_log), nopass, pointer :: op1_log => null ()
procedure(unary_int), nopass, pointer :: op1_int => null ()
procedure(unary_real), nopass, pointer :: op1_real => null ()
procedure(unary_cmplx), nopass, pointer :: op1_cmplx => null ()
procedure(unary_pdg), nopass, pointer :: op1_pdg => null ()
procedure(unary_ptl), nopass, pointer :: op1_ptl => null ()
procedure(unary_str), nopass, pointer :: op1_str => null ()
procedure(unary_cut), nopass, pointer :: op1_cut => null ()
procedure(unary_num), nopass, pointer :: op1_num => null ()
procedure(binary_log), nopass, pointer :: op2_log => null ()
procedure(binary_int), nopass, pointer :: op2_int => null ()
procedure(binary_real), nopass, pointer :: op2_real => null ()
procedure(binary_cmplx), nopass, pointer :: op2_cmplx => null ()
procedure(binary_pdg), nopass, pointer :: op2_pdg => null ()
procedure(binary_ptl), nopass, pointer :: op2_ptl => null ()
procedure(binary_str), nopass, pointer :: op2_str => null ()
procedure(binary_cut), nopass, pointer :: op2_cut => null ()
procedure(binary_num), nopass, pointer :: op2_num => null ()
end type eval_node_t

```

Finalize a node recursively. Allocated constants are deleted, pointers are ignored.

(Expressions: procedures)≡

```

recursive subroutine eval_node_final_rec (node)
  type(eval_node_t), intent(inout) :: node
  select case (node%type)
  case (EN_UNARY)
    call eval_node_final_rec (node%arg1)
  case (EN_BINARY)
    call eval_node_final_rec (node%arg1)
    call eval_node_final_rec (node%arg2)
  case (EN_CONDITIONAL)
    call eval_node_final_rec (node%arg0)
    call eval_node_final_rec (node%arg1)
    call eval_node_final_rec (node%arg2)
  case (EN_BLOCK)
    call eval_node_final_rec (node%arg0)
    call eval_node_final_rec (node%arg1)
  case (EN_PRT_FUN_UNARY, EN_EVAL_FUN_UNARY, &
        EN_LOG_FUN_UNARY, EN_INT_FUN_UNARY)
    if (associated (node%arg0)) call eval_node_final_rec (node%arg0)
    call eval_node_final_rec (node%arg1)
    deallocate (node%index)
    deallocate (node%prt1)
  case (EN_PRT_FUN_BINARY, EN_EVAL_FUN_BINARY, &
        EN_LOG_FUN_BINARY, EN_INT_FUN_BINARY)
    if (associated (node%arg0)) call eval_node_final_rec (node%arg0)
    call eval_node_final_rec (node%arg1)
    call eval_node_final_rec (node%arg2)
    deallocate (node%index)
    deallocate (node%prt1)
    deallocate (node%prt2)
  end select

```

```

select case (node%type)
case (EN_UNARY, EN_BINARY, EN_CONDITIONAL, EN_CONSTANT, EN_BLOCK, &
      EN_PRT_FUN_UNARY, EN_PRT_FUN_BINARY, &
      EN_EVAL_FUN_UNARY, EN_EVAL_FUN_BINARY, &
      EN_LOG_FUN_UNARY, EN_LOG_FUN_BINARY, &
      EN_INT_FUN_UNARY, EN_INT_FUN_BINARY)
  select case (node%result_type)
  case (V_LOG); deallocate (node%lval)
  case (V_INT); deallocate (node%ival)
  case (V_REAL); deallocate (node%rval)
  case (V_CMPLX); deallocate (node%cval)
  case (V_PTL); deallocate (node%pval)
  case (V_PDG); deallocate (node%aval)
  case (V_STR); deallocate (node%sval)
  end select
  deallocate (node%value_is_known)
end select
end subroutine eval_node_final_rec

```

Leaf nodes

Initialize a leaf node with a literal constant.

(Expressions: procedures) +=

```

subroutine eval_node_init_log (node, lval)
  type(eval_node_t), intent(out) :: node
  logical, intent(in) :: lval
  node%type = EN_CONSTANT
  node%result_type = V_LOG
  allocate (node%lval, node%value_is_known)
  node%lval = lval
  node%value_is_known = .true.
end subroutine eval_node_init_log

subroutine eval_node_init_int (node, ival)
  type(eval_node_t), intent(out) :: node
  integer, intent(in) :: ival
  node%type = EN_CONSTANT
  node%result_type = V_INT
  allocate (node%ival, node%value_is_known)
  node%ival = ival
  node%value_is_known = .true.
end subroutine eval_node_init_int

subroutine eval_node_init_real (node, rval)
  type(eval_node_t), intent(out) :: node
  real(default), intent(in) :: rval
  node%type = EN_CONSTANT
  node%result_type = V_REAL
  allocate (node%rval, node%value_is_known)
  node%rval = rval
  node%value_is_known = .true.
end subroutine eval_node_init_real

```

```

subroutine eval_node_init_cmplx (node, cval)
  type(eval_node_t), intent(out) :: node
  complex(default), intent(in) :: cval
  node%type = EN_CONSTANT
  node%result_type = V_CMPLX
  allocate (node%cval, node%value_is_known)
  node%cval = cval
  node%value_is_known = .true.
end subroutine eval_node_init_cmplx

subroutine eval_node_init_prt_list (node, pval)
  type(eval_node_t), intent(out) :: node
  type(prt_list_t), intent(in) :: pval
  node%type = EN_CONSTANT
  node%result_type = V_PTL
  allocate (node%pval, node%value_is_known)
  node%pval = pval
  node%value_is_known = .true.
end subroutine eval_node_init_prt_list

subroutine eval_node_init_pdg_array (node, aval)
  type(eval_node_t), intent(out) :: node
  type(pdg_array_t), intent(in) :: aval
  node%type = EN_CONSTANT
  node%result_type = V_PDG
  allocate (node%aval, node%value_is_known)
  node%aval = aval
  node%value_is_known = .true.
end subroutine eval_node_init_pdg_array

subroutine eval_node_init_string (node, sval)
  type(eval_node_t), intent(out) :: node
  type(string_t), intent(in) :: sval
  node%type = EN_CONSTANT
  node%result_type = V_STR
  allocate (node%sval, node%value_is_known)
  node%sval = sval
  node%value_is_known = .true.
end subroutine eval_node_init_string

```

Initialize a leaf node with a pointer to a named parameter

(*Expressions: procedures*) + ≡

```

subroutine eval_node_init_log_ptr (node, name, lval, is_known)
  type(eval_node_t), intent(out) :: node
  type(string_t), intent(in) :: name
  logical, intent(in), target :: lval
  logical, intent(in), target :: is_known
  node%type = EN_VARIABLE
  node%tag = name
  node%result_type = V_LOG
  node%lval => lval
  node%value_is_known => is_known
end subroutine eval_node_init_log_ptr

```

```

subroutine eval_node_init_int_ptr (node, name, ival, is_known)
  type(eval_node_t), intent(out) :: node
  type(string_t), intent(in) :: name
  integer, intent(in), target :: ival
  logical, intent(in), target :: is_known
  node%type = EN_VARIABLE
  node%tag = name
  node%result_type = V_INT
  node%ival => ival
  node%value_is_known => is_known
end subroutine eval_node_init_int_ptr

subroutine eval_node_init_real_ptr (node, name, rval, is_known)
  type(eval_node_t), intent(out) :: node
  type(string_t), intent(in) :: name
  real(default), intent(in), target :: rval
  logical, intent(in), target :: is_known
  node%type = EN_VARIABLE
  node%tag = name
  node%result_type = V_REAL
  node%rval => rval
  node%value_is_known => is_known
end subroutine eval_node_init_real_ptr

subroutine eval_node_init_cmplx_ptr (node, name, cval, is_known)
  type(eval_node_t), intent(out) :: node
  type(string_t), intent(in) :: name
  complex(default), intent(in), target :: cval
  logical, intent(in), target :: is_known
  node%type = EN_VARIABLE
  node%tag = name
  node%result_type = V_CMPLX
  node%cval => cval
  node%value_is_known => is_known
end subroutine eval_node_init_cmplx_ptr

subroutine eval_node_init_prt_list_ptr (node, name, pval, is_known)
  type(eval_node_t), intent(out) :: node
  type(string_t), intent(in) :: name
  type(prt_list_t), intent(in), target :: pval
  logical, intent(in), target :: is_known
  node%type = EN_VARIABLE
  node%tag = name
  node%result_type = V_PTL
  node%pval => pval
  node%value_is_known => is_known
end subroutine eval_node_init_prt_list_ptr

subroutine eval_node_init_pdg_array_ptr (node, name, aval, is_known)
  type(eval_node_t), intent(out) :: node
  type(string_t), intent(in) :: name
  type(pdg_array_t), intent(in), target :: aval
  logical, intent(in), target :: is_known
  node%type = EN_VARIABLE

```

```

node%tag = name
node%result_type = V_PDG
node%aval => aval
node%value_is_known => is_known
end subroutine eval_node_init_pdg_array_ptr

subroutine eval_node_init_string_ptr (node, name, sval, is_known)
type(eval_node_t), intent(out) :: node
type(string_t), intent(in) :: name
type(string_t), intent(in), target :: sval
logical, intent(in), target :: is_known
node%type = EN_VARIABLE
node%tag = name
node%result_type = V_STR
node%sval => sval
node%value_is_known => is_known
end subroutine eval_node_init_string_ptr

```

Initialize a leaf node with an observable. This includes a procedures pointer. The input is a variable entry from the stack which holds the necessary information.

(Expressions: procedures) +=

```

subroutine eval_node_init_obs (node, var)
type(eval_node_t), intent(out) :: node
type(var_entry_t), intent(in), target :: var
node%tag = var_entry_get_name (var)
select case (var_entry_get_type (var))
case (V_OBS1_INT)
node%type = EN_OBS1_INT
call var_entry_assign_obs1_int_ptr (node%obs1_int, var)
case (V_OBS2_INT)
node%type = EN_OBS2_INT
call var_entry_assign_obs2_int_ptr (node%obs2_int, var)
case (V_OBS1_REAL)
node%type = EN_OBS1_REAL
call var_entry_assign_obs1_real_ptr (node%obs1_real, var)
case (V_OBS2_REAL)
node%type = EN_OBS2_REAL
call var_entry_assign_obs2_real_ptr (node%obs2_real, var)
end select
select case (var_entry_get_type (var))
case (V_OBS1_INT, V_OBS2_INT)
node%result_type = V_INT
allocate (node%ival, node%value_is_known)
node%value_is_known = .false.
case (V_OBS1_REAL, V_OBS2_REAL)
node%result_type = V_REAL
allocate (node%rval, node%value_is_known)
node%value_is_known = .false.
end select
select case (var_entry_get_type (var))
case (V_OBS1_INT, V_OBS1_REAL)
node%prt1 => var_entry_get_prt1_ptr (var)

```

```

    case (V_OBS2_INT, V_OBS2_REAL)
        node%prt1 => var_entry_get_prt1_ptr (var)
        node%prt2 => var_entry_get_prt2_ptr (var)
    end select
end subroutine eval_node_init_obs

```

Branch nodes

Initialize a branch node, sub-nodes are given.

(Expressions: procedures)+≡

```

subroutine eval_node_init_branch (node, tag, result_type, arg1, arg2)
    type(eval_node_t), intent(out) :: node
    type(string_t), intent(in) :: tag
    integer, intent(in) :: result_type
    type(eval_node_t), intent(in), target :: arg1
    type(eval_node_t), intent(in), target, optional :: arg2
    if (present (arg2)) then
        node%type = EN_BINARY
    else
        node%type = EN_UNARY
    end if
    node%tag = tag
    node%result_type = result_type
    call eval_node_allocate_value (node)
    node%arg1 => arg1
    if (present (arg2)) node%arg2 => arg2
end subroutine eval_node_init_branch

```

Allocate the node value according to the result type. Type 'pdg array' is not listed since this is not a scalar.

(Expressions: procedures)+≡

```

subroutine eval_node_allocate_value (node)
    type(eval_node_t), intent(inout) :: node
    select case (node%result_type)
    case (V_LOG); allocate (node%lval)
    case (V_INT); allocate (node%ival)
    case (V_REAL); allocate (node%rval)
    case (V_CMPLX); allocate (node%cval)
    case (V_PDG); allocate (node%aval)
    case (V_PTL); allocate (node%pval)
        call prt_list_init (node%pval)
    case (V_STR); allocate (node%sval)
    end select
    allocate (node%value_is_known)
end subroutine eval_node_allocate_value

```

Initialize a block node which contains, in addition to the expression to be evaluated, a variable definition. The result type is not yet assigned, because we can compile the enclosed expression only after the var list is set up.

(Expressions: procedures)+≡

```

subroutine eval_node_init_block (node, var_name, var_type, var_def, var_list)

```

```

type(eval_node_t), intent(out), target :: node
type(string_t), intent(in) :: var_name
integer, intent(in) :: var_type
type(eval_node_t), intent(in), target :: var_def
type(var_list_t), intent(in), target :: var_list
type(string_t) :: name
name = var_name
node%type = EN_BLOCK
node%tag = "var_def"
node%var_name = var_name
node%arg1 => var_def
allocate (node%var_list)
call var_list_link (node%var_list, var_list)
if (var_def%type == EN_CONSTANT) then
  select case (var_type)
    case (V_LOG)
      call var_list_append_log (node%var_list, name, var_def%lval)
    case (V_INT)
      call var_list_append_int (node%var_list, name, var_def%ival)
    case (V_REAL)
      call var_list_append_real (node%var_list, name, var_def%rval)
    case (V_CMPLX)
      call var_list_append_cmplx (node%var_list, name, var_def%cval)
    case (V_PDG)
      call var_list_append_pdg_array &
        (node%var_list, name, var_def%aval)
    case (V_PTL)
      call var_list_append_prt_list &
        (node%var_list, name, var_def%pval)
    case (V_STR)
      call var_list_append_string (node%var_list, name, var_def%sval)
  end select
else
  select case (var_type)
    case (V_LOG); call var_list_append_log_ptr &
      (node%var_list, name, var_def%lval, var_def%value_is_known)
    case (V_INT); call var_list_append_int_ptr &
      (node%var_list, name, var_def%ival, var_def%value_is_known)
    case (V_REAL); call var_list_append_real_ptr &
      (node%var_list, name, var_def%rval, var_def%value_is_known)
    case (V_CMPLX); call var_list_append_cmplx_ptr &
      (node%var_list, name, var_def%cval, var_def%value_is_known)
    case (V_PDG); call var_list_append_pdg_array_ptr &
      (node%var_list, name, var_def%aval, var_def%value_is_known)
    case (V_PTL); call var_list_append_prt_list_ptr &
      (node%var_list, name, var_def%pval, var_def%value_is_known)
    case (V_STR); call var_list_append_string_ptr &
      (node%var_list, name, var_def%sval, var_def%value_is_known)
  end select
end if
end subroutine eval_node_init_block

```

Complete block initialization by assigning the expression to evaluate to `arg0`.

(Expressions: procedures) + \equiv

```

subroutine eval_node_set_expr (node, arg, result_type)
  type(eval_node_t), intent(inout) :: node
  type(eval_node_t), intent(in), target :: arg
  integer, intent(in), optional :: result_type
  if (present (result_type)) then
    node%result_type = result_type
  else
    node%result_type = arg%result_type
  end if
  call eval_node_allocate_value (node)
  node%arg0 => arg
end subroutine eval_node_set_expr

```

Initialize a conditional. There are three branches: the condition (evaluates to logical) and the two alternatives (evaluate both to the same arbitrary type).

(Expressions: procedures)+≡

```

subroutine eval_node_init_conditional (node, result_type, cond, arg1, arg2)
  type(eval_node_t), intent(out) :: node
  integer, intent(in) :: result_type
  type(eval_node_t), intent(in), target :: cond, arg1, arg2
  node%type = EN_CONDITIONAL
  node%tag = "cond"
  node%result_type = result_type
  call eval_node_allocate_value (node)
  node%arg0 => cond
  node%arg1 => arg1
  node%arg2 => arg2
end subroutine eval_node_init_conditional

```

Initialize a recording command (which evaluates to a logical constant). The first branch is the ID of the analysis object to be filled, the optional branches 1 and 2 are the values to be recorded.

(Expressions: procedures)+≡

```

subroutine eval_node_init_record_cmd (node, id, arg1, arg2)
  type(eval_node_t), intent(out) :: node
  type(eval_node_t), intent(in), target :: id
  type(eval_node_t), intent(in), optional, target :: arg1, arg2
  call eval_node_init_log (node, .true.)
  node%type = EN_RECORD_CMD
  node%tag = "record_cmd"
  node%arg0 => id
  if (present (arg1)) then
    node%arg1 => arg1
    if (present (arg2)) then
      node%arg2 => arg2
    end if
  end if
end subroutine eval_node_init_record_cmd

```

Initialize a node for operations on particle lists. The particle lists (one or two) are inserted as **arg1** and **arg2**. We allocated particle pointers as temporaries for iterating over particle lists. The procedure pointer which holds the function

to evaluate for the particle lists (e.g., combine, select) is also initialized.

(Expressions: procedures)+≡

```

subroutine eval_node_init_prt_fun_unary (node, arg1, name, proc)
  type(eval_node_t), intent(out) :: node
  type(eval_node_t), intent(in), target :: arg1
  type(string_t), intent(in) :: name
  procedure(unary_ptl) :: proc
  node%type = EN_PRT_FUN_UNARY
  node%tag = name
  node%result_type = V_PTL
  call eval_node_allocate_value (node)
  node%arg1 => arg1
  allocate (node%index)
  allocate (node%prt1)
  node%op1_ptl => proc
end subroutine eval_node_init_prt_fun_unary

subroutine eval_node_init_prt_fun_binary (node, arg1, arg2, name, proc)
  type(eval_node_t), intent(out) :: node
  type(eval_node_t), intent(in), target :: arg1, arg2
  type(string_t), intent(in) :: name
  procedure(binary_ptl) :: proc
  node%type = EN_PRT_FUN_BINARY
  node%tag = name
  node%result_type = V_PTL
  call eval_node_allocate_value (node)
  node%arg1 => arg1
  node%arg2 => arg2
  allocate (node%index)
  allocate (node%prt1)
  allocate (node%prt2)
  node%op2_ptl => proc
end subroutine eval_node_init_prt_fun_binary

```

Similar, but for particle-list functions that evaluate to a real value.

(Expressions: procedures)+≡

```

subroutine eval_node_init_eval_fun_unary (node, arg1, name)
  type(eval_node_t), intent(out) :: node
  type(eval_node_t), intent(in), target :: arg1
  type(string_t), intent(in) :: name
  node%type = EN_EVAL_FUN_UNARY
  node%tag = name
  node%result_type = V_REAL
  call eval_node_allocate_value (node)
  node%arg1 => arg1
  allocate (node%index)
  allocate (node%prt1)
end subroutine eval_node_init_eval_fun_unary

subroutine eval_node_init_eval_fun_binary (node, arg1, arg2, name)
  type(eval_node_t), intent(out) :: node
  type(eval_node_t), intent(in), target :: arg1, arg2
  type(string_t), intent(in) :: name

```

```

node%type = EN_EVAL_FUN_BINARY
node%tag = name
node%result_type = V_REAL
call eval_node_allocate_value (node)
node%arg1 => arg1
node%arg2 => arg2
allocate (node%index)
allocate (node%prt1)
allocate (node%prt2)
end subroutine eval_node_init_eval_fun_binary

```

These are for particle-list functions that evaluate to a logical value.

(Expressions: procedures)+≡

```

subroutine eval_node_init_log_fun_unary (node, arg1, name, proc)
  type(eval_node_t), intent(out) :: node
  type(eval_node_t), intent(in), target :: arg1
  type(string_t), intent(in) :: name
  procedure(unary_cut) :: proc
  node%type = EN_LOG_FUN_UNARY
  node%tag = name
  node%result_type = V_LOG
  call eval_node_allocate_value (node)
  node%arg1 => arg1
  allocate (node%index)
  allocate (node%prt1)
  node%op1_cut => proc
end subroutine eval_node_init_log_fun_unary

subroutine eval_node_init_log_fun_binary (node, arg1, arg2, name, proc)
  type(eval_node_t), intent(out) :: node
  type(eval_node_t), intent(in), target :: arg1, arg2
  type(string_t), intent(in) :: name
  procedure(binary_cut) :: proc
  node%type = EN_LOG_FUN_BINARY
  node%tag = name
  node%result_type = V_LOG
  call eval_node_allocate_value (node)
  node%arg1 => arg1
  node%arg2 => arg2
  allocate (node%index)
  allocate (node%prt1)
  allocate (node%prt2)
  node%op2_cut => proc
end subroutine eval_node_init_log_fun_binary

```

These are for particle-list functions that evaluate to an integer value.

(Expressions: procedures)+≡

```

subroutine eval_node_init_int_fun_unary (node, arg1, name, proc)
  type(eval_node_t), intent(out) :: node
  type(eval_node_t), intent(in), target :: arg1
  type(string_t), intent(in) :: name
  procedure(unary_num) :: proc
  node%type = EN_INT_FUN_UNARY

```

```

node%tag = name
node%result_type = V_INT
call eval_node_allocate_value (node)
node%arg1 => arg1
allocate (node%index)
allocate (node%prt1)
node%op1_num => proc
end subroutine eval_node_init_int_fun_unary

subroutine eval_node_init_int_fun_binary (node, arg1, arg2, name, proc)
type(eval_node_t), intent(out) :: node
type(eval_node_t), intent(in), target :: arg1, arg2
type(string_t), intent(in) :: name
procedure(binary_num) :: proc
node%type = EN_INT_FUN_BINARY
node%tag = name
node%result_type = V_INT
call eval_node_allocate_value (node)
node%arg1 => arg1
node%arg2 => arg2
allocate (node%index)
allocate (node%prt1)
allocate (node%prt2)
node%op2_num => proc
end subroutine eval_node_init_int_fun_binary

```

If particle functions depend upon a condition (or an expression is evaluated), the observables that can be evaluated for the given particles have to be thrown on the local variable stack. This is done here. Each observable is initialized with the particle pointers which have been allocated for the node.

The integer variable that is referred to by the `Index` pseudo-observable is always known when it is referred to.

(Expressions: procedures) + \equiv

```

subroutine eval_node_set_observables (node, var_list)
type(eval_node_t), intent(inout) :: node
type(var_list_t), intent(in), target :: var_list
logical, save, target :: known = .true.
allocate (node%var_list)
call var_list_link (node%var_list, var_list)
allocate (node%index)
call var_list_append_int_ptr &
  (node%var_list, var_str ("Index"), node%index, known, intrinsic=.true.)
if (.not. associated (node%prt2)) then
  call var_list_set_observables_unary &
    (node%var_list, node%prt1)
else
  call var_list_set_observables_binary &
    (node%var_list, node%prt1, node%prt2)
end if
end subroutine eval_node_set_observables

```

Output

(Expressions: procedures)+≡

```
subroutine eval_node_write (node, unit, indent)
  type(eval_node_t), intent(in) :: node
  integer, intent(in), optional :: unit
  integer, intent(in), optional :: indent
  integer :: u, ind
  u = output_unit (unit); if (u < 0) return
  ind = 0; if (present (indent)) ind = indent
  write (u, "(A)", advance="no") repeat ("| ", ind) // "o "
  select case (node%type)
  case (EN_UNARY, EN_BINARY, EN_CONDITIONAL, &
        EN_PRT_FUN_UNARY, EN_PRT_FUN_BINARY, &
        EN_EVAL_FUN_UNARY, EN_EVAL_FUN_BINARY, &
        EN_LOG_FUN_UNARY, EN_LOG_FUN_BINARY, &
        EN_INT_FUN_UNARY, EN_INT_FUN_BINARY)
    write (u, "(A)", advance="no") "[" // char (node%tag) // "]" = "
  case (EN_CONSTANT)
    write (u, "(A)", advance="no") "[const] ="
  case (EN_VARIABLE)
    write (u, "(A)", advance="no") char (node%tag) // " ->"
  case (EN_OBS1_INT, EN_OBS2_INT, EN_OBS1_REAL, EN_OBS2_REAL)
    write (u, "(A)", advance="no") char (node%tag) // " ="
  case (EN_BLOCK)
    write (u, "(A)", advance="no") "[" // char (node%tag) // "]" // &
      char (node%var_name) // " [expr] ="
  case default
    write (u, "(A)", advance="no") "[???" = "
  end select
  select case (node%result_type)
  case (V_LOG)
    if (node%value_is_known) then
      if (node%lval) then
        write (u, *) "true"
      else
        write (u, *) "false"
      end if
    else
      write (u, *) "[unknown logical]"
    end if
  case (V_INT)
    if (node%value_is_known) then
      write (u, *) node%ival
    else
      write (u, *) "[unknown integer]"
    end if
  case (V_REAL)
    if (node%value_is_known) then
      write (u, *) node%rval
    else
      write (u, *) "[unknown real]"
    end if
  case (V_CMPLX)
```

```

        if (node%value_is_known) then
            write (u, *) node%cval
        else
            write (u, *) "[unknown complex]"
        end if
    case (V_PTL)
        if (char (node%tag) == "@evt") then
            write (u, *) "[event particle list]"
        else if (node%value_is_known) then
            call prt_list_write &
                (node%pval, unit, prefix = repeat ("| ", ind + 1))
        else
            write (u, *) "[unknown particle list]"
        end if
    case (V_PDG)
        call pdg_array_write (node%aval, u); write (u, *)
    case (V_STR)
        if (node%value_is_known) then
            write (u, "(A)") ' ' // char (node%sval) // ' '
        else
            write (u, *) "[unknown string]"
        end if
    case default
        write (u, *) "[empty]"
    end select
select case (node%type)
case (EN_OBS1_INT, EN_OBS1_REAL)
    write (u, "(A,6x,A)", advance="no") repeat ("| ", ind), "prt1 ="
    call prt_write (node%prt1, unit)
case (EN_OBS2_INT, EN_OBS2_REAL)
    write (u, "(A,6x,A)", advance="no") repeat ("| ", ind), "prt1 ="
    call prt_write (node%prt1, unit)
    write (u, "(A,6x,A)", advance="no") repeat ("| ", ind), "prt2 ="
    call prt_write (node%prt2, unit)
end select
end subroutine eval_node_write

recursive subroutine eval_node_write_rec (node, unit, indent)
    type(eval_node_t), intent(in) :: node
    integer, intent(in), optional :: unit
    integer, intent(in), optional :: indent
    integer :: u, ind
    u = output_unit (unit); if (u < 0) return
    ind = 0; if (present (indent)) ind = indent
    call eval_node_write (node, unit, indent)
    select case (node%type)
    case (EN_UNARY)
        if (associated (node%arg0)) &
            call eval_node_write_rec (node%arg0, unit, ind+1)
        call eval_node_write_rec (node%arg1, unit, ind+1)
    case (EN_BINARY)
        if (associated (node%arg0)) &
            call eval_node_write_rec (node%arg0, unit, ind+1)
        call eval_node_write_rec (node%arg1, unit, ind+1)
    end select
end subroutine eval_node_write_rec

```

```

        call eval_node_write_rec (node%arg2, unit, ind+1)
case (EN_BLOCK)
    call eval_node_write_rec (node%arg1, unit, ind+1)
    call eval_node_write_rec (node%arg0, unit, ind+1)
case (EN_CONDITIONAL)
    call eval_node_write_rec (node%arg0, unit, ind+1)
    call eval_node_write_rec (node%arg1, unit, ind+1)
    call eval_node_write_rec (node%arg2, unit, ind+1)
case (EN_PRT_FUN_UNARY, EN_EVAL_FUN_UNARY, &
      EN_LOG_FUN_UNARY, EN_INT_FUN_UNARY)
    if (associated (node%arg0)) &
        call eval_node_write_rec (node%arg0, unit, ind+1)
    call eval_node_write_rec (node%arg1, unit, ind+1)
case (EN_PRT_FUN_BINARY, EN_EVAL_FUN_BINARY, &
      EN_LOG_FUN_BINARY, EN_INT_FUN_BINARY)
    if (associated (node%arg0)) &
        call eval_node_write_rec (node%arg0, unit, ind+1)
    call eval_node_write_rec (node%arg1, unit, ind+1)
    call eval_node_write_rec (node%arg2, unit, ind+1)
end select
end subroutine eval_node_write_rec

```

5.5.2 Operation types

For the operations associated to evaluation tree nodes, we define abstract interfaces for all cases.

Particles/particle lists are transferred by-reference, to avoid unnecessary copying. Therefore, subroutines instead of functions. (Furthermore, the function version of `unary_prt` triggers an obscure bug in nagfor 5.2(649) [invalid C code].)

(Expressions: interfaces)≡

```

abstract interface
    logical function unary_log (arg)
        import eval_node_t
        type(eval_node_t), intent(in) :: arg
    end function unary_log
end interface
abstract interface
    integer function unary_int (arg)
        import eval_node_t
        type(eval_node_t), intent(in) :: arg
    end function unary_int
end interface
abstract interface
    real(default) function unary_real (arg)
        import default
        import eval_node_t
        type(eval_node_t), intent(in) :: arg
    end function unary_real
end interface
abstract interface
    complex(default) function unary_cmplx (arg)

```

```

        import default
        import eval_node_t
        type(eval_node_t), intent(in) :: arg
    end function unary_cplx
end interface
abstract interface
    subroutine unary_pdg (pdg_array, arg)
        import pdg_array_t
        import eval_node_t
        type(pdg_array_t), intent(out) :: pdg_array
        type(eval_node_t), intent(in) :: arg
    end subroutine unary_pdg
end interface
abstract interface
    subroutine unary_ptl (prt_list, arg, arg0)
        import prt_list_t
        import eval_node_t
        type(prt_list_t), intent(inout) :: prt_list
        type(eval_node_t), intent(in) :: arg
        type(eval_node_t), intent(inout), optional :: arg0
    end subroutine unary_ptl
end interface
abstract interface
    subroutine unary_str (string, arg)
        import string_t
        import eval_node_t
        type(string_t), intent(out) :: string
        type(eval_node_t), intent(in) :: arg
    end subroutine unary_str
end interface
abstract interface
    logical function unary_cut (arg1, arg0)
        import eval_node_t
        type(eval_node_t), intent(in) :: arg1
        type(eval_node_t), intent(inout) :: arg0
    end function unary_cut
end interface
abstract interface
    subroutine unary_num (ival, arg1, arg0)
        import eval_node_t
        integer, intent(out) :: ival
        type(eval_node_t), intent(in) :: arg1
        type(eval_node_t), intent(inout), optional :: arg0
    end subroutine unary_num
end interface
abstract interface
    logical function binary_log (arg1, arg2)
        import eval_node_t
        type(eval_node_t), intent(in) :: arg1, arg2
    end function binary_log
end interface
abstract interface
    integer function binary_int (arg1, arg2)
        import eval_node_t

```

```

        type(eval_node_t), intent(in) :: arg1, arg2
    end function binary_int
end interface
abstract interface
    real(default) function binary_real (arg1, arg2)
        import default
        import eval_node_t
        type(eval_node_t), intent(in) :: arg1, arg2
    end function binary_real
end interface
abstract interface
    complex(default) function binary_cmplx (arg1, arg2)
        import default
        import eval_node_t
        type(eval_node_t), intent(in) :: arg1, arg2
    end function binary_cmplx
end interface
abstract interface
    subroutine binary_pdg (pdg_array, arg1, arg2)
        import pdg_array_t
        import eval_node_t
        type(pdg_array_t), intent(out) :: pdg_array
        type(eval_node_t), intent(in) :: arg1, arg2
    end subroutine binary_pdg
end interface
abstract interface
    subroutine binary_ptl (prt_list, arg1, arg2, arg0)
        import prt_list_t
        import eval_node_t
        type(prt_list_t), intent(inout) :: prt_list
        type(eval_node_t), intent(in) :: arg1, arg2
        type(eval_node_t), intent(inout), optional :: arg0
    end subroutine binary_ptl
end interface
abstract interface
    subroutine binary_str (string, arg1, arg2)
        import string_t
        import eval_node_t
        type(string_t), intent(out) :: string
        type(eval_node_t), intent(in) :: arg1, arg2
    end subroutine binary_str
end interface
abstract interface
    logical function binary_cut (arg1, arg2, arg0)
        import eval_node_t
        type(eval_node_t), intent(in) :: arg1, arg2
        type(eval_node_t), intent(inout) :: arg0
    end function binary_cut
end interface
abstract interface
    subroutine binary_num (ival, arg1, arg2, arg0)
        import eval_node_t
        integer, intent(out) :: ival
        type(eval_node_t), intent(in) :: arg1, arg2

```

```

        type(eval_node_t), intent(inout), optional :: arg0
    end subroutine binary_num
end interface

```

The following subroutines set the procedure pointer:

(Expressions: procedures)+≡

```

subroutine eval_node_set_op1_log (en, op)
    type(eval_node_t), intent(inout) :: en
    procedure(unary_log) :: op
    en%op1_log => op
end subroutine eval_node_set_op1_log

subroutine eval_node_set_op1_int (en, op)
    type(eval_node_t), intent(inout) :: en
    procedure(unary_int) :: op
    en%op1_int => op
end subroutine eval_node_set_op1_int

subroutine eval_node_set_op1_real (en, op)
    type(eval_node_t), intent(inout) :: en
    procedure(unary_real) :: op
    en%op1_real => op
end subroutine eval_node_set_op1_real

subroutine eval_node_set_op1_cmplx (en, op)
    type(eval_node_t), intent(inout) :: en
    procedure(unary_cmplx) :: op
    en%op1_cmplx => op
end subroutine eval_node_set_op1_cmplx

subroutine eval_node_set_op1_pdg (en, op)
    type(eval_node_t), intent(inout) :: en
    procedure(unary_pdg) :: op
    en%op1_pdg => op
end subroutine eval_node_set_op1_pdg

subroutine eval_node_set_op1_ptl (en, op)
    type(eval_node_t), intent(inout) :: en
    procedure(unary_ptl) :: op
    en%op1_ptl => op
end subroutine eval_node_set_op1_ptl

subroutine eval_node_set_op1_str (en, op)
    type(eval_node_t), intent(inout) :: en
    procedure(unary_str) :: op
    en%op1_str => op
end subroutine eval_node_set_op1_str

subroutine eval_node_set_op2_log (en, op)
    type(eval_node_t), intent(inout) :: en
    procedure(binary_log) :: op
    en%op2_log => op
end subroutine eval_node_set_op2_log

```

```

subroutine eval_node_set_op2_int (en, op)
  type(eval_node_t), intent(inout) :: en
  procedure(binary_int) :: op
  en%op2_int => op
end subroutine eval_node_set_op2_int

subroutine eval_node_set_op2_real (en, op)
  type(eval_node_t), intent(inout) :: en
  procedure(binary_real) :: op
  en%op2_real => op
end subroutine eval_node_set_op2_real

subroutine eval_node_set_op2_cmplx (en, op)
  type(eval_node_t), intent(inout) :: en
  procedure(binary_cmplx) :: op
  en%op2_cmplx => op
end subroutine eval_node_set_op2_cmplx

subroutine eval_node_set_op2_pdg (en, op)
  type(eval_node_t), intent(inout) :: en
  procedure(binary_pdg) :: op
  en%op2_pdg => op
end subroutine eval_node_set_op2_pdg

subroutine eval_node_set_op2_ptl (en, op)
  type(eval_node_t), intent(inout) :: en
  procedure(binary_ptl) :: op
  en%op2_ptl => op
end subroutine eval_node_set_op2_ptl

subroutine eval_node_set_op2_str (en, op)
  type(eval_node_t), intent(inout) :: en
  procedure(binary_str) :: op
  en%op2_str => op
end subroutine eval_node_set_op2_str

```

5.5.3 Specific operators

Our expression syntax contains all Fortran functions that make sense. These functions have to be provided in a form that they can be used in procedures pointers, and have the abstract interfaces above. For some intrinsic functions, we could use specific versions provided by Fortran directly. However, this has two drawbacks: (i) We should work with the values instead of the eval-nodes as argument, which complicates the interface; (ii) more importantly, the **default** real type need not be equivalent to double precision. This would, at least, introduce system dependencies. Finally, for operators there are no specific versions.

Therefore, we write wrappers for all possible functions, at the expense of some overhead.

Binary numerical functions

$\langle \textit{Expressions: procedures} \rangle + \equiv$

```

integer function add_ii (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival + en2%ival
end function add_ii
real(default) function add_ir (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival + en2%rval
end function add_ir
complex(default) function add_ic (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival + en2%cval
end function add_ic
real(default) function add_ri (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval + en2%ival
end function add_ri
complex(default) function add_ci (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%cval + en2%ival
end function add_ci
complex(default) function add_cr (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%cval + en2%rval
end function add_cr
complex(default) function add_rc (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval + en2%cval
end function add_rc
real(default) function add_rr (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval + en2%rval
end function add_rr
complex(default) function add_cc (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%cval + en2%cval
end function add_cc

integer function sub_ii (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival - en2%ival
end function sub_ii
real(default) function sub_ir (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival - en2%rval
end function sub_ir
real(default) function sub_ri (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval - en2%ival
end function sub_ri
complex(default) function sub_ic (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival - en2%cval
end function sub_ic
complex(default) function sub_ci (en1, en2) result (y)

```

```

        type(eval_node_t), intent(in) :: en1, en2
        y = en1%cval - en2%ival
    end function sub_ci
complex(default) function sub_cr (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%cval - en2%rval
end function sub_cr
complex(default) function sub_rc (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval - en2%cval
end function sub_rc
real(default) function sub_rr (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval - en2%rval
end function sub_rr
complex(default) function sub_cc (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%cval - en2%cval
end function sub_cc

integer function mul_ii (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival * en2%ival
end function mul_ii
real(default) function mul_ir (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival * en2%rval
end function mul_ir
real(default) function mul_ri (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval * en2%ival
end function mul_ri
complex(default) function mul_ic (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival * en2%cval
end function mul_ic
complex(default) function mul_ci (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%cval * en2%ival
end function mul_ci
complex(default) function mul_rc (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval * en2%cval
end function mul_rc
complex(default) function mul_cr (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%cval * en2%rval
end function mul_cr
real(default) function mul_rr (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval * en2%rval
end function mul_rr
complex(default) function mul_cc (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2

```

```

    y = en1%cval * en2%cval
end function mul_cc

integer function div_ii (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival / en2%ival
end function div_ii
real(default) function div_ir (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival / en2%rval
end function div_ir
real(default) function div_ri (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval / en2%ival
end function div_ri
complex(default) function div_ic (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival / en2%cval
end function div_ic
complex(default) function div_ci (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%cval / en2%ival
end function div_ci
complex(default) function div_rc (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval / en2%cval
end function div_rc
complex(default) function div_cr (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%cval / en2%rval
end function div_cr
real(default) function div_rr (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval / en2%rval
end function div_rr
complex(default) function div_cc (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%cval / en2%cval
end function div_cc

integer function pow_ii (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival ** en2%ival
end function pow_ii
real(default) function pow_ri (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval ** en2%ival
end function pow_ri
complex(default) function pow_ci (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%cval ** en2%ival
end function pow_ci
real(default) function pow_rr (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2

```

```

        y = en1%rval ** en2%rval
    end function pow_rr
    complex(default) function pow_cr (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = en1%cval ** en2%rval
    end function pow_cr
    complex(default) function pow_cc (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = en1%cval ** en2%cval
    end function pow_cc

    integer function max_ii (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = max (en1%ival, en2%ival)
    end function max_ii
    real(default) function max_ir (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = max (real (en1%ival, default), en2%rval)
    end function max_ir
    real(default) function max_ri (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = max (en1%rval, real (en2%ival, default))
    end function max_ri
    real(default) function max_rr (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = max (en1%rval, en2%rval)
    end function max_rr
    integer function min_ii (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = min (en1%ival, en2%ival)
    end function min_ii
    real(default) function min_ir (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = min (real (en1%ival, default), en2%rval)
    end function min_ir
    real(default) function min_ri (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = min (en1%rval, real (en2%ival, default))
    end function min_ri
    real(default) function min_rr (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = min (en1%rval, en2%rval)
    end function min_rr

    integer function mod_ii (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = mod (en1%ival, en2%ival)
    end function mod_ii
    real(default) function mod_ir (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = mod (real (en1%ival, default), en2%rval)
    end function mod_ir
    real(default) function mod_ri (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2

```

```

        y = mod (en1%rval, real (en2%ival, default))
    end function mod_ri
    real(default) function mod_rr (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = mod (en1%rval, en2%rval)
    end function mod_rr
    integer function modulo_ii (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = modulo (en1%ival, en2%ival)
    end function modulo_ii
    real(default) function modulo_ir (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = modulo (real (en1%ival, default), en2%rval)
    end function modulo_ir
    real(default) function modulo_ri (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = modulo (en1%rval, real (en2%ival, default))
    end function modulo_ri
    real(default) function modulo_rr (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = modulo (en1%rval, en2%rval)
    end function modulo_rr

```

Unary numeric functions

(Expressions: procedures)+≡

```

    real(default) function real_i (en) result (y)
        type(eval_node_t), intent(in) :: en
        y = en%ival
    end function real_i
    integer function int_r (en) result (y)
        type(eval_node_t), intent(in) :: en
        y = en%rval
    end function int_r
    complex(default) function cmplx_i (en) result (y)
        type(eval_node_t), intent(in) :: en
        y = en%ival
    end function cmplx_i
    integer function int_c (en) result (y)
        type(eval_node_t), intent(in) :: en
        y = en%cval
    end function int_c
    complex(default) function cmplx_r (en) result (y)
        type(eval_node_t), intent(in) :: en
        y = en%rval
    end function cmplx_r
    integer function nint_r (en) result (y)
        type(eval_node_t), intent(in) :: en
        y = nint (en%rval)
    end function nint_r
    integer function floor_r (en) result (y)
        type(eval_node_t), intent(in) :: en
        y = floor (en%rval)

```

```

end function floor_r
integer function ceiling_r (en) result (y)
    type(eval_node_t), intent(in) :: en
    y = ceiling (en%rval)
end function ceiling_r

integer function neg_i (en) result (y)
    type(eval_node_t), intent(in) :: en
    y = - en%ival
end function neg_i
real(default) function neg_r (en) result (y)
    type(eval_node_t), intent(in) :: en
    y = - en%rval
end function neg_r
complex(default) function neg_c (en) result (y)
    type(eval_node_t), intent(in) :: en
    y = - en%cval
end function neg_c
integer function abs_i (en) result (y)
    type(eval_node_t), intent(in) :: en
    y = abs (en%ival)
end function abs_i
real(default) function abs_r (en) result (y)
    type(eval_node_t), intent(in) :: en
    y = abs (en%rval)
end function abs_r
real(default) function abs_c (en) result (y)
    type(eval_node_t), intent(in) :: en
    y = abs (en%cval)
end function abs_c
integer function sgn_i (en) result (y)
    type(eval_node_t), intent(in) :: en
    y = sign (1, en%ival)
end function sgn_i
real(default) function sgn_r (en) result (y)
    type(eval_node_t), intent(in) :: en
    y = sign (1._default, en%rval)
end function sgn_r

real(default) function sqrt_r (en) result (y)
    type(eval_node_t), intent(in) :: en
    y = sqrt (en%rval)
end function sqrt_r
real(default) function exp_r (en) result (y)
    type(eval_node_t), intent(in) :: en
    y = exp (en%rval)
end function exp_r
real(default) function log_r (en) result (y)
    type(eval_node_t), intent(in) :: en
    y = log (en%rval)
end function log_r
real(default) function log10_r (en) result (y)
    type(eval_node_t), intent(in) :: en
    y = log10 (en%rval)

```

```

end function log10_r

complex(default) function sqrt_c (en) result (y)
  type(eval_node_t), intent(in) :: en
  y = sqrt (en%cval)
end function sqrt_c
complex(default) function exp_c (en) result (y)
  type(eval_node_t), intent(in) :: en
  y = exp (en%cval)
end function exp_c
complex(default) function log_c (en) result (y)
  type(eval_node_t), intent(in) :: en
  y = log (en%cval)
end function log_c

real(default) function sin_r (en) result (y)
  type(eval_node_t), intent(in) :: en
  y = sin (en%rval)
end function sin_r
real(default) function cos_r (en) result (y)
  type(eval_node_t), intent(in) :: en
  y = cos (en%rval)
end function cos_r
real(default) function tan_r (en) result (y)
  type(eval_node_t), intent(in) :: en
  y = tan (en%rval)
end function tan_r
real(default) function asin_r (en) result (y)
  type(eval_node_t), intent(in) :: en
  y = asin (en%rval)
end function asin_r
real(default) function acos_r (en) result (y)
  type(eval_node_t), intent(in) :: en
  y = acos (en%rval)
end function acos_r
real(default) function atan_r (en) result (y)
  type(eval_node_t), intent(in) :: en
  y = atan (en%rval)
end function atan_r

complex(default) function sin_c (en) result (y)
  type(eval_node_t), intent(in) :: en
  y = sin (en%cval)
end function sin_c
complex(default) function cos_c (en) result (y)
  type(eval_node_t), intent(in) :: en
  y = cos (en%cval)
end function cos_c

real(default) function sinh_r (en) result (y)
  type(eval_node_t), intent(in) :: en
  y = sinh (en%rval)
end function sinh_r
real(default) function cosh_r (en) result (y)

```

```

        type(eval_node_t), intent(in) :: en
        y = cosh (en%rval)
    end function cosh_r
    real(default) function tanh_r (en) result (y)
        type(eval_node_t), intent(in) :: en
        y = tanh (en%rval)
    end function tanh_r
!   real(default) function asinh_r (en) result (y)
!       type(eval_node_t), intent(in) :: en
!       y = asinh (en%rval)
!   end function asinh_r
!   real(default) function acosh_r (en) result (y)
!       type(eval_node_t), intent(in) :: en
!       y = acosh (en%rval)
!   end function acosh_r
!   real(default) function atanh_r (en) result (y)
!       type(eval_node_t), intent(in) :: en
!       y = atanh (en%rval)
!   end function atanh_r

```

Binary logical functions

Logical expressions:

(Expressions: procedures)+≡

```

    logical function or_ll (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = en1%lval .or. en2%lval
    end function or_ll
    logical function and_ll (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = en1%lval .and. en2%lval
    end function and_ll

```

Comparisons:

(Expressions: procedures)+≡

```

    logical function comp_lt_ii (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = en1%ival < en2%ival
    end function comp_lt_ii
    logical function comp_lt_ir (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = en1%ival < en2%rval
    end function comp_lt_ir
    logical function comp_lt_ri (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = en1%rval < en2%ival
    end function comp_lt_ri
    logical function comp_lt_rr (en1, en2) result (y)
        type(eval_node_t), intent(in) :: en1, en2
        y = en1%rval < en2%rval
    end function comp_lt_rr

```

```

logical function comp_gt_ii (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival > en2%ival
end function comp_gt_ii
logical function comp_gt_ir (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival > en2%rval
end function comp_gt_ir
logical function comp_gt_ri (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval > en2%ival
end function comp_gt_ri
logical function comp_gt_rr (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval > en2%rval
end function comp_gt_rr

logical function comp_le_ii (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival <= en2%ival
end function comp_le_ii
logical function comp_le_ir (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival <= en2%rval
end function comp_le_ir
logical function comp_le_ri (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval <= en2%ival
end function comp_le_ri
logical function comp_le_rr (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval <= en2%rval
end function comp_le_rr

logical function comp_ge_ii (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival >= en2%ival
end function comp_ge_ii
logical function comp_ge_ir (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival >= en2%rval
end function comp_ge_ir
logical function comp_ge_ri (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval >= en2%ival
end function comp_ge_ri
logical function comp_ge_rr (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval >= en2%rval
end function comp_ge_rr

logical function comp_eq_ii (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival == en2%ival

```

```

end function comp_eq_ii
logical function comp_eq_ir (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival == en2%rval
end function comp_eq_ir
logical function comp_eq_ri (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval == en2%ival
end function comp_eq_ri
logical function comp_eq_rr (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval == en2%rval
end function comp_eq_rr
logical function comp_eq_ss (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%sval == en2%sval
end function comp_eq_ss

logical function comp_ne_ii (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival /= en2%ival
end function comp_ne_ii
logical function comp_ne_ir (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%ival /= en2%rval
end function comp_ne_ir
logical function comp_ne_ri (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval /= en2%ival
end function comp_ne_ri
logical function comp_ne_rr (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%rval /= en2%rval
end function comp_ne_rr
logical function comp_ne_ss (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    y = en1%sval /= en2%sval
end function comp_ne_ss

logical function comp_sim_ii (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    if (associated (en1%tolerance)) then
        y = abs (en1%ival - en2%ival) <= en1%tolerance
    else
        y = en1%ival == en2%ival
    end if
end function comp_sim_ii
logical function comp_sim_ri (en1, en2) result (y)
    type(eval_node_t), intent(in) :: en1, en2
    if (associated (en1%tolerance)) then
        y = abs (en1%rval - en2%ival) <= en1%tolerance
    else
        y = en1%rval == en2%ival
    end if

```

```

end function comp_sim_ri
logical function comp_sim_ir (en1, en2) result (y)
  type(eval_node_t), intent(in) :: en1, en2
  if (associated (en1%tolerance)) then
    y = abs (en1%ival - en2%rval) <= en1%tolerance
  else
    y = en1%ival == en2%rval
  end if
end function comp_sim_ir
logical function comp_sim_rr (en1, en2) result (y)
  type(eval_node_t), intent(in) :: en1, en2
  if (associated (en1%tolerance)) then
    y = abs (en1%rval - en2%rval) <= en1%tolerance
  else
    y = en1%rval == en2%rval
  end if
end function comp_sim_rr
logical function comp_nsim_ii (en1, en2) result (y)
  type(eval_node_t), intent(in) :: en1, en2
  if (associated (en1%tolerance)) then
    y = abs (en1%ival - en2%ival) > en1%tolerance
  else
    y = en1%ival /= en2%ival
  end if
end function comp_nsim_ii
logical function comp_nsim_ri (en1, en2) result (y)
  type(eval_node_t), intent(in) :: en1, en2
  if (associated (en1%tolerance)) then
    y = abs (en1%rval - en2%ival) > en1%tolerance
  else
    y = en1%rval /= en2%ival
  end if
end function comp_nsim_ri
logical function comp_nsim_ir (en1, en2) result (y)
  type(eval_node_t), intent(in) :: en1, en2
  if (associated (en1%tolerance)) then
    y = abs (en1%ival - en2%rval) > en1%tolerance
  else
    y = en1%ival /= en2%rval
  end if
end function comp_nsim_ir
logical function comp_nsim_rr (en1, en2) result (y)
  type(eval_node_t), intent(in) :: en1, en2
  if (associated (en1%tolerance)) then
    y = abs (en1%rval - en2%rval) > en1%tolerance
  else
    y = en1%rval /= en2%rval
  end if
end function comp_nsim_rr

```

Unary logical functions

$\langle \text{Expressions: procedures} \rangle + \equiv$

```

logical function not_1 (en) result (y)
  type(eval_node_t), intent(in) :: en
  y = .not. en%lval
end function not_1

```

Unary PDG-array functions

Make a PDG-array object from an integer.

(Expressions: procedures)+≡

```

subroutine pdg_i (pdg_array, en)
  type(pdg_array_t), intent(out) :: pdg_array
  type(eval_node_t), intent(in) :: en
  pdg_array = en%ival
end subroutine pdg_i

```

Binary PDG-array functions

Concatenate two PDG-array objects.

(Expressions: procedures)+≡

```

subroutine concat_cc (pdg_array, en1, en2)
  type(pdg_array_t), intent(out) :: pdg_array
  type(eval_node_t), intent(in) :: en1, en2
  pdg_array = en1%aval // en2%aval
end subroutine concat_cc

```

Unary particle-list functions

Combine all particles of the first argument. If **en0** is present, create a mask which is true only for those particles that pass the test.

(Expressions: procedures)+≡

```

subroutine collect_p (prt_list, en1, en0)
  type(prt_list_t), intent(inout) :: prt_list
  type(eval_node_t), intent(in) :: en1
  type(eval_node_t), intent(inout), optional :: en0
  logical, dimension(:), allocatable :: mask1
  integer :: n, i
  n = prt_list_get_length (en1%pval)
  allocate (mask1 (n))
  if (present (en0)) then
    do i = 1, n
      en0%index = i
      en0%prt1 = prt_list_get_prt (en1%pval, i)
      call eval_node_evaluate (en0)
      mask1(i) = en0%lval
    end do
  else
    mask1 = .true.
  end if
  call prt_list_collect (prt_list, en1%pval, mask1)

```

```
end subroutine collect_p
```

Select all particles of the first argument. If `en0` is present, create a mask which is true only for those particles that pass the test.

(Expressions: procedures)+≡

```
subroutine select_p (prt_list, en1, en0)
  type(prt_list_t), intent(inout) :: prt_list
  type(eval_node_t), intent(in) :: en1
  type(eval_node_t), intent(inout), optional :: en0
  logical, dimension(:), allocatable :: mask1
  integer :: n, i
  n = prt_list_get_length (en1%pval)
  allocate (mask1 (n))
  if (present (en0)) then
    do i = 1, prt_list_get_length (en1%pval)
      en0%index = i
      en0%prt1 = prt_list_get_prt (en1%pval, i)
      call eval_node_evaluate (en0)
      mask1(i) = en0%lval
    end do
  else
    mask1 = .true.
  end if
  call prt_list_select (prt_list, en1%pval, mask1)
end subroutine select_p
```

Extract the particle with index given by `en0` from the argument list. Negative indices count from the end. If `en0` is absent, extract the first particle. The result is a list with a single entry, or no entries if the original list was empty or if the index is out of range.

This function has no counterpart with two arguments.

(Expressions: procedures)+≡

```
subroutine extract_p (prt_list, en1, en0)
  type(prt_list_t), intent(inout) :: prt_list
  type(eval_node_t), intent(in) :: en1
  type(eval_node_t), intent(inout), optional :: en0
  integer :: index
  if (present (en0)) then
    call eval_node_evaluate (en0)
    select case (en0%result_type)
    case (V_INT); index = en0%ival
    case default
      call eval_node_write (en0)
      call msg_fatal (" Index parameter of 'extract' must be integer.")
    end select
  else
    index = 1
  end if
  call prt_list_extract (prt_list, en1%pval, index)
end subroutine extract_p
```

Sort the particle list according to the result of evaluating `en0`. If `en0` is absent,

sort by default method (PDG code, particles before antiparticles).

(Expressions: procedures)+≡

```

subroutine sort_p (prt_list, en1, en0)
  type(prt_list_t), intent(inout) :: prt_list
  type(eval_node_t), intent(in) :: en1
  type(eval_node_t), intent(inout), optional :: en0
  integer, dimension(:), allocatable :: ival
  real(default), dimension(:), allocatable :: rval
  integer :: i, n
  n = prt_list_get_length (en1%pval)
  if (present (en0)) then
    select case (en0%result_type)
    case (V_INT); allocate (ival (n))
    case (V_REAL); allocate (rval (n))
    end select
    do i = 1, n
      en0%index = i
      en0%prt1 = prt_list_get_prt (en1%pval, i)
      call eval_node_evaluate (en0)
      select case (en0%result_type)
      case (V_INT); ival(i) = en0%ival
      case (V_REAL); rval(i) = en0%rval
      end select
    end do
    select case (en0%result_type)
    case (V_INT); call prt_list_sort (prt_list, en1%pval, ival)
    case (V_REAL); call prt_list_sort (prt_list, en1%pval, rval)
    end select
  else
    call prt_list_sort (prt_list, en1%pval)
  end if
end subroutine sort_p

```

The following functions return a logical value. `all` evaluates to true if the condition `en0` is true for all elements of the particle list. `any` and `no` are analogous.

(Expressions: procedures)+≡

```

function all_p (en1, en0) result (lval)
  logical :: lval
  type(eval_node_t), intent(in) :: en1
  type(eval_node_t), intent(inout) :: en0
  integer :: i, n
  n = prt_list_get_length (en1%pval)
  lval = .true.
  do i = 1, n
    en0%index = i
    en0%prt1 = prt_list_get_prt (en1%pval, i)
    call eval_node_evaluate (en0)
    lval = en0%lval
    if (.not. lval) exit
  end do
end function all_p

function any_p (en1, en0) result (lval)

```

```

logical :: lval
type(eval_node_t), intent(in) :: en1
type(eval_node_t), intent(inout) :: en0
integer :: i, n
n = prt_list_get_length (en1%pval)
lval = .false.
do i = 1, n
    en0%index = i
    en0%prt1 = prt_list_get_prt (en1%pval, i)
    call eval_node_evaluate (en0)
    lval = en0%lval
    if (lval) exit
end do
end function any_p

function no_p (en1, en0) result (lval)
logical :: lval
type(eval_node_t), intent(in) :: en1
type(eval_node_t), intent(inout) :: en0
integer :: i, n
n = prt_list_get_length (en1%pval)
lval = .true.
do i = 1, n
    en0%index = i
    en0%prt1 = prt_list_get_prt (en1%pval, i)
    call eval_node_evaluate (en0)
    lval = .not. en0%lval
    if (lval) exit
end do
end function no_p

```

The following function returns an integer value, namely the number of particles for which the condition is true. If there is no condition, it returns simply the length of the particle list.

A function would be more natural. Making it a subroutine avoids another compiler bug (internal error in nagfor 5.2 (649)). (See the interface `unary_num`.)

(Expressions: procedures)+≡

```

subroutine count_a (ival, en1, en0)
integer, intent(out) :: ival
type(eval_node_t), intent(in) :: en1
type(eval_node_t), intent(inout), optional :: en0
integer :: i, n, count
n = prt_list_get_length (en1%pval)
if (present (en0)) then
    count = 0
    do i = 1, n
        en0%index = i
        en0%prt1 = prt_list_get_prt (en1%pval, i)
        call eval_node_evaluate (en0)
        if (en0%lval) count = count + 1
    end do
    ival = count
else

```

```

        ival = n
    end if
end subroutine count_a

```

Binary particle-list functions

This joins two particle lists, stored in the evaluation nodes **en1** and **en2**. If **en0** is also present, it amounts to a logical test returning true or false for every pair of particles. A particle of the second list gets a mask entry only if it passes the test for all particles of the first list.

(*Expressions: procedures*) +=

```

subroutine join_pp (prt_list, en1, en2, en0)
    type(prt_list_t), intent(inout) :: prt_list
    type(eval_node_t), intent(in) :: en1, en2
    type(eval_node_t), intent(inout), optional :: en0
    logical, dimension(:), allocatable :: mask2
    integer :: i, j, n1, n2
    n1 = prt_list_get_length (en1%pval)
    n2 = prt_list_get_length (en2%pval)
    allocate (mask2 (n2))
    mask2 = .true.
    if (present (en0)) then
        do i = 1, n1
            en0%index = i
            en0%prt1 = prt_list_get_prt (en1%pval, i)
            do j = 1, n2
                en0%prt2 = prt_list_get_prt (en2%pval, j)
                call eval_node_evaluate (en0)
                mask2(j) = mask2(j) .and. en0%lval
            end do
        end do
    end if
    call prt_list_join (prt_list, en1%pval, en2%pval, mask2)
end subroutine join_pp

```

Combine two particle lists, i.e., make a list of composite particles built from all possible particle pairs from the two lists. If **en0** is present, create a mask which is true only for those pairs that pass the test.

(*Expressions: procedures*) +=

```

subroutine combine_pp (prt_list, en1, en2, en0)
    type(prt_list_t), intent(inout) :: prt_list
    type(eval_node_t), intent(in) :: en1, en2
    type(eval_node_t), intent(inout), optional :: en0
    logical, dimension(:,:), allocatable :: mask12
    integer :: i, j, n1, n2
    n1 = prt_list_get_length (en1%pval)
    n2 = prt_list_get_length (en2%pval)
    if (present (en0)) then
        allocate (mask12 (n1, n2))
        do i = 1, n1
            en0%index = i
            en0%prt1 = prt_list_get_prt (en1%pval, i)

```

```

        do j = 1, n2
            en0%prt2 = prt_list_get_prt (en2%pval, j)
            call eval_node_evaluate (en0)
            mask12(i,j) = en0%lval
        end do
    end do
    call prt_list_combine (prt_list, en1%pval, en2%pval, mask12)
else
    call prt_list_combine (prt_list, en1%pval, en2%pval)
end if
end subroutine combine_pp

```

Combine all particles of the first argument. If `en0` is present, create a mask which is true only for those particles that pass the test w.r.t. all particles in the second argument. If `en0` is absent, the second argument is ignored.

(Expressions: procedures)+≡

```

subroutine collect_pp (prt_list, en1, en2, en0)
    type(prt_list_t), intent(inout) :: prt_list
    type(eval_node_t), intent(in) :: en1, en2
    type(eval_node_t), intent(inout), optional :: en0
    logical, dimension(:), allocatable :: mask1
    integer :: i, j, n1, n2
    n1 = prt_list_get_length (en1%pval)
    n2 = prt_list_get_length (en2%pval)
    allocate (mask1 (n1))
    mask1 = .true.
    if (present (en0)) then
        do i = 1, n1
            en0%index = i
            en0%prt1 = prt_list_get_prt (en1%pval, i)
            do j = 1, n2
                en0%prt2 = prt_list_get_prt (en2%pval, j)
                call eval_node_evaluate (en0)
                mask1(i) = mask1(i) .and. en0%lval
            end do
        end do
    end if
    call prt_list_collect (prt_list, en1%pval, mask1)
end subroutine collect_pp

```

Select all particles of the first argument. If `en0` is present, create a mask which is true only for those particles that pass the test w.r.t. all particles in the second argument. If `en0` is absent, the second argument is ignored, and the first argument is transferred unchanged. (This case is not very useful, of course.)

(Expressions: procedures)+≡

```

subroutine select_pp (prt_list, en1, en2, en0)
    type(prt_list_t), intent(inout) :: prt_list
    type(eval_node_t), intent(in) :: en1, en2
    type(eval_node_t), intent(inout), optional :: en0
    logical, dimension(:), allocatable :: mask1
    integer :: i, j, n1, n2
    n1 = prt_list_get_length (en1%pval)
    n2 = prt_list_get_length (en2%pval)

```

```

allocate (mask1 (n1))
mask1 = .true.
if (present (en0)) then
  do i = 1, n1
    en0%index = i
    en0%prt1 = prt_list_get_prt (en1%pval, i)
    do j = 1, n2
      en0%prt2 = prt_list_get_prt (en2%pval, j)
      call eval_node_evaluate (en0)
      mask1(i) = mask1(i) .and. en0%lval
    end do
  end do
end if
call prt_list_select (prt_list, en1%pval, mask1)
end subroutine select_pp

```

Sort the first particle list according to the result of evaluating `en0`. From the second particle list, only the first element is taken as reference. If `en0` is absent, we sort by default method (PDG code, particles before antiparticles).

(Expressions: procedures)+≡

```

subroutine sort_pp (prt_list, en1, en2, en0)
  type(prt_list_t), intent(inout) :: prt_list
  type(eval_node_t), intent(in) :: en1, en2
  type(eval_node_t), intent(inout), optional :: en0
  integer, dimension(:), allocatable :: ival
  real(default), dimension(:), allocatable :: rval
  integer :: i, n1, n2
  n1 = prt_list_get_length (en1%pval)
  n2 = prt_list_get_length (en2%pval)
  if (present (en0)) then
    select case (en0%result_type)
    case (V_INT); allocate (ival (n1))
    case (V_REAL); allocate (rval (n1))
    end select
    do i = 1, n1
      en0%index = i
      en0%prt1 = prt_list_get_prt (en1%pval, i)
      en0%prt2 = prt_list_get_prt (en2%pval, 1)
      call eval_node_evaluate (en0)
      select case (en0%result_type)
      case (V_INT); ival(i) = en0%ival
      case (V_REAL); rval(i) = en0%rval
      end select
    end do
    select case (en0%result_type)
    case (V_INT); call prt_list_sort (prt_list, en1%pval, ival)
    case (V_REAL); call prt_list_sort (prt_list, en1%pval, rval)
    end select
  else
    call prt_list_sort (prt_list, en1%pval)
  end if
end subroutine sort_pp

```

The following functions return a logical value. `all` evaluates to true if the condition `en0` is true for all valid element pairs of both particle lists. Invalid pairs (with common `src` entry) are ignored.

`any` and `no` are analogous.

(Expressions: procedures)+≡

```
function all_pp (en1, en2, en0) result (lval)
  logical :: lval
  type(eval_node_t), intent(in) :: en1, en2
  type(eval_node_t), intent(inout) :: en0
  integer :: i, j, n1, n2
  n1 = prt_list_get_length (en1%pval)
  n2 = prt_list_get_length (en2%pval)
  lval = .true.
  LOOP1: do i = 1, n1
    en0%index = i
    en0%prt1 = prt_list_get_prt (en1%pval, i)
    do j = 1, n2
      en0%prt2 = prt_list_get_prt (en2%pval, j)
      if (are_disjoint (en0%prt1, en0%prt2)) then
        call eval_node_evaluate (en0)
        lval = en0%lval
        if (.not. lval) exit LOOP1
      end if
    end do
  end do LOOP1
end function all_pp
```

```
function any_pp (en1, en2, en0) result (lval)
  logical :: lval
  type(eval_node_t), intent(in) :: en1, en2
  type(eval_node_t), intent(inout) :: en0
  integer :: i, j, n1, n2
  n1 = prt_list_get_length (en1%pval)
  n2 = prt_list_get_length (en2%pval)
  lval = .false.
  LOOP1: do i = 1, n1
    en0%index = i
    en0%prt1 = prt_list_get_prt (en1%pval, i)
    do j = 1, n2
      en0%prt2 = prt_list_get_prt (en2%pval, j)
      if (are_disjoint (en0%prt1, en0%prt2)) then
        call eval_node_evaluate (en0)
        lval = en0%lval
        if (lval) exit LOOP1
      end if
    end do
  end do LOOP1
end function any_pp
```

```
function no_pp (en1, en2, en0) result (lval)
  logical :: lval
  type(eval_node_t), intent(in) :: en1, en2
  type(eval_node_t), intent(inout) :: en0
  integer :: i, j, n1, n2
```

```

n1 = prt_list_get_length (en1%pval)
n2 = prt_list_get_length (en2%pval)
lval = .true.
LOOP1: do i = 1, n1
  en0%index = i
  en0%prt1 = prt_list_get_prt (en1%pval, i)
  do j = 1, n2
    en0%prt2 = prt_list_get_prt (en2%pval, j)
    if (are_disjoint (en0%prt1, en0%prt2)) then
      call eval_node_evaluate (en0)
      lval = .not. en0%lval
      if (lval) exit LOOP1
    end if
  end do
end do LOOP1
end function no_pp

```

The following function returns an integer value, namely the number of valid particle-pairs from both lists for which the condition is true. Invalid pairs (with common `src` entry) are ignored. If there is no condition, it returns the number of valid particle pairs.

A function would be more natural. Making it a subroutine avoids another compiler bug (internal error in nagfor 5.2 (649)). (See the interface `binary_num`.)

(*Expressions: procedures*) +=

```

subroutine count_pp (ival, en1, en2, en0)
  integer, intent(out) :: ival
  type(eval_node_t), intent(in) :: en1, en2
  type(eval_node_t), intent(inout), optional :: en0
  integer :: i, j, n1, n2, count
  n1 = prt_list_get_length (en1%pval)
  n2 = prt_list_get_length (en2%pval)
  if (present (en0)) then
    count = 0
    do i = 1, n1
      en0%index = i
      en0%prt1 = prt_list_get_prt (en1%pval, i)
      do j = 1, n2
        en0%prt2 = prt_list_get_prt (en2%pval, j)
        if (are_disjoint (en0%prt1, en0%prt2)) then
          call eval_node_evaluate (en0)
          if (en0%lval) count = count + 1
        end if
      end do
    end do
  else
    count = 0
    do i = 1, n1
      do j = 1, n2
        if (are_disjoint (prt_list_get_prt (en1%pval, i), &
                          prt_list_get_prt (en2%pval, j))) then
          count = count + 1
        end if
      end do
    end do
  end if
end subroutine count_pp

```

```

        end do
    end do
end if
ival = count
end subroutine count_pp

```

This function makes up a particle list from the second argument which consists only of particles which match the PDG code array (first argument).

(Expressions: procedures) +≡

```

subroutine select_pdg_ca (prt_list, en1, en2, en0)
    type(prt_list_t), intent(inout) :: prt_list
    type(eval_node_t), intent(in) :: en1, en2
    type(eval_node_t), intent(inout), optional :: en0
    if (present (en0)) then
        call prt_list_select_pdg_code (prt_list, en1%aval, en2%pval, en0%ival)
    else
        call prt_list_select_pdg_code (prt_list, en1%aval, en2%pval)
    end if
end subroutine select_pdg_ca

```

Binary string functions

Currently, the only string operation is concatenation.

(Expressions: procedures) +≡

```

subroutine concat_ss (string, en1, en2)
    type(string_t), intent(out) :: string
    type(eval_node_t), intent(in) :: en1, en2
    string = en1%sval // en2%sval
end subroutine concat_ss

```

5.5.4 Compiling the parse tree

The evaluation tree is built recursively by following a parse tree. Debug option:

(Expressions: variables) ≡

```

logical, parameter :: debug = .false.

```

Evaluate an expression. The requested type is given as an optional argument; default is numeric (integer or real).

(Expressions: procedures) +≡

```

recursive subroutine eval_node_compile_genexpr &
    (en, pn, var_list, result_type)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    integer, intent(in), optional :: result_type
    if (debug) then
        print *, "read genexpr"; call parse_node_write (pn)
    end if
    if (present (result_type)) then

```

```

select case (result_type)
case (V_INT, V_REAL, V_CMPLX)
    call eval_node_compile_expr (en, pn, var_list)
case (V_LOG)
    call eval_node_compile_lexpr (en, pn, var_list)
case (V_PTL)
    call eval_node_compile_pexpr (en, pn, var_list)
case (V_PDG)
    call eval_node_compile_cexpr (en, pn, var_list)
case (V_STR)
    call eval_node_compile_sexpr (en, pn, var_list)
end select
else
    call eval_node_compile_expr (en, pn, var_list)
end if
if (debug) then
    call eval_node_write (en)
    print *, "done genexpr"
end if
end subroutine eval_node_compile_genexpr

```

Numeric expressions

This procedure compiles a numerical expression. This is a single term or a sum or difference of terms. We have to account for all combinations of integer and real arguments. If both are constant, we immediately do the calculation and allocate a constant node.

(Expressions: procedures) +=

```

recursive subroutine eval_node_compile_expr (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    type(parse_node_t), pointer :: pn_term, pn_addition, pn_op, pn_arg
    type(eval_node_t), pointer :: en1, en2
    type(string_t) :: key
    integer :: t1, t2, t
    if (debug) then
        print *, "read expr"; call parse_node_write (pn)
    end if
    pn_term => parse_node_get_sub_ptr (pn)
    select case (char (parse_node_get_rule_key (pn_term)))
    case ("term")
        call eval_node_compile_term (en, pn_term, var_list)
        pn_addition => parse_node_get_next_ptr (pn_term, tag="addition")
    case ("addition")
        en => null ()
        pn_addition => pn_term
    case default
        call parse_node_mismatch ("term|addition", pn)
    end select
    do while (associated (pn_addition))
        pn_op => parse_node_get_sub_ptr (pn_addition)

```

```

pn_arg => parse_node_get_next_ptr (pn_op, tag="term")
call eval_node_compile_term (en2, pn_arg, var_list)
t2 = en2%result_type
if (associated (en)) then
    en1 => en
    t1 = en1%result_type
else
    allocate (en1)
    select case (t2)
    case (V_INT); call eval_node_init_int (en1, 0)
    case (V_REAL); call eval_node_init_real (en1, 0._default)
    case (V_CMPLX); call eval_node_init_cmplx (en1, cmplx &
                                                (0._default, 0._default, kind=default))
    end select
    t1 = t2
end if
t = numeric_result_type (t1, t2)
allocate (en)
key = parse_node_get_key (pn_op)
if (en1%type == EN_CONSTANT .and. en2%type == EN_CONSTANT) then
    select case (char (key))
    case ("+")
        select case (t1)
        case (V_INT)
            select case (t2)
            case (V_INT); call eval_node_init_int (en, add_ii (en1, en2))
            case (V_REAL); call eval_node_init_real (en, add_ir (en1, en2))
            case (V_CMPLX); call eval_node_init_cmplx (en, add_ic (en1, en2))
            end select
        case (V_REAL)
            select case (t2)
            case (V_INT); call eval_node_init_real (en, add_ri (en1, en2))
            case (V_REAL); call eval_node_init_real (en, add_rr (en1, en2))
            case (V_CMPLX); call eval_node_init_cmplx (en, add_rc (en1, en2))
            end select
        case (V_CMPLX)
            select case (t2)
            case (V_INT); call eval_node_init_cmplx (en, add_ci (en1, en2))
            case (V_REAL); call eval_node_init_cmplx (en, add_cr (en1, en2))
            case (V_CMPLX); call eval_node_init_cmplx (en, add_cc (en1, en2))
            end select
        end select
    case ("-")
        select case (t1)
        case (V_INT)
            select case (t2)
            case (V_INT); call eval_node_init_int (en, sub_ii (en1, en2))
            case (V_REAL); call eval_node_init_real (en, sub_ir (en1, en2))
            case (V_CMPLX); call eval_node_init_cmplx (en, sub_ic (en1, en2))
            end select
        case (V_REAL)
            select case (t2)
            case (V_INT); call eval_node_init_real (en, sub_ri (en1, en2))
            case (V_REAL); call eval_node_init_real (en, sub_rr (en1, en2))
            end select
        end select
    end select
end if

```

```

        case (V_CMPLX); call eval_node_init_cmplx (en, sub_rc (en1, en2))
    end select
case (V_CMPLX)
    select case (t2)
        case (V_INT);  call eval_node_init_cmplx (en, sub_ci (en1, en2))
        case (V_REAL); call eval_node_init_cmplx (en, sub_cr (en1, en2))
        case (V_CMPLX); call eval_node_init_cmplx (en, sub_cc (en1, en2))
    end select
end select
end select
call eval_node_final_rec (en1)
call eval_node_final_rec (en2)
deallocate (en1, en2)
else
call eval_node_init_branch (en, key, t, en1, en2)
select case (char (key))
case ("+")
    select case (t1)
        case (V_INT)
            select case (t2)
                case (V_INT);  call eval_node_set_op2_int  (en, add_ii)
                case (V_REAL);  call eval_node_set_op2_real (en, add_ir)
                case (V_CMPLX);  call eval_node_set_op2_cmplx (en, add_ic)
            end select
        case (V_REAL)
            select case (t2)
                case (V_INT);  call eval_node_set_op2_real (en, add_ri)
                case (V_REAL);  call eval_node_set_op2_real (en, add_rr)
                case (V_CMPLX);  call eval_node_set_op2_cmplx (en, add_rc)
            end select
        case (V_CMPLX)
            select case (t2)
                case (V_INT);  call eval_node_set_op2_cmplx (en, add_ci)
                case (V_REAL);  call eval_node_set_op2_cmplx (en, add_cr)
                case (V_CMPLX);  call eval_node_set_op2_cmplx (en, add_cc)
            end select
        end select
    end select
case ("-")
    select case (t1)
        case (V_INT)
            select case (t2)
                case (V_INT);  call eval_node_set_op2_int  (en, sub_ii)
                case (V_REAL);  call eval_node_set_op2_real (en, sub_ir)
                case (V_CMPLX);  call eval_node_set_op2_cmplx (en, sub_ic)
            end select
        case (V_REAL)
            select case (t2)
                case (V_INT);  call eval_node_set_op2_real (en, sub_ri)
                case (V_REAL);  call eval_node_set_op2_real (en, sub_rr)
                case (V_CMPLX);  call eval_node_set_op2_cmplx (en, sub_rc)
            end select
        case (V_CMPLX)
            select case (t2)
                case (V_INT);  call eval_node_set_op2_cmplx (en, sub_ci)

```

```

        case (V_REAL); call eval_node_set_op2_cmplx (en, sub_cr)
        case (V_CMPLX); call eval_node_set_op2_cmplx (en, sub_cc)
    end select
end select
end select
end if
pn_addition => parse_node_get_next_ptr (pn_addition)
end do
if (debug) then
    call eval_node_write (en)
    print *, "done expr"
end if
end subroutine eval_node_compile_expr

```

(Expressions: procedures)+≡

```

recursive subroutine eval_node_compile_term (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    type(parse_node_t), pointer :: pn_factor, pn_multiplication, pn_op, pn_arg
    type(eval_node_t), pointer :: en1, en2
    type(string_t) :: key
    integer :: t1, t2, t
    if (debug) then
        print *, "read term"; call parse_node_write (pn)
    end if
    pn_factor => parse_node_get_sub_ptr (pn, tag="factor")
    call eval_node_compile_factor (en, pn_factor, var_list)
    pn_multiplication => &
        parse_node_get_next_ptr (pn_factor, tag="multiplication")
    do while (associated (pn_multiplication))
        pn_op => parse_node_get_sub_ptr (pn_multiplication)
        pn_arg => parse_node_get_next_ptr (pn_op, tag="factor")
        en1 => en
        call eval_node_compile_factor (en2, pn_arg, var_list)
        t1 = en1%result_type
        t2 = en2%result_type
        t = numeric_result_type (t1, t2)
        allocate (en)
        key = parse_node_get_key (pn_op)
        if (en1%type == EN_CONSTANT .and. en2%type == EN_CONSTANT) then
            select case (char (key))
            case ("*")
                select case (t1)
                case (V_INT)
                    select case (t2)
                    case (V_INT); call eval_node_init_int (en, mul_ii (en1, en2))
                    case (V_REAL); call eval_node_init_real (en, mul_ir (en1, en2))
                    case (V_CMPLX); call eval_node_init_cmplx (en, mul_ic (en1, en2))
                    end select
                case (V_REAL)
                    select case (t2)
                    case (V_INT); call eval_node_init_real (en, mul_ri (en1, en2))
                    case (V_REAL); call eval_node_init_real (en, mul_rr (en1, en2))

```

```

        case (V_CMPLX); call eval_node_init_cmplx (en, mul_rc (en1, en2))
    end select
case (V_CMPLX)
    select case (t2)
        case (V_INT);   call eval_node_init_cmplx (en, mul_ci (en1, en2))
        case (V_REAL);  call eval_node_init_cmplx (en, mul_cr (en1, en2))
        case (V_CMPLX); call eval_node_init_cmplx (en, mul_cc (en1, en2))
    end select
end select
case ("/")
    select case (t1)
        case (V_INT)
            select case (t2)
                case (V_INT);   call eval_node_init_int   (en, div_ii (en1, en2))
                case (V_REAL);  call eval_node_init_real  (en, div_ir (en1, en2))
                case (V_CMPLX); call eval_node_init_real  (en, div_ir (en1, en2))
            end select
        case (V_REAL)
            select case (t2)
                case (V_INT);   call eval_node_init_real  (en, div_ri (en1, en2))
                case (V_REAL);  call eval_node_init_real  (en, div_rr (en1, en2))
                case (V_CMPLX); call eval_node_init_cmplx (en, div_rc (en1, en2))
            end select
        case (V_CMPLX)
            select case (t2)
                case (V_INT);   call eval_node_init_cmplx (en, div_ci (en1, en2))
                case (V_REAL);  call eval_node_init_cmplx (en, div_cr (en1, en2))
                case (V_CMPLX); call eval_node_init_cmplx (en, div_cc (en1, en2))
            end select
    end select
end select
call eval_node_final_rec (en1)
call eval_node_final_rec (en2)
deallocate (en1, en2)
else
    call eval_node_init_branch (en, key, t, en1, en2)
    select case (char (key))
        case ("*")
            select case (t1)
                case (V_INT)
                    select case (t2)
                        case (V_INT);   call eval_node_set_op2_int   (en, mul_ii)
                        case (V_REAL);  call eval_node_set_op2_real  (en, mul_ir)
                        case (V_CMPLX);  call eval_node_set_op2_cmplx (en, mul_ic)
                    end select
                case (V_REAL)
                    select case (t2)
                        case (V_INT);   call eval_node_set_op2_real  (en, mul_ri)
                        case (V_REAL);  call eval_node_set_op2_real  (en, mul_rr)
                        case (V_CMPLX);  call eval_node_set_op2_cmplx (en, mul_rc)
                    end select
                case (V_CMPLX)
                    select case (t2)
                        case (V_INT);   call eval_node_set_op2_cmplx (en, mul_ci)

```

```

        case (V_REAL); call eval_node_set_op2_cmplx (en, mul_cr)
        case (V_CMPLX); call eval_node_set_op2_cmplx (en, mul_cc)
    end select
end select
case ("/")
select case (t1)
case (V_INT)
select case (t2)
case (V_INT); call eval_node_set_op2_int (en, div_ii)
case (V_REAL); call eval_node_set_op2_real (en, div_ir)
case (V_CMPLX); call eval_node_set_op2_cmplx (en, div_ic)
end select
case (V_REAL)
select case (t2)
case (V_INT); call eval_node_set_op2_real (en, div_ri)
case (V_REAL); call eval_node_set_op2_real (en, div_rr)
case (V_CMPLX); call eval_node_set_op2_cmplx (en, div_rc)
end select
case (V_CMPLX)
select case (t2)
case (V_INT); call eval_node_set_op2_cmplx (en, div_ci)
case (V_REAL); call eval_node_set_op2_cmplx (en, div_cr)
case (V_CMPLX); call eval_node_set_op2_cmplx (en, div_cc)
end select
end select
end select
end if
pn_multiplication => parse_node_get_next_ptr (pn_multiplication)
end do
if (debug) then
call eval_node_write (en)
print *, "done term"
end if
end subroutine eval_node_compile_term

```

(Expressions: procedures)+≡

```

recursive subroutine eval_node_compile_factor (en, pn, var_list)
type(eval_node_t), pointer :: en
type(parse_node_t), intent(in) :: pn
type(var_list_t), intent(in), target :: var_list
type(parse_node_t), pointer :: pn_value, pn_exponentiation, pn_op, pn_arg
type(eval_node_t), pointer :: en1, en2
type(string_t) :: key
integer :: t1, t2, t
if (debug) then
print *, "read factor"; call parse_node_write (pn)
end if
pn_value => parse_node_get_sub_ptr (pn)
call eval_node_compile_signed_value (en, pn_value, var_list)
pn_exponentiation => &
    parse_node_get_next_ptr (pn_value, tag="exponentiation")
if (associated (pn_exponentiation)) then
pn_op => parse_node_get_sub_ptr (pn_exponentiation)
pn_arg => parse_node_get_next_ptr (pn_op)

```

```

en1 => en
call eval_node_compile_signed_value (en2, pn_arg, var_list)
t1 = en1%result_type
t2 = en2%result_type
t = numeric_result_type (t1, t2)
allocate (en)
key = parse_node_get_key (pn_op)
if (en1%type == EN_CONSTANT .and. en2%type == EN_CONSTANT) then
  select case (t1)
    case (V_INT)
      select case (t2)
        case (V_INT); call eval_node_init_int (en, pow_ii (en1, en2))
        case (V_REAL,V_CMPLX); call eval_type_error (pn, "exponentiation", t1)
      end select
    case (V_REAL)
      select case (t2)
        case (V_INT); call eval_node_init_real (en, pow_ri (en1, en2))
        case (V_REAL); call eval_node_init_real (en, pow_rr (en1, en2))
        case (V_CMPLX); call eval_type_error (pn, "exponentiation", t1)
      end select
    case (V_CMPLX)
      select case (t2)
        case (V_INT); call eval_node_init_cmplx (en, pow_ci (en1, en2))
        case (V_REAL); call eval_node_init_cmplx (en, pow_cr (en1, en2))
        case (V_CMPLX); call eval_node_init_cmplx (en, pow_cc (en1, en2))
      end select
  end select
  call eval_node_final_rec (en1)
  call eval_node_final_rec (en2)
  deallocate (en1, en2)
else
  call eval_node_init_branch (en, key, t, en1, en2)
  select case (t1)
    case (V_INT)
      select case (t2)
        case (V_INT); call eval_node_set_op2_int (en, pow_ii)
        case (V_REAL,V_CMPLX); call eval_type_error (pn, "exponentiation", t1)
      end select
    case (V_REAL)
      select case (t2)
        case (V_INT); call eval_node_set_op2_real (en, pow_ri)
        case (V_REAL); call eval_node_set_op2_real (en, pow_rr)
        case (V_CMPLX); call eval_type_error (pn, "exponentiation", t1)
      end select
    case (V_CMPLX)
      select case (t2)
        case (V_INT); call eval_node_set_op2_cmplx (en, pow_ci)
        case (V_REAL); call eval_node_set_op2_cmplx (en, pow_cr)
        case (V_CMPLX); call eval_node_set_op2_cmplx (en, pow_cc)
      end select
  end select
end if
end if
if (debug) then

```

```

        call eval_node_write (en)
        print *, "done factor"
    end if
end subroutine eval_node_compile_factor

```

(Expressions: procedures)+≡

```

recursive subroutine eval_node_compile_signed_value (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    type(parse_node_t), pointer :: pn_arg
    type(eval_node_t), pointer :: en1
    integer :: t
    if (debug) then
        print *, "read signed value"; call parse_node_write (pn)
    end if
    select case (char (parse_node_get_rule_key (pn)))
    case ("signed_value")
        pn_arg => parse_node_get_sub_ptr (pn, 2)
        call eval_node_compile_value (en1, pn_arg, var_list)
        t = en1%result_type
        allocate (en)
        if (en1%type == EN_CONSTANT) then
            select case (t)
            case (V_INT); call eval_node_init_int (en, neg_i (en1))
            case (V_REAL); call eval_node_init_real (en, neg_r (en1))
            case (V_CMPLX); call eval_node_init_cmplx (en, neg_c (en1))
            end select
            call eval_node_final_rec (en1)
            deallocate (en1)
        else
            call eval_node_init_branch (en, var_str ("-"), t, en1)
            select case (t)
            case (V_INT); call eval_node_set_op1_int (en, neg_i)
            case (V_REAL); call eval_node_set_op1_real (en, neg_r)
            case (V_CMPLX); call eval_node_set_op1_cmplx (en, neg_c)
            end select
        end if
    case default
        call eval_node_compile_value (en, pn, var_list)
    end select
    if (debug) then
        call eval_node_write (en)
        print *, "done signed value"
    end if
end subroutine eval_node_compile_signed_value

```

Integer and real values have an optional unit. The unit is extracted and applied immediately. An integer with unit evaluates to a real constant.

(Expressions: procedures)+≡

```

recursive subroutine eval_node_compile_value (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn

```

```

type(var_list_t), intent(in), target :: var_list
if (debug) then
    print *, "read value"; call parse_node_write (pn)
end if
select case (char (parse_node_get_rule_key (pn)))
case ("integer_value", "real_value", "complex_value")
    call eval_node_compile_numeric_value (en, pn)
case ("pi")
    call eval_node_compile_constant (en, pn)
case ("variable")
    call eval_node_compile_variable (en, pn, var_list)
case ("result")
    call eval_node_compile_result (en, pn, var_list)
case ("expr")
    call eval_node_compile_expr (en, pn, var_list)
case ("block_expr")
    call eval_node_compile_block_expr (en, pn, var_list)
case ("conditional_expr")
    call eval_node_compile_conditional (en, pn, var_list)
case ("unary_function")
    call eval_node_compile_unary_function (en, pn, var_list)
case ("binary_function")
    call eval_node_compile_binary_function (en, pn, var_list)
case ("eval_fun")
    call eval_node_compile_eval_function (en, pn, var_list)
case ("count_fun")
    call eval_node_compile_int_function (en, pn, var_list)
case default
    call parse_node_mismatch &
        ("integer|real|complex|constant|variable|" // &
         "expr|block_expr|conditional_expr|" // &
         "unary_function|binary_function|numeric_pexpr", pn)
end select
if (debug) then
    call eval_node_write (en)
    print *, "done value"
end if
end subroutine eval_node_compile_value

```

Real, complex and integer values are numeric literals with an optional unit attached. In case of an integer, the unit actually makes it a real value in disguise. The signed version of real values is not possible in generic expressions; it is a special case for numeric constants in model files (see below). We do not introduce signed versions of complex values.

(Expressions: procedures)+≡

```

subroutine eval_node_compile_numeric_value (en, pn)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in), target :: pn
    type(parse_node_t), pointer :: pn_val, pn_unit
    allocate (en)
    pn_val => parse_node_get_sub_ptr (pn)
    pn_unit => parse_node_get_next_ptr (pn_val)
    select case (char (parse_node_get_rule_key (pn)))

```

```

case ("integer_value")
  if (associated (pn_unit)) then
    call eval_node_init_real (en, &
      parse_node_get_integer (pn_val) * parse_node_get_unit (pn_unit))
  else
    call eval_node_init_int (en, parse_node_get_integer (pn_val))
  end if
case ("real_value")
  if (associated (pn_unit)) then
    call eval_node_init_real (en, &
      parse_node_get_real (pn_val) * parse_node_get_unit (pn_unit))
  else
    call eval_node_init_real (en, parse_node_get_real (pn_val))
  end if
case ("complex_value")
  if (associated (pn_unit)) then
    call eval_node_init_cmplx (en, &
      parse_node_get_cmplx (pn_val) * parse_node_get_unit (pn_unit))
  else
    call eval_node_init_cmplx (en, parse_node_get_cmplx (pn_val))
  end if
case ("neg_real_value")
  pn_val => parse_node_get_sub_ptr (parse_node_get_sub_ptr (pn, 2))
  pn_unit => parse_node_get_next_ptr (pn_val)
  if (associated (pn_unit)) then
    call eval_node_init_real (en, &
      - parse_node_get_real (pn_val) * parse_node_get_unit (pn_unit))
  else
    call eval_node_init_real (en, - parse_node_get_real (pn_val))
  end if
case ("pos_real_value")
  pn_val => parse_node_get_sub_ptr (parse_node_get_sub_ptr (pn, 2))
  pn_unit => parse_node_get_next_ptr (pn_val)
  if (associated (pn_unit)) then
    call eval_node_init_real (en, &
      parse_node_get_real (pn_val) * parse_node_get_unit (pn_unit))
  else
    call eval_node_init_real (en, parse_node_get_real (pn_val))
  end if
case default
  call parse_node_mismatch &
    ("integer_value|real_value|complex_value|neg_real_value|pos_real_value", pn)
end select
end subroutine eval_node_compile_numeric_value

```

These are the units, predefined and hardcoded. The default energy unit is GeV, the default angular unit is radians. We include units for observables of dimension energy squared. Luminosities are normalized in inverse femtobarns.

(Expressions: procedures) +≡

```

function parse_node_get_unit (pn) result (factor)
  real(default) :: factor
  real(default) :: unit
  type(parse_node_t), intent(in) :: pn

```

```

type(parse_node_t), pointer :: pn_unit, pn_unit_power
type(parse_node_t), pointer :: pn_frac, pn_num, pn_int, pn_div, pn_den
integer :: num, den
pn_unit => parse_node_get_sub_ptr (pn)
select case (char (parse_node_get_key (pn_unit)))
case ("TeV"); unit = 1.e3_default
case ("GeV"); unit = 1
case ("MeV"); unit = 1.e-3_default
case ("keV"); unit = 1.e-6_default
case ("eV"); unit = 1.e-9_default
case ("meV"); unit = 1.e-12_default
case ("nbarn"); unit = 1.e6_default
case ("pbarn"); unit = 1.e3_default
case ("fbarn"); unit = 1
case ("abarn"); unit = 1.e-3_default
case ("rad"); unit = 1
case ("mrad"); unit = 1.e-3_default
case ("degree"); unit = degree
case ("%"); unit = 1.e-2_default
case default
    call msg_bug (" Unit '" // &
        char (parse_node_get_key (pn)) // "' is undefined.")
end select
pn_unit_power => parse_node_get_next_ptr (pn_unit)
if (associated (pn_unit_power)) then
    pn_frac => parse_node_get_sub_ptr (pn_unit_power, 2)
    pn_num => parse_node_get_sub_ptr (pn_frac)
    select case (char (parse_node_get_rule_key (pn_num)))
    case ("neg_int")
        pn_int => parse_node_get_sub_ptr (pn_num, 2)
        num = - parse_node_get_integer (pn_int)
    case ("pos_int")
        pn_int => parse_node_get_sub_ptr (pn_num, 2)
        num = parse_node_get_integer (pn_int)
    case ("integer_literal")
        num = parse_node_get_integer (pn_num)
    case default
        call parse_node_mismatch ("neg_int|pos_int|integer_literal", pn_num)
    end select
    pn_div => parse_node_get_next_ptr (pn_num)
    if (associated (pn_div)) then
        pn_den => parse_node_get_sub_ptr (pn_div, 2)
        den = parse_node_get_integer (pn_den)
    else
        den = 1
    end if
else
    num = 1
    den = 1
end if
factor = unit ** (real (num, default) / den)
end function parse_node_get_unit

```

There is only one predefined constant, but more can be added easily.

(Expressions: procedures)+≡

```

subroutine eval_node_compile_constant (en, pn)
  type(eval_node_t), pointer :: en
  type(parse_node_t), intent(in) :: pn
  if (debug) then
    print *, "read constant"; call parse_node_write (pn)
  end if
  allocate (en)
  select case (char (parse_node_get_key (pn)))
  case ("pi"); call eval_node_init_real (en, pi)
  case default
    call parse_node_mismatch ("pi", pn)
  end select
  if (debug) then
    call eval_node_write (en)
    print *, "done constant"
  end if
end subroutine eval_node_compile_constant

```

Take the list of variables, look for the name and make a node with a pointer to the value. If no type is provided, the variable is numeric, and the stored value determines whether it is real or integer.

Variables of type V_PDG (pdg-code array) are not treated here. They are handled by eval_node_compile_cvariable.

(Expressions: procedures)+≡

```

subroutine eval_node_compile_variable (en, pn, var_list, var_type)
  type(eval_node_t), pointer :: en
  type(parse_node_t), intent(in), target :: pn
  type(var_list_t), intent(in), target :: var_list
  integer, intent(in), optional :: var_type
  type(parse_node_t), pointer :: pn_name
  type(string_t) :: var_name
  type(var_entry_t), pointer :: var
  logical, target, save :: no_lval
  real(default), target, save :: no_rval
  type(prt_list_t), target, save :: no_pval
  type(string_t), target, save :: no_sval
  logical, target, save :: unknown = .false.
  if (debug) then
    print *, "read variable"; call parse_node_write (pn)
  end if
  if (present (var_type)) then
    select case (var_type)
    case (V_REAL, V_OBS1_REAL, V_OBS2_REAL, V_INT, V_OBS1_INT, &
          V_OBS2_INT, V_CMPLX)
      pn_name => pn
    case default
      pn_name => parse_node_get_sub_ptr (pn, 2)
    end select
  else
    pn_name => pn
  end if
  var_name = parse_node_get_string (pn_name)

```

```

if (present (var_type)) then
  select case (var_type)
    case (V_LOG); var_name = "?" // var_name
    case (V_PTL); var_name = "@" // var_name
    case (V_STR); var_name = "$" // var_name
  end select
end if
var => var_list_get_var_ptr (var_list, var_name, var_type)
allocate (en)
if (associated (var)) then
  select case (var_entry_get_type (var))
    case (V_LOG)
      call eval_node_init_log_ptr &
        (en, var_entry_get_name (var), var_entry_get_lval_ptr (var), &
          var_entry_get_known_ptr (var))
    case (V_INT)
      call eval_node_init_int_ptr &
        (en, var_entry_get_name (var), var_entry_get_ival_ptr (var), &
          var_entry_get_known_ptr (var))
    case (V_REAL)
      call eval_node_init_real_ptr &
        (en, var_entry_get_name (var), var_entry_get_rval_ptr (var), &
          var_entry_get_known_ptr (var))
    case (V_CMPLX)
      call eval_node_init_cmplx_ptr &
        (en, var_entry_get_name (var), var_entry_get_cval_ptr (var), &
          var_entry_get_known_ptr (var))
    case (V_PTL)
      call eval_node_init_prt_list_ptr &
        (en, var_entry_get_name (var), var_entry_get_pval_ptr (var), &
          var_entry_get_known_ptr (var))
    case (V_STR)
      call eval_node_init_string_ptr &
        (en, var_entry_get_name (var), var_entry_get_sval_ptr (var), &
          var_entry_get_known_ptr (var))
    case (V_OBS1_INT, V_OBS2_INT, V_OBS1_REAL, V_OBS2_REAL)
      call eval_node_init_obs (en, var)
    case default
      call parse_node_write (pn)
      call msg_fatal ("Variable of this type " // &
        "is not allowed in the present context")
  end select
  if (present (var_type)) then
    select case (var_type)
      case (V_LOG)
        call eval_node_init_log_ptr (en, var_name, no_lval, unknown)
      case (V_PTL)
        call eval_node_init_prt_list_ptr &
          (en, var_name, no_pval, unknown)
      case (V_STR)
        call eval_node_init_string_ptr (en, var_name, no_sval, unknown)
    end select
  else
    call eval_node_init_real_ptr (en, var_name, no_rval, unknown)
  end if
end if

```

```

        end select
    else
        call parse_node_write (pn)
        call msg_error ("This variable is undefined at this point")
        if (present (var_type)) then
            select case (var_type)
            case (V_LOG)
                call eval_node_init_log_ptr (en, var_name, no_lval, unknown)
            case (V_PTL)
                call eval_node_init_prt_list_ptr (en, var_name, no_pval, unknown)
            case (V_STR)
                call eval_node_init_string_ptr (en, var_name, no_sval, unknown)
            end select
        else
            call eval_node_init_real_ptr (en, var_name, no_rval, unknown)
        end if
    end if
    if (debug) then
        call eval_node_write (en)
        print *, "done variable"
    end if
end subroutine eval_node_compile_variable

```

In a given context, a variable has to have a certain type.

(Expressions: procedures) +=

```

subroutine check_var_type (pn, ok, type_actual, type_requested)
    type(parse_node_t), intent(in) :: pn
    logical, intent(out) :: ok
    integer, intent(in) :: type_actual
    integer, intent(in), optional :: type_requested
    if (present (type_requested)) then
        select case (type_requested)
        case (V_LOG)
            select case (type_actual)
            case (V_LOG)
            case default
                call parse_node_write (pn)
                call msg_fatal ("Variable type is invalid (should be logical)")
                ok = .false.
            end select
        case (V_PTL)
            select case (type_actual)
            case (V_PTL)
            case default
                call parse_node_write (pn)
                call msg_fatal &
                    ("Variable type is invalid (should be particle set)")
                ok = .false.
            end select
        case (V_PDG)
            select case (type_actual)
            case (V_PDG)
            case default
                call parse_node_write (pn)

```

```

        call msg_fatal &
            ("Variable type is invalid (should be PDG array)")
        ok = .false.
    end select
case (V_STR)
    select case (type_actual)
    case (V_STR)
    case default
        call parse_node_write (pn)
        call msg_fatal &
            ("Variable type is invalid (should be string)")
        ok = .false.
    end select
case default
    call parse_node_write (pn)
    call msg_bug ("Variable type is unknown")
end select
else
    select case (type_actual)
    case (V_REAL, V_OBS1_REAL, V_OBS2_REAL, V_INT, V_OBS1_INT, &
        V_OBS2_INT, V_CMPLX)
    case default
        call parse_node_write (pn)
        call msg_fatal ("Variable type is invalid (should be numeric)")
        ok = .false.
    end select
end if
ok = .true.
end subroutine check_var_type

```

Retrieve the result of an integration. If the requested process has been integrated, the results are available as special variables. (The variables cannot be accessed in the usual way since they contain brackets in their names.)

(Expressions: procedures)+≡

```

subroutine eval_node_compile_result (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in), target :: pn
    type(var_list_t), intent(in), target :: var_list
    type(parse_node_t), pointer :: pn_key, pn_prc_id
    type(string_t) :: key, prc_id, var_name
    type(var_entry_t), pointer :: var
    real(default), target, save :: no_rval
    logical, target, save :: unknown = .false.
    if (debug) then
        print *, "read result"; call parse_node_write (pn)
    end if
    pn_key => parse_node_get_sub_ptr (pn)
    pn_prc_id => parse_node_get_next_ptr (pn_key)
    key = parse_node_get_key (pn_key)
    prc_id = parse_node_get_string (pn_prc_id)
    var_name = key // "(" // prc_id // ")"
    var => var_list_get_var_ptr (var_list, var_name)
    allocate (en)

```

```

if (associated (var)) then
  select case (char(key))
  case ("n_calls")
    call eval_node_init_int_ptr &
      (en, var_name, var_entry_get_ival_ptr (var), &
        var_entry_get_known_ptr (var))
  case ("integral", "error", "accuracy", "chi2", "efficiency")
    call eval_node_init_real_ptr &
      (en, var_name, var_entry_get_rval_ptr (var), &
        var_entry_get_known_ptr (var))
  case default
    call msg_bug ("Unknown result variable '" // char (key) // "'")
  end select
else
  call parse_node_write (pn)
  call msg_error ("Process '" // char (prc_id) &
    // "' is undefined at this point")
  call eval_node_init_real_ptr (en, var_name, no_rval, unknown)
end if
if (debug) then
  call eval_node_write (en)
  print *, "done result"
end if
end subroutine eval_node_compile_result

```

Functions with a single argument. For non-constant arguments, watch for functions which convert their argument to a different type.

(Expressions: procedures)+≡

```

recursive subroutine eval_node_compile_unary_function (en, pn, var_list)
  type(eval_node_t), pointer :: en
  type(parse_node_t), intent(in) :: pn
  type(var_list_t), intent(in), target :: var_list
  type(parse_node_t), pointer :: pn_fname, pn_arg
  type(eval_node_t), pointer :: en1
  type(string_t) :: key
  integer :: t
  if (debug) then
    print *, "read unary function"; call parse_node_write (pn)
  end if
  pn_fname => parse_node_get_sub_ptr (pn)
  pn_arg => parse_node_get_next_ptr (pn_fname, tag="function_arg1")
  call eval_node_compile_expr &
    (en1, parse_node_get_sub_ptr (pn_arg, tag="expr"), var_list)
  t = en1%result_type
  allocate (en)
  key = parse_node_get_key (pn_fname)
  if (en1%type == EN_CONSTANT) then
    select case (char (key))
    case ("real")
      select case (t)
      case (V_INT); call eval_node_init_real (en, real_i (en1))
      case (V_REAL); deallocate (en); en => en1
      case default; call eval_type_error (pn, char (key), t)

```

```

        end select
case ("int")
    select case (t)
        case (V_INT); deallocate (en); en => en1
        case (V_REAL); call eval_node_init_int (en, int_r (en1))
        case (V_CMPLX); call eval_node_init_int (en, int_c (en1))
    end select
case ("nint")
    select case (t)
        case (V_INT); deallocate (en); en => en1
        case (V_REAL); call eval_node_init_int (en, nint_r (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("floor")
    select case (t)
        case (V_INT); deallocate (en); en => en1
        case (V_REAL); call eval_node_init_int (en, floor_r (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("ceiling")
    select case (t)
        case (V_INT); deallocate (en); en => en1
        case (V_REAL); call eval_node_init_int (en, ceiling_r (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("abs")
    select case (t)
        case (V_INT); call eval_node_init_int (en, abs_i (en1))
        case (V_REAL); call eval_node_init_real (en, abs_r (en1))
        case (V_CMPLX); call eval_node_init_real (en, abs_c (en1))
    end select
case ("sgn")
    select case (t)
        case (V_INT); call eval_node_init_int (en, sgn_i (en1))
        case (V_REAL); call eval_node_init_real (en, sgn_r (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("sqrt")
    select case (t)
        case (V_REAL); call eval_node_init_real (en, sqrt_r (en1))
        case (V_CMPLX); call eval_node_init_cmplx (en, sqrt_c (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("exp")
    select case (t)
        case (V_REAL); call eval_node_init_real (en, exp_r (en1))
        case (V_CMPLX); call eval_node_init_cmplx (en, exp_c (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("log")
    select case (t)
        case (V_REAL); call eval_node_init_real (en, log_r (en1))
        case (V_CMPLX); call eval_node_init_cmplx (en, log_c (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select

```

```

        end select
case ("log10")
    select case (t)
        case (V_REAL); call eval_node_init_real (en, log10_r (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("sin")
    select case (t)
        case (V_REAL); call eval_node_init_real (en, sin_r (en1))
        case (V_CMPLX); call eval_node_init_cmplx (en, sin_c (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("cos")
    select case (t)
        case (V_REAL); call eval_node_init_real (en, cos_r (en1))
        case (V_CMPLX); call eval_node_init_cmplx (en, cos_c (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("tan")
    select case (t)
        case (V_REAL); call eval_node_init_real (en, tan_r (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("asin")
    select case (t)
        case (V_REAL); call eval_node_init_real (en, asin_r (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("acos")
    select case (t)
        case (V_REAL); call eval_node_init_real (en, acos_r (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("atan")
    select case (t)
        case (V_REAL); call eval_node_init_real (en, atan_r (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("sinh")
    select case (t)
        case (V_REAL); call eval_node_init_real (en, sinh_r (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("cosh")
    select case (t)
        case (V_REAL); call eval_node_init_real (en, cosh_r (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("tanh")
    select case (t)
        case (V_REAL); call eval_node_init_real (en, tanh_r (en1))
        case default; call eval_type_error (pn, char (key), t)
    end select
case default

```

```

        call parse_node_mismatch ("function name", pn_fname)
    end select
    call eval_node_final_rec (en1)
    deallocate (en1)
else
    select case (char (key))
    case ("real")
        call eval_node_init_branch (en, key, V_REAL, en1)
    case ("int", "nint", "floor", "ceiling")
        call eval_node_init_branch (en, key, V_INT, en1)
    case default
        call eval_node_init_branch (en, key, t, en1)
    end select
    select case (char (key))
    case ("real")
        select case (t)
        case (V_INT); call eval_node_set_op1_real (en, real_i)
        case (V_REAL); deallocate (en); en => en1
        case default; call eval_type_error (pn, char (key), t)
        end select
    case ("int")
        select case (t)
        case (V_INT); deallocate (en); en => en1
        case (V_REAL); call eval_node_set_op1_int (en, int_r)
        case (V_CMPLX); call eval_node_set_op1_int (en, int_c)
        end select
    case ("nint")
        select case (t)
        case (V_INT); deallocate (en); en => en1
        case (V_REAL); call eval_node_set_op1_int (en, nint_r)
        case default; call eval_type_error (pn, char (key), t)
        end select
    case ("floor")
        select case (t)
        case (V_INT); deallocate (en); en => en1
        case (V_REAL); call eval_node_set_op1_int (en, floor_r)
        case default; call eval_type_error (pn, char (key), t)
        end select
    case ("ceiling")
        select case (t)
        case (V_INT); deallocate (en); en => en1
        case (V_REAL); call eval_node_set_op1_int (en, ceiling_r)
        case default; call eval_type_error (pn, char (key), t)
        end select
    case ("abs")
        select case (t)
        case (V_INT); call eval_node_set_op1_int (en, abs_i)
        case (V_REAL); call eval_node_set_op1_real (en, abs_r)
        case (V_CMPLX); call eval_node_set_op1_real (en, abs_c)
        end select
    case ("sgn")
        select case (t)
        case (V_INT); call eval_node_set_op1_int (en, sgn_i)
        case (V_REAL); call eval_node_set_op1_real (en, sgn_r)

```

```

        case default; call eval_type_error (pn, char (key), t)
    end select
case ("sqrt")
    select case (t)
        case (V_REAL); call eval_node_set_op1_real (en, sqrt_r)
        case (V_CMPLX); call eval_node_set_op1_cmplx (en, sqrt_c)
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("exp")
    select case (t)
        case (V_REAL); call eval_node_set_op1_real (en, exp_r)
        case (V_CMPLX); call eval_node_set_op1_cmplx (en, exp_c)
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("log")
    select case (t)
        case (V_REAL); call eval_node_set_op1_real (en, log_r)
        case (V_CMPLX); call eval_node_set_op1_cmplx (en, log_c)
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("log10")
    select case (t)
        case (V_REAL); call eval_node_set_op1_real (en, log10_r)
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("sin")
    select case (t)
        case (V_REAL); call eval_node_set_op1_real (en, sin_r)
        case (V_CMPLX); call eval_node_set_op1_cmplx (en, sin_c)
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("cos")
    select case (t)
        case (V_REAL); call eval_node_set_op1_real (en, cos_r)
        case (V_CMPLX); call eval_node_set_op1_cmplx (en, cos_c)
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("tan")
    select case (t)
        case (V_REAL); call eval_node_set_op1_real (en, tan_r)
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("asin")
    select case (t)
        case (V_REAL); call eval_node_set_op1_real (en, asin_r)
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("acos")
    select case (t)
        case (V_REAL); call eval_node_set_op1_real (en, acos_r)
        case default; call eval_type_error (pn, char (key), t)
    end select
case ("atan")
    select case (t)

```

```

        case (V_REAL); call eval_node_set_op1_real (en, atan_r)
        case default; call eval_type_error (pn, char (key), t)
        end select
    case ("sinh")
        select case (t)
            case (V_REAL); call eval_node_set_op1_real (en, sinh_r)
            case default; call eval_type_error (pn, char (key), t)
            end select
    case ("cosh")
        select case (t)
            case (V_REAL); call eval_node_set_op1_real (en, cosh_r)
            case default; call eval_type_error (pn, char (key), t)
            end select
    case ("tanh")
        select case (t)
            case (V_REAL); call eval_node_set_op1_real (en, tanh_r)
            case default; call eval_type_error (pn, char (key), t)
            end select
    case default
        call parse_node_mismatch ("function name", pn_fname)
        end select
end if
if (debug) then
    call eval_node_write (en)
    print *, "done function"
end if
end subroutine eval_node_compile_unary_function

```

Functions with two arguments.

(Expressions: procedures)+≡

```

recursive subroutine eval_node_compile_binary_function (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    type(parse_node_t), pointer :: pn_fname, pn_arg, pn_arg1, pn_arg2
    type(eval_node_t), pointer :: en1, en2
    type(string_t) :: key
    integer :: t1, t2
    if (debug) then
        print *, "read binary function"; call parse_node_write (pn)
    end if
    pn_fname => parse_node_get_sub_ptr (pn)
    pn_arg => parse_node_get_next_ptr (pn_fname, tag="function_arg2")
    pn_arg1 => parse_node_get_sub_ptr (pn_arg, tag="expr")
    pn_arg2 => parse_node_get_next_ptr (pn_arg1, tag="expr")
    call eval_node_compile_expr (en1, pn_arg1, var_list)
    call eval_node_compile_expr (en2, pn_arg2, var_list)
    t1 = en1%result_type
    t2 = en2%result_type
    allocate (en)
    key = parse_node_get_key (pn_fname)
    if (en1%type == EN_CONSTANT .and. en2%type == EN_CONSTANT) then
        select case (char (key))
            case ("max")

```

```

select case (t1)
case (V_INT)
  select case (t2)
    case (V_INT); call eval_node_init_int  (en, max_ii (en1, en2))
    case (V_REAL); call eval_node_init_real (en, max_ir (en1, en2))
    case default; call eval_type_error (pn, char (key), t2)
  end select
case (V_REAL)
  select case (t2)
    case (V_INT); call eval_node_init_real (en, max_ri (en1, en2))
    case (V_REAL); call eval_node_init_real (en, max_rr (en1, en2))
    case default; call eval_type_error (pn, char (key), t2)
  end select
  case default; call eval_type_error (pn, char (key), t1)
end select
case ("min")
  select case (t1)
  case (V_INT)
    select case (t2)
      case (V_INT); call eval_node_init_int  (en, min_ii (en1, en2))
      case (V_REAL); call eval_node_init_real (en, min_ir (en1, en2))
      case default; call eval_type_error (pn, char (key), t2)
    end select
  case (V_REAL)
    select case (t2)
      case (V_INT); call eval_node_init_real (en, min_ri (en1, en2))
      case (V_REAL); call eval_node_init_real (en, min_rr (en1, en2))
      case default; call eval_type_error (pn, char (key), t2)
    end select
  case default; call eval_type_error (pn, char (key), t1)
end select
case ("mod")
  select case (t1)
  case (V_INT)
    select case (t2)
      case (V_INT); call eval_node_init_int  (en, mod_ii (en1, en2))
      case (V_REAL); call eval_node_init_real (en, mod_ir (en1, en2))
      case default; call eval_type_error (pn, char (key), t2)
    end select
  case (V_REAL)
    select case (t2)
      case (V_INT); call eval_node_init_real (en, mod_ri (en1, en2))
      case (V_REAL); call eval_node_init_real (en, mod_rr (en1, en2))
      case default; call eval_type_error (pn, char (key), t2)
    end select
  case default; call eval_type_error (pn, char (key), t1)
end select
case ("modulo")
  select case (t1)
  case (V_INT)
    select case (t2)
      case (V_INT); call eval_node_init_int  (en, modulo_ii (en1, en2))
      case (V_REAL); call eval_node_init_real (en, modulo_ir (en1, en2))
      case default; call eval_type_error (pn, char (key), t2)
    end select
  end select
end select

```

```

        end select
    case (V_REAL)
        select case (t2)
            case (V_INT); call eval_node_init_real (en, modulo_ri (en1, en2))
            case (V_REAL); call eval_node_init_real (en, modulo_rr (en1, en2))
            case default; call eval_type_error (pn, char (key), t2)
        end select
        case default; call eval_type_error (pn, char (key), t2)
    end select
case default
    call parse_node_mismatch ("function name", pn_fname)
end select
call eval_node_final_rec (en1)
deallocate (en1)
else
    call eval_node_init_branch (en, key, t1, en1, en2)
    select case (char (key))
    case ("max")
        select case (t1)
        case (V_INT)
            select case (t2)
            case (V_INT); call eval_node_set_op2_int (en, max_ii)
            case (V_REAL); call eval_node_set_op2_real (en, max_ir)
            case default; call eval_type_error (pn, char (key), t2)
            end select
        case (V_REAL)
            select case (t2)
            case (V_INT); call eval_node_set_op2_real (en, max_ri)
            case (V_REAL); call eval_node_set_op2_real (en, max_rr)
            case default; call eval_type_error (pn, char (key), t2)
            end select
        case default; call eval_type_error (pn, char (key), t2)
        end select
    case ("min")
        select case (t1)
        case (V_INT)
            select case (t2)
            case (V_INT); call eval_node_set_op2_int (en, min_ii)
            case (V_REAL); call eval_node_set_op2_real (en, min_ir)
            case default; call eval_type_error (pn, char (key), t2)
            end select
        case (V_REAL)
            select case (t2)
            case (V_INT); call eval_node_set_op2_real (en, min_ri)
            case (V_REAL); call eval_node_set_op2_real (en, min_rr)
            case default; call eval_type_error (pn, char (key), t2)
            end select
        case default; call eval_type_error (pn, char (key), t2)
        end select
    case ("mod")
        select case (t1)
        case (V_INT)
            select case (t2)
            case (V_INT); call eval_node_set_op2_int (en, mod_ii)

```

```

        case (V_REAL); call eval_node_set_op2_real (en, mod_ir)
        case default;  call eval_type_error (pn, char (key), t2)
    end select
case (V_REAL)
    select case (t2)
        case (V_INT);  call eval_node_set_op2_real (en, mod_ri)
        case (V_REAL); call eval_node_set_op2_real (en, mod_rr)
        case default;  call eval_type_error (pn, char (key), t2)
    end select
    case default;  call eval_type_error (pn, char (key), t2)
end select
case ("modulo")
    select case (t1)
        case (V_INT)
            select case (t2)
                case (V_INT); call eval_node_set_op2_int  (en, modulo_ii)
                case (V_REAL); call eval_node_set_op2_real (en, modulo_ir)
                case default;  call eval_type_error (pn, char (key), t2)
            end select
        case (V_REAL)
            select case (t2)
                case (V_INT); call eval_node_set_op2_real (en, modulo_ri)
                case (V_REAL); call eval_node_set_op2_real (en, modulo_rr)
                case default;  call eval_type_error (pn, char (key), t2)
            end select
            case default;  call eval_type_error (pn, char (key), t2)
        end select
    case default
        call parse_node_mismatch ("function name", pn_fname)
    end select
end if
if (debug) then
    call eval_node_write (en)
    print *, "done function"
end if
end subroutine eval_node_compile_binary_function

```

Variable definition

A block expression contains a variable definition (first argument) and an expression where the definition can be used (second argument). The `result_type` decides which type of expression is expected for the second argument. For numeric variables, if there is a mismatch between real and integer type, insert an extra node for type conversion.

(Expressions: procedures)+≡

```

recursive subroutine eval_node_compile_block_expr &
    (en, pn, var_list, result_type)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    integer, intent(in), optional :: result_type
    type(parse_node_t), pointer :: pn_var_spec

```

```

type(parse_node_t), pointer :: pn_var_type, pn_var_name, pn_var_expr
type(parse_node_t), pointer :: pn_expr
type(string_t) :: var_name
type(eval_node_t), pointer :: en1, en2
integer :: var_type
if (debug) then
    print *, "read block expr"; call parse_node_write (pn)
end if
pn_var_spec => parse_node_get_sub_ptr (pn, 2)
select case (char (parse_node_get_rule_key (pn_var_spec)))
case ("var_num");      var_type = V_REAL
    pn_var_name => parse_node_get_sub_ptr (pn_var_spec)
case ("var_int");      var_type = V_INT
    pn_var_name => parse_node_get_sub_ptr (pn_var_spec, 2)
case ("var_real");     var_type = V_REAL
    pn_var_name => parse_node_get_sub_ptr (pn_var_spec, 2)
case ("var_cmplx");    var_type = V_CMPLX
    pn_var_name => parse_node_get_sub_ptr (pn_var_spec, 2)
case ("var_logical");  var_type = V_LOG
    pn_var_name => parse_node_get_sub_ptr (pn_var_spec, 2)
case ("var_plist");    var_type = V_PTL
    pn_var_name => parse_node_get_sub_ptr (pn_var_spec, 2)
case ("var_alias");    var_type = V_PDG
    pn_var_name => parse_node_get_sub_ptr (pn_var_spec, 2)
case ("var_string");   var_type = V_STR
    pn_var_name => parse_node_get_sub_ptr (pn_var_spec, 2)
case default
    call parse_node_mismatch &
        ("logical|int|real|plist|alias", pn_var_type)
end select
pn_var_expr => parse_node_get_next_ptr (pn_var_name, 2)
pn_expr => parse_node_get_next_ptr (pn_var_spec, 2)
var_name = parse_node_get_string (pn_var_name)
select case (var_type)
case (V_LOG);  var_name = "?" // var_name
case (V_PTL);  var_name = "@" // var_name
case (V_STR);  var_name = "$" // var_name
end select
call eval_node_compile_genexpr (en1, pn_var_expr, var_list, var_type)
call insert_conversion_node (en1, var_type)
allocate (en)
call eval_node_init_block (en, var_name, var_type, en1, var_list)
call eval_node_compile_genexpr (en2, pn_expr, en%var_list, result_type)
call eval_node_set_expr (en, en2)
if (debug) then
    call eval_node_write (en)
    print *, "done block expr"
end if
end subroutine eval_node_compile_block_expr

```

Insert a conversion node for integer/real/complex transformation if necessary.
 What shall we do for the complex to integer/real conversion?

(Expressions: procedures)+≡

```

subroutine insert_conversion_node (en, result_type)
  type(eval_node_t), pointer :: en
  integer, intent(in) :: result_type
  type(eval_node_t), pointer :: en_conv
  select case (en%result_type)
  case (V_INT)
    select case (result_type)
    case (V_REAL)
      allocate (en_conv)
      call eval_node_init_branch (en_conv, var_str ("real"), V_REAL, en)
      call eval_node_set_op1_real (en_conv, real_i)
      en => en_conv
    case (V_CMPLX)
      allocate (en_conv)
      call eval_node_init_branch (en_conv, var_str ("cmplx"), V_CMPLX, en)
      call eval_node_set_op1_cmplx (en_conv, cmplx_i)
      en => en_conv
    end select
  case (V_REAL)
    select case (result_type)
    case (V_INT)
      allocate (en_conv)
      call eval_node_init_branch (en_conv, var_str ("int"), V_INT, en)
      call eval_node_set_op1_int (en_conv, int_r)
      en => en_conv
    case (V_CMPLX)
      allocate (en_conv)
      call eval_node_init_branch (en_conv, var_str ("cmplx"), V_CMPLX, en)
      call eval_node_set_op1_cmplx (en_conv, cmplx_r)
      en => en_conv
    end select
  case default
  end select
end subroutine insert_conversion_node

```

Conditionals

A conditional has the structure `if lexpr then expr else expr`. So we first evaluate the logical expression, then depending on the result the first or second expression. Note that the second expression is mandatory.

The `result_type`, if present, defines the requested type of the `then` and `else` clauses. Default is numeric (int/real). If there is a mismatch between real and integer result types, insert conversion nodes.

(Expressions: procedures)+≡

```

recursive subroutine eval_node_compile_conditional &
  (en, pn, var_list, result_type)
  type(eval_node_t), pointer :: en
  type(parse_node_t), intent(in) :: pn
  type(var_list_t), intent(in), target :: var_list
  integer, intent(in), optional :: result_type
  type(parse_node_t), pointer :: pn_condition, pn_expr1, pn_expr2
  type(eval_node_t), pointer :: en0, en1, en2

```

```

integer :: t1, t2
if (debug) then
    print *, "read conditional"; call parse_node_write (pn)
end if
pn_condition => parse_node_get_sub_ptr (pn, 2, tag="lexpr")
pn_expr1 => parse_node_get_next_ptr (pn_condition, 2)
pn_expr2 => parse_node_get_next_ptr (pn_expr1, 2)
call eval_node_compile_lexpr (en0, pn_condition, var_list)
call eval_node_compile_genexpr (en1, pn_expr1, var_list, result_type)
call eval_node_compile_genexpr (en2, pn_expr2, var_list, result_type)
t1 = en1%result_type
t2 = en2%result_type
if (t1 == t2) then
    if (en0%type == EN_CONSTANT) then
        if (en0%lval) then
            en => en1
            call eval_node_final_rec (en2)
            deallocate (en2)
        else
            en => en2
            call eval_node_final_rec (en1)
            deallocate (en1)
        end if
        call eval_node_final_rec (en0)
        deallocate (en0)
    else
        allocate (en)
        call eval_node_init_conditional (en, t1, en0, en1, en2)
    end if
else if (t1 == V_INT) then
    call insert_conversion_node (en1, V_REAL)
else if (t2 == V_INT) then
    call insert_conversion_node (en2, V_REAL)
else
    call parse_node_write (pn)
    call msg_bug &
        (" The 'then' and 'else' expressions have incompatible types")
end if
if (debug) then
    call eval_node_write (en)
    print *, "done conditional"
end if
end subroutine eval_node_compile_conditional

```

Logical expressions

A logical expression consists of one or more logical terms concatenated by **or**.

(Expressions: procedures) + \equiv

```

recursive subroutine eval_node_compile_lexpr (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    type(parse_node_t), pointer :: pn_term, pn_alternative, pn_arg

```

```

type(eval_node_t), pointer :: en1, en2
if (debug) then
    print *, "read lexpr"; call parse_node_write (pn)
end if
pn_term => parse_node_get_sub_ptr (pn, tag="lterm")
call eval_node_compile_lterm (en, pn_term, var_list)
pn_alternative => parse_node_get_next_ptr (pn_term, tag="alternative")
do while (associated (pn_alternative))
    pn_arg => parse_node_get_sub_ptr (pn_alternative, 2, tag="lterm")
    en1 => en
    call eval_node_compile_lterm (en2, pn_arg, var_list)
    allocate (en)
    if (en1%type == EN_CONSTANT .and. en2%type == EN_CONSTANT) then
        call eval_node_init_log (en, or_ll (en1, en2))
        call eval_node_final_rec (en1)
        call eval_node_final_rec (en2)
        deallocate (en1, en2)
    else
        call eval_node_init_branch &
            (en, var_str ("alternative"), V_LOG, en1, en2)
        call eval_node_set_op2_log (en, or_ll)
    end if
    pn_alternative => parse_node_get_next_ptr (pn_alternative)
end do
if (debug) then
    call eval_node_write (en)
    print *, "done lexpr"
end if
end subroutine eval_node_compile_lexpr

```

A logical term consists of one or more logical values concatenated by **and**.

(Expressions: procedures)+≡

```

recursive subroutine eval_node_compile_lterm (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    type(parse_node_t), pointer :: pn_term, pn_coincidence, pn_arg
    type(eval_node_t), pointer :: en1, en2
    if (debug) then
        print *, "read lterm"; call parse_node_write (pn)
    end if
    pn_term => parse_node_get_sub_ptr (pn)
    call eval_node_compile_lvalue (en, pn_term, var_list)
    pn_coincidence => parse_node_get_next_ptr (pn_term, tag="coincidence")
    do while (associated (pn_coincidence))
        pn_arg => parse_node_get_sub_ptr (pn_coincidence, 2)
        en1 => en
        call eval_node_compile_lvalue (en2, pn_arg, var_list)
        allocate (en)
        if (en1%type == EN_CONSTANT .and. en2%type == EN_CONSTANT) then
            call eval_node_init_log (en, and_ll (en1, en2))
            call eval_node_final_rec (en1)
            call eval_node_final_rec (en2)
            deallocate (en1, en2)
        end if
        pn_coincidence => parse_node_get_next_ptr (pn_coincidence)
    end do
end subroutine eval_node_compile_lterm

```

```

else
    call eval_node_init_branch &
        (en, var_str ("coincidence"), V_LOG, en1, en2)
    call eval_node_set_op2_log (en, and_ll)
end if
pn_coincidence => parse_node_get_next_ptr (pn_coincidence)
end do
if (debug) then
    call eval_node_write (en)
    print *, "done lterm"
end if
end subroutine eval_node_compile_lterm

```

Logical variables are disabled, because they are confused with the l.h.s. of compared expressions.

(Expressions: procedures) +=

```

recursive subroutine eval_node_compile_lvalue (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    if (debug) then
        print *, "read lvalue"; call parse_node_write (pn)
    end if
    select case (char (parse_node_get_rule_key (pn)))
    case ("true")
        allocate (en)
        call eval_node_init_log (en, .true.)
    case ("false")
        allocate (en)
        call eval_node_init_log (en, .false.)
    case ("negation")
        call eval_node_compile_negation (en, pn, var_list)
    case ("lvariable")
        call eval_node_compile_variable (en, pn, var_list, V_LOG)
    case ("lexpr")
        call eval_node_compile_lexpr (en, pn, var_list)
    case ("block_lexpr")
        call eval_node_compile_block_expr (en, pn, var_list, V_LOG)
    case ("conditional_lexpr")
        call eval_node_compile_conditional (en, pn, var_list, V_LOG)
    case ("compared_expr")
        call eval_node_compile_compared_expr (en, pn, var_list, V_REAL)
    case ("compared_sexpr")
        call eval_node_compile_compared_expr (en, pn, var_list, V_STR)
    case ("all_fun", "any_fun", "no_fun")
        call eval_node_compile_log_function (en, pn, var_list)
    case ("record_cmd")
        call eval_node_compile_record_cmd (en, pn, var_list)
    case default
        call parse_node_mismatch &
            ("true|false|negation|lvariable|" // &
            "lexpr|block_lexpr|conditional_lexpr|" // &
            "compared_expr|compared_sexpr|logical_pexpr", pn)

```

```

end select
if (debug) then
    call eval_node_write (en)
    print *, "done lvalue"
end if
end subroutine eval_node_compile_lvalue

```

A negation consists of the keyword `not` and a logical value.

(Expressions: procedures) +≡

```

recursive subroutine eval_node_compile_negation (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    type(parse_node_t), pointer :: pn_arg
    type(eval_node_t), pointer :: en1
    if (debug) then
        print *, "read negation"; call parse_node_write (pn)
    end if
    pn_arg => parse_node_get_sub_ptr (pn, 2)
    call eval_node_compile_lvalue (en1, pn_arg, var_list)
    allocate (en)
    if (en1%type == EN_CONSTANT) then
        call eval_node_init_log (en, not_1 (en1))
        call eval_node_final_rec (en1)
        deallocate (en1)
    else
        call eval_node_init_branch (en, var_str ("not"), V_LOG, en1)
        call eval_node_set_op1_log (en, not_1)
    end if
    if (debug) then
        call eval_node_write (en)
        print *, "done negation"
    end if
end subroutine eval_node_compile_negation

```

Comparisons

Up to the loop, this is easy. There is always at least one comparison. This is evaluated, and the result is the logical node `en`. If it is constant, we keep its second sub-node as `en2`. (Thus, at the very end `en2` has to be deleted if `en` is (still) constant.)

If there is another comparison, we first check if the first comparison was constant. In that case, there are two possibilities: (i) it was true. Then, its right-hand side is compared with the new right-hand side, and the result replaces the previous one which is deleted. (ii) it was false. In this case, the result of the whole comparison is false, and we can exit the loop without evaluating anything else.

Now assume that the first comparison results in a valid branch, its second sub-node kept as `en2`. We first need a copy of this, which becomes the new left-hand side. If `en2` is constant, we make an identical constant node `en1`. Otherwise, we make `en1` an appropriate pointer node. Next, the first branch is

saved as `en0` and we evaluate the comparison between `en1` and the a right-hand side. If this turns out to be constant, there are again two possibilities: (i) true, then we revert to the previous result. (ii) false, then the wh

(Expressions: procedures) +=

```

recursive subroutine eval_node_compile_compared_expr (en, pn, var_list, type)
  type(eval_node_t), pointer :: en
  type(parse_node_t), intent(in) :: pn
  type(var_list_t), intent(in), target :: var_list
  integer, intent(in) :: type
  type(parse_node_t), pointer :: pn_comparison, pn_expr1
  type(eval_node_t), pointer :: en0, en1, en2
  if (debug) then
    print *, "read comparison"; call parse_node_write (pn)
  end if
  select case (type)
  case (V_INT, V_REAL)
    pn_expr1 => parse_node_get_sub_ptr (pn, tag="expr")
    call eval_node_compile_expr (en1, pn_expr1, var_list)
    pn_comparison => parse_node_get_next_ptr (pn_expr1, tag="comparison")
  case (V_STR)
    pn_expr1 => parse_node_get_sub_ptr (pn, tag="sexpr")
    call eval_node_compile_sexpr (en1, pn_expr1, var_list)
    pn_comparison => parse_node_get_next_ptr (pn_expr1, tag="str_comparison")
  end select
  call eval_node_compile_comparison &
    (en, en1, en2, pn_comparison, var_list, type)
  pn_comparison => parse_node_get_next_ptr (pn_comparison)
  SCAN_FURTHER: do while (associated (pn_comparison))
    if (en%type == EN_CONSTANT) then
      if (en%lval) then
        en1 => en2
        call eval_node_final_rec (en); deallocate (en)
        call eval_node_compile_comparison &
          (en, en1, en2, pn_comparison, var_list, type)
      else
        exit SCAN_FURTHER
      end if
    else
      allocate (en1)
      if (en2%type == EN_CONSTANT) then
        select case (en2%result_type)
        case (V_INT); call eval_node_init_int    (en1, en2%ival)
        case (V_REAL); call eval_node_init_real  (en1, en2%rval)
        case (V_STR); call eval_node_init_string (en1, en2%sval)
        end select
      else
        select case (en2%result_type)
        case (V_INT); call eval_node_init_int_ptr &
          (en1, var_str ("(previous)"), en2%ival, en2%value_is_known)
        case (V_REAL); call eval_node_init_real_ptr &
          (en1, var_str ("(previous)"), en2%rval, en2%value_is_known)
        case (V_STR); call eval_node_init_string_ptr &
          (en1, var_str ("(previous)"), en2%sval, en2%value_is_known)
        end select
      end select
    end if
  end do
end subroutine

```

```

end if
en0 => en
call eval_node_compile_comparison &
    (en, en1, en2, pn_comparison, var_list, type)
if (en%type == EN_CONSTANT) then
    if (en%lval) then
        call eval_node_final_rec (en); deallocate (en)
        en => en0
    else
        call eval_node_final_rec (en0); deallocate (en0)
        exit SCAN_FURTHER
    end if
else
    en1 => en
    allocate (en)
    call eval_node_init_branch (en, var_str ("and"), V_LOG, en0, en1)
    call eval_node_set_op2_log (en, and_ll)
end if
end if
pn_comparison => parse_node_get_next_ptr (pn_comparison)
end do SCAN_FURTHER
if (en%type == EN_CONSTANT .and. associated (en2)) then
    call eval_node_final_rec (en2); deallocate (en2)
end if
if (debug) then
    call eval_node_write (en)
    print *, "done compared_expr"
end if
end subroutine eval_node_compile_compared_expr

```

This takes two extra arguments: **en1**, the left-hand-side of the comparison, is already allocated and evaluated. **en2** (the right-hand side) and **en** (the result) are allocated by the routine. **pn** is the parse node which contains the operator and the right-hand side as subnodes.

If the result of the comparison is constant, **en1** is deleted but **en2** is kept, because it may be used in a subsequent comparison. **en** then becomes a constant. If the result is variable, **en** becomes a branch node which refers to **en1** and **en2**.

(*Expressions: procedures*) +=

```

recursive subroutine eval_node_compile_comparison &
    (en, en1, en2, pn, var_list, type)
type(eval_node_t), pointer :: en, en1, en2
type(parse_node_t), intent(in) :: pn
type(var_list_t), intent(in), target :: var_list
integer, intent(in) :: type
type(parse_node_t), pointer :: pn_op, pn_arg
type(string_t) :: key
integer :: t1, t2
type(var_entry_t), pointer :: var
pn_op => parse_node_get_sub_ptr (pn)
key = parse_node_get_key (pn_op)
select case (type)
case (V_INT, V_REAL)
    pn_arg => parse_node_get_next_ptr (pn_op, tag="expr")

```

```

        call eval_node_compile_expr (en2, pn_arg, var_list)
case (V_STR)
    pn_arg => parse_node_get_next_ptr (pn_op, tag="sexpr")
    call eval_node_compile_sexpr (en2, pn_arg, var_list)
end select
t1 = en1%result_type
t2 = en2%result_type
allocate (en)
if (en1%type == EN_CONSTANT .and. en2%type == EN_CONSTANT) then
    select case (char (key))
    case ("<")
        select case (t1)
        case (V_INT)
            select case (t2)
            case (V_INT); call eval_node_init_log (en, comp_lt_ii (en1, en2))
            case (V_REAL); call eval_node_init_log (en, comp_lt_ir (en1, en2))
            end select
        case (V_REAL)
            select case (t2)
            case (V_INT); call eval_node_init_log (en, comp_lt_ri (en1, en2))
            case (V_REAL); call eval_node_init_log (en, comp_lt_rr (en1, en2))
            end select
        end select
    case (">")
        select case (t1)
        case (V_INT)
            select case (t2)
            case (V_INT); call eval_node_init_log (en, comp_gt_ii (en1, en2))
            case (V_REAL); call eval_node_init_log (en, comp_gt_ir (en1, en2))
            end select
        case (V_REAL)
            select case (t2)
            case (V_INT); call eval_node_init_log (en, comp_gt_ri (en1, en2))
            case (V_REAL); call eval_node_init_log (en, comp_gt_rr (en1, en2))
            end select
        end select
    case ("<=")
        select case (t1)
        case (V_INT)
            select case (t2)
            case (V_INT); call eval_node_init_log (en, comp_le_ii (en1, en2))
            case (V_REAL); call eval_node_init_log (en, comp_le_ir (en1, en2))
            end select
        case (V_REAL)
            select case (t2)
            case (V_INT); call eval_node_init_log (en, comp_le_ri (en1, en2))
            case (V_REAL); call eval_node_init_log (en, comp_le_rr (en1, en2))
            end select
        end select
    case (">=")
        select case (t1)
        case (V_INT)
            select case (t2)
            case (V_INT); call eval_node_init_log (en, comp_ge_ii (en1, en2))

```

```

        case (V_REAL); call eval_node_init_log (en, comp_ge_ir (en1, en2))
    end select
case (V_REAL)
    select case (t2)
        case (V_INT); call eval_node_init_log (en, comp_ge_ri (en1, en2))
        case (V_REAL); call eval_node_init_log (en, comp_ge_rr (en1, en2))
    end select
end select
case ("==")
    select case (t1)
        case (V_INT)
            select case (t2)
                case (V_INT); call eval_node_init_log (en, comp_eq_ii (en1, en2))
                case (V_REAL); call eval_node_init_log (en, comp_eq_ir (en1, en2))
            end select
        case (V_REAL)
            select case (t2)
                case (V_INT); call eval_node_init_log (en, comp_eq_ri (en1, en2))
                case (V_REAL); call eval_node_init_log (en, comp_eq_rr (en1, en2))
            end select
        case (V_STR)
            select case (t2)
                case (V_STR); call eval_node_init_log (en, comp_eq_ss (en1, en2))
            end select
    end select
case ("/=")
    select case (t1)
        case (V_INT)
            select case (t2)
                case (V_INT); call eval_node_init_log (en, comp_ne_ii (en1, en2))
                case (V_REAL); call eval_node_init_log (en, comp_ne_ir (en1, en2))
            end select
        case (V_REAL)
            select case (t2)
                case (V_INT); call eval_node_init_log (en, comp_ne_ri (en1, en2))
                case (V_REAL); call eval_node_init_log (en, comp_ne_rr (en1, en2))
            end select
        case (V_STR)
            select case (t2)
                case (V_STR); call eval_node_init_log (en, comp_ne_ss (en1, en2))
            end select
    end select
case ("~~")
    var => var_list_get_var_ptr (var_list, var_str ("tolerance"))
    en1%tolerance => var_entry_get_rval_ptr (var)
    select case (t1)
        case (V_INT)
            select case (t2)
                case (V_INT); call eval_node_init_log (en, comp_sim_ii (en1, en2))
                case (V_REAL); call eval_node_init_log (en, comp_sim_ir (en1, en2))
            end select
        case (V_REAL)
            select case (t2)
                case (V_INT); call eval_node_init_log (en, comp_sim_ri (en1, en2))
            end select
    end select

```

```

        case (V_REAL); call eval_node_init_log (en, comp_sim_rr (en1, en2))
    end select
case (V_STR)
    select case (t2)
        case (V_STR); call eval_node_init_log (en, comp_eq_ss (en1, en2))
    end select
end select
case ("/~")
    var => var_list_get_var_ptr (var_list, var_str ("tolerance"))
    en1%tolerance => var_entry_get_rval_ptr (var)
    select case (t1)
        case (V_INT)
            select case (t2)
                case (V_INT)
                    call eval_node_init_log (en, comp_nsim_ii (en1, en2))
                case (V_REAL)
                    call eval_node_init_log (en, comp_nsim_ir (en1, en2))
            end select
        case (V_REAL)
            select case (t2)
                case (V_INT)
                    call eval_node_init_log (en, comp_nsim_ri (en1, en2))
                case (V_REAL)
                    call eval_node_init_log (en, comp_nsim_rr(en1, en2))
            end select
        case (V_STR)
            select case (t2)
                case (V_STR); call eval_node_init_log (en, comp_ne_ss (en1, en2))
            end select
    end select
end select
call eval_node_final_rec (en1)
deallocate (en1)
else
    call eval_node_init_branch (en, key, V_LOG, en1, en2)
    select case (char (key))
        case ("<")
            select case (t1)
                case (V_INT)
                    select case (t2)
                        case (V_INT); call eval_node_set_op2_log (en, comp_lt_ii)
                        case (V_REAL); call eval_node_set_op2_log (en, comp_lt_ir)
                    end select
                case (V_REAL)
                    select case (t2)
                        case (V_INT); call eval_node_set_op2_log (en, comp_lt_ri)
                        case (V_REAL); call eval_node_set_op2_log (en, comp_lt_rr)
                    end select
            end select
        case (">")
            select case (t1)
                case (V_INT)
                    select case (t2)
                        case (V_INT); call eval_node_set_op2_log (en, comp_gt_ii)

```

```

        case (V_REAL); call eval_node_set_op2_log (en, comp_gt_ir)
    end select
case (V_REAL)
    select case (t2)
        case (V_INT); call eval_node_set_op2_log (en, comp_gt_ri)
        case (V_REAL); call eval_node_set_op2_log (en, comp_gt_rr)
    end select
end select
case ("<=")
    select case (t1)
        case (V_INT)
            select case (t2)
                case (V_INT); call eval_node_set_op2_log (en, comp_le_ii)
                case (V_REAL); call eval_node_set_op2_log (en, comp_le_ir)
            end select
        case (V_REAL)
            select case (t2)
                case (V_INT); call eval_node_set_op2_log (en, comp_le_ri)
                case (V_REAL); call eval_node_set_op2_log (en, comp_le_rr)
            end select
        end select
    case (">=")
        select case (t1)
            case (V_INT)
                select case (t2)
                    case (V_INT); call eval_node_set_op2_log (en, comp_ge_ii)
                    case (V_REAL); call eval_node_set_op2_log (en, comp_ge_ir)
                end select
            case (V_REAL)
                select case (t2)
                    case (V_INT); call eval_node_set_op2_log (en, comp_ge_ri)
                    case (V_REAL); call eval_node_set_op2_log (en, comp_ge_rr)
                end select
            end select
        case ("==")
            select case (t1)
                case (V_INT)
                    select case (t2)
                        case (V_INT); call eval_node_set_op2_log (en, comp_eq_ii)
                        case (V_REAL); call eval_node_set_op2_log (en, comp_eq_ir)
                    end select
                case (V_REAL)
                    select case (t2)
                        case (V_INT); call eval_node_set_op2_log (en, comp_eq_ri)
                        case (V_REAL); call eval_node_set_op2_log (en, comp_eq_rr)
                    end select
                case (V_STR)
                    select case (t2)
                        case (V_STR); call eval_node_set_op2_log (en, comp_eq_ss)
                    end select
                end select
            case ("!=")
                select case (t1)
                    case (V_INT)

```

```

        select case (t2)
        case (V_INT); call eval_node_set_op2_log (en, comp_ne_ii)
        case (V_REAL); call eval_node_set_op2_log (en, comp_ne_ir)
        end select
    case (V_REAL)
        select case (t2)
        case (V_INT); call eval_node_set_op2_log (en, comp_ne_ri)
        case (V_REAL); call eval_node_set_op2_log (en, comp_ne_rr)
        end select
    case (V_STR)
        select case (t2)
        case (V_STR); call eval_node_set_op2_log (en, comp_ne_ss)
        end select
    end select
case ("~~")
    select case (t1)
    case (V_INT)
        select case (t2)
        case (V_INT); call eval_node_set_op2_log (en, comp_sim_ii)
        case (V_REAL); call eval_node_set_op2_log (en, comp_sim_ir)
        end select
    case (V_REAL)
        select case (t2)
        case (V_INT); call eval_node_set_op2_log (en, comp_sim_ri)
        case (V_REAL); call eval_node_set_op2_log (en, comp_sim_rr)
        end select
    case (V_STR)
        select case (t2)
        case (V_STR); call eval_node_set_op2_log (en, comp_eq_ss)
        end select
    end select
    var => var_list_get_var_ptr (var_list, var_str ("tolerance"))
    en1%tolerance => var_entry_get_rval_ptr (var)
case ("/~")
    select case (t1)
    case (V_INT)
        select case (t2)
        case (V_INT); call eval_node_set_op2_log (en, comp_nsim_ii)
        case (V_REAL); call eval_node_set_op2_log (en, comp_nsim_ir)
        end select
    case (V_REAL)
        select case (t2)
        case (V_INT); call eval_node_set_op2_log (en, comp_nsim_ri)
        case (V_REAL); call eval_node_set_op2_log (en, comp_nsim_rr)
        end select
    case (V_STR)
        select case (t2)
        case (V_STR); call eval_node_set_op2_log (en, comp_ne_ss)
        end select
    end select
    var => var_list_get_var_ptr (var_list, var_str ("tolerance"))
    en1%tolerance => var_entry_get_rval_ptr (var)
    end select
end if

```

```
end subroutine eval_node_compile_comparison
```

Recording analysis data

The `record` command is actually a logical expression which always evaluates true.

(Expressions: procedures)+≡

```
recursive subroutine eval_node_compile_record_cmd (en, pn, var_list)
  type(eval_node_t), pointer :: en
  type(parse_node_t), intent(in) :: pn
  type(var_list_t), intent(in), target :: var_list
  type(parse_node_t), pointer :: pn_tag, pn_arg, pn_arg1, pn_arg2
  type(eval_node_t), pointer :: en0, en1, en2
  if (debug) then
    print *, "read record_cmd"; call parse_node_write (pn)
  end if
  pn_tag => parse_node_get_sub_ptr (pn, 2)
  pn_arg => parse_node_get_next_ptr (pn_tag)
  select case (char (parse_node_get_rule_key (pn_tag)))
  case ("analysis_id")
    allocate (en0)
    call eval_node_init_string (en0, parse_node_get_string (pn_tag))
  case default
    call eval_node_compile_sexpr (en0, pn_tag, var_list)
  end select
  allocate (en)
  if (associated (pn_arg)) then
    pn_arg1 => parse_node_get_sub_ptr (pn_arg)
    call eval_node_compile_expr (en1, pn_arg1, var_list)
    if (en1%result_type == V_INT) &
      call insert_conversion_node (en1, V_REAL)
    pn_arg2 => parse_node_get_next_ptr (pn_arg1)
    if (associated (pn_arg2)) then
      call eval_node_compile_expr (en2, pn_arg2, var_list)
      if (en2%result_type == V_INT) &
        call insert_conversion_node (en2, V_REAL)
      call eval_node_init_record_cmd (en, en0, en1, en2)
    else
      call eval_node_init_record_cmd (en, en0, en1)
    end if
  else
    call eval_node_init_record_cmd (en, en0)
  end if
  if (debug) then
    call eval_node_write (en)
    print *, "done record_cmd"
  end if
end subroutine eval_node_compile_record_cmd
```

Particle-list expressions

A particle expression is a particle list or a combination of particle-list value.

(*Expressions: procedures*) +=

```

recursive subroutine eval_node_compile_pexpr (en, pn, var_list)
  type(eval_node_t), pointer :: en
  type(parse_node_t), intent(in) :: pn
  type(var_list_t), intent(in), target :: var_list
  type(parse_node_t), pointer :: pn_pvalue, pn_combination, pn_op, pn_arg
  type(eval_node_t), pointer :: en1, en2
  type(prt_list_t) :: prt_list
  if (debug) then
    print *, "read pexpr"; call parse_node_write (pn)
  end if
  pn_pvalue => parse_node_get_sub_ptr (pn)
  call eval_node_compile_pvalue (en, pn_pvalue, var_list)
  pn_combination => parse_node_get_next_ptr (pn_pvalue, tag="combination")
  do while (associated (pn_combination))
    pn_op => parse_node_get_sub_ptr (pn_combination)
    pn_arg => parse_node_get_next_ptr (pn_op)
    en1 => en
    call eval_node_compile_pvalue (en2, pn_arg, var_list)
    allocate (en)
    if (en1%type == EN_CONSTANT .and. en2%type == EN_CONSTANT) then
      call prt_list_combine (prt_list, en1%pval, en2%pval)
      call eval_node_init_prt_list (en, prt_list)
      call eval_node_final_rec (en1)
      call eval_node_final_rec (en2)
      deallocate (en1, en2)
    else
      call eval_node_init_branch &
        (en, var_str ("combine"), V_PTL, en1, en2)
      call eval_node_set_op2_ptl (en, combine_pp)
    end if
    pn_combination => parse_node_get_next_ptr (pn_combination)
  end do
  if (debug) then
    call eval_node_write (en)
    print *, "done pexpr"
  end if
end subroutine eval_node_compile_pexpr

```

A particle-list value is a PDG-code array, a particle identifier, a variable, a (grouped) pexpr, a block pexpr, a conditional, or a particle-list function.

The `cexpr` node is responsible for transforming a constant PDG-code array into a particle list. It takes the code array as its first argument, the event particle list as its second argument, and the requested particle type (incoming/outgoing) as its zero-th argument. The result is the list of particle in the event that match the code array.

(*Expressions: procedures*) +=

```

recursive subroutine eval_node_compile_pvalue (en, pn, var_list)
  type(eval_node_t), pointer :: en
  type(parse_node_t), intent(in) :: pn

```

```

type(var_list_t), intent(in), target :: var_list
type(parse_node_t), pointer :: pn_prefix_cexpr
type(eval_node_t), pointer :: en1, en2, en0
type(string_t) :: key
type(var_entry_t), pointer :: var
logical, save, target :: known = .true.
if (debug) then
    print *, "read pvalue"; call parse_node_write (pn)
end if
select case (char (parse_node_get_rule_key (pn)))
case ("pexpr_src")
    call eval_node_compile_prefix_cexpr (en1, pn, var_list)
    allocate (en2)
    var => var_list_get_var_ptr (var_list, var_str ("%evt"))
    if (associated (var)) then
        call eval_node_init_prt_list_ptr &
            (en2, var_str ("%evt"), var_entry_get_pval_ptr (var), known)
        allocate (en)
        call eval_node_init_branch &
            (en, var_str ("prt_selection"), V_PTL, en1, en2)
        call eval_node_set_op2_ptl (en, select_pdg_ca)
        allocate (en0)
        pn_prefix_cexpr => parse_node_get_sub_ptr (pn)
        key = parse_node_get_rule_key (pn_prefix_cexpr)
        select case (char (key))
        case ("incoming_prt")
            call eval_node_init_int (en0, PRT_INCOMING)
            en%arg0 => en0
        case ("outgoing_prt")
            call eval_node_init_int (en0, PRT_OUTGOING)
            en%arg0 => en0
        end select
    else
        call parse_node_write (pn)
        call msg_bug (" Missing event data while compiling pvalue")
    end if
case ("pvariable")
    call eval_node_compile_variable (en, pn, var_list, V_PTL)
case ("pexpr")
    call eval_node_compile_pexpr (en, pn, var_list)
case ("block_pexpr")
    call eval_node_compile_block_expr (en, pn, var_list, V_PTL)
case ("conditional_pexpr")
    call eval_node_compile_conditional (en, pn, var_list, V_PTL)
case ("join_fun", "combine_fun", "collect_fun", "select_fun", &
    "extract_fun", "sort_fun")
    call eval_node_compile_prt_function (en, pn, var_list)
case default
    call parse_node_mismatch &
        ("prefix_cexpr|pvariable|" // &
        "grouped_pexpr|block_pexpr|conditional_pexpr|" // &
        "prt_function", pn)
end select
if (debug) then

```

```

        call eval_node_write (en)
        print *, "done pvalue"
    end if
end subroutine eval_node_compile_pvalue

```

Particle functions

This combines the treatment of 'join', 'combine', 'collect', 'select', and 'extract' which all have the same syntax. The one or two argument nodes are allocated. If there is a condition, the condition node is also allocated as a logical expression, for which the variable list is augmented by the appropriate (unary/binary) observables.

(*Expressions: procedures*) +=

```

recursive subroutine eval_node_compile_prt_function (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    type(parse_node_t), pointer :: pn_clause, pn_key, pn_cond, pn_args
    type(parse_node_t), pointer :: pn_arg0, pn_arg1, pn_arg2
    type(eval_node_t), pointer :: en0, en1, en2
    type(string_t) :: key
    if (debug) then
        print *, "read prt_function"; call parse_node_write (pn)
    end if
    pn_clause => parse_node_get_sub_ptr (pn)
    pn_key => parse_node_get_sub_ptr (pn_clause)
    pn_cond => parse_node_get_next_ptr (pn_key)
    if (associated (pn_cond)) &
        pn_arg0 => parse_node_get_sub_ptr (pn_cond, 2)
    pn_args => parse_node_get_next_ptr (pn_clause)
    pn_arg1 => parse_node_get_sub_ptr (pn_args)
    pn_arg2 => parse_node_get_next_ptr (pn_arg1)
    key = parse_node_get_key (pn_key)
    call eval_node_compile_pexpr (en1, pn_arg1, var_list)
    allocate (en)
    if (.not. associated (pn_arg2)) then
        select case (char (key))
            case ("collect")
                call eval_node_init_prt_fun_unary (en, en1, key, collect_p)
            case ("select")
                call eval_node_init_prt_fun_unary (en, en1, key, select_p)
            case ("extract")
                call eval_node_init_prt_fun_unary (en, en1, key, extract_p)
            case ("sort")
                call eval_node_init_prt_fun_unary (en, en1, key, sort_p)
            case default
                call msg_bug (" Unary particle function '" // char (key) // &
                    "' undefined")
        end select
    else
        call eval_node_compile_pexpr (en2, pn_arg2, var_list)
        select case (char (key))

```

```

case ("join")
    call eval_node_init_prt_fun_binary (en, en1, en2, key, join_pp)
case ("combine")
    call eval_node_init_prt_fun_binary (en, en1, en2, key, combine_pp)
case ("collect")
    call eval_node_init_prt_fun_binary (en, en1, en2, key, collect_pp)
case ("select")
    call eval_node_init_prt_fun_binary (en, en1, en2, key, select_pp)
case ("sort")
    call eval_node_init_prt_fun_binary (en, en1, en2, key, sort_pp)
case default
    call msg_bug (" Binary particle function '" // char (key) // &
        "' undefined")
end select
end if
if (associated (pn_cond)) then
    call eval_node_set_observables (en, var_list)
    select case (char (key))
    case ("extract", "sort")
        call eval_node_compile_expr (en0, pn_arg0, en%var_list)
    case default
        call eval_node_compile_lexpr (en0, pn_arg0, en%var_list)
    end select
    en%arg0 => en0
end if
if (debug) then
    call eval_node_write (en)
    print *, "done prt_function"
end if
end subroutine eval_node_compile_prt_function

```

The `eval` expression is similar, but here the expression `arg0` is mandatory, and the whole thing evaluates to a numeric value.

(Expressions: procedures)+≡

```

recursive subroutine eval_node_compile_eval_function (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    type(parse_node_t), pointer :: pn_key, pn_arg0, pn_args, pn_arg1, pn_arg2
    type(eval_node_t), pointer :: en0, en1, en2
    type(string_t) :: key
    if (debug) then
        print *, "read eval_function"; call parse_node_write (pn)
    end if
    pn_key => parse_node_get_sub_ptr (pn)
    pn_arg0 => parse_node_get_next_ptr (pn_key)
    pn_args => parse_node_get_next_ptr (pn_arg0)
    pn_arg1 => parse_node_get_sub_ptr (pn_args)
    pn_arg2 => parse_node_get_next_ptr (pn_arg1)
    key = parse_node_get_key (pn_key)
    call eval_node_compile_pexpr (en1, pn_arg1, var_list)
    allocate (en)
    if (.not. associated (pn_arg2)) then

```

```

        call eval_node_init_eval_fun_unary (en, en1, key)
    else
        call eval_node_compile_pexpr (en2, pn_arg2, var_list)
        call eval_node_init_eval_fun_binary (en, en1, en2, key)
    end if
    call eval_node_set_observables (en, var_list)
    call eval_node_compile_expr (en0, pn_arg0, en%var_list)
    if (en0%result_type /= V_REAL) &
        call msg_fatal (" 'eval' function does not result in real value")
    call eval_node_set_expr (en, en0)
    if (debug) then
        call eval_node_write (en)
        print *, "done eval_function"
    end if
end subroutine eval_node_compile_eval_function

```

Logical functions of particle lists.

(Expressions: procedures)+≡

```

recursive subroutine eval_node_compile_log_function (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    type(parse_node_t), pointer :: pn_key, pn_arg0, pn_args, pn_arg1, pn_arg2
    type(eval_node_t), pointer :: en0, en1, en2
    type(string_t) :: key
    if (debug) then
        print *, "read log_function"; call parse_node_write (pn)
    end if
    pn_key => parse_node_get_sub_ptr (pn)
    pn_arg0 => parse_node_get_next_ptr (pn_key)
    pn_args => parse_node_get_next_ptr (pn_arg0)
    pn_arg1 => parse_node_get_sub_ptr (pn_args)
    pn_arg2 => parse_node_get_next_ptr (pn_arg1)
    key = parse_node_get_key (pn_key)
    call eval_node_compile_pexpr (en1, pn_arg1, var_list)
    allocate (en)
    if (.not. associated (pn_arg2)) then
        select case (char (key))
            case ("all")
                call eval_node_init_log_fun_unary (en, en1, key, all_p)
            case ("any")
                call eval_node_init_log_fun_unary (en, en1, key, any_p)
            case ("no")
                call eval_node_init_log_fun_unary (en, en1, key, no_p)
        end select
    else
        call eval_node_compile_pexpr (en2, pn_arg2, var_list)
        select case (char (key))
            case ("all")
                call eval_node_init_log_fun_binary (en, en1, en2, key, all_pp)
            case ("any")
                call eval_node_init_log_fun_binary (en, en1, en2, key, any_pp)
            case ("no")
                call eval_node_init_log_fun_binary (en, en1, en2, key, no_pp)
        end select
    end if
end subroutine eval_node_compile_log_function

```

```

        end select
    end if
    call eval_node_set_observables (en, var_list)
    call eval_node_compile_lexpr (en0, pn_arg0, en%var_list)
    call eval_node_set_expr (en, en0)
    if (debug) then
        call eval_node_write (en)
        print *, "done log_function"
    end if
end subroutine eval_node_compile_log_function

```

Integer functions of particle lists.

(Expressions: procedures)+≡

```

recursive subroutine eval_node_compile_int_function (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    type(parse_node_t), pointer :: pn_clause, pn_key, pn_cond, pn_args
    type(parse_node_t), pointer :: pn_arg0, pn_arg1, pn_arg2
    type(eval_node_t), pointer :: en0, en1, en2
    type(string_t) :: key
    if (debug) then
        print *, "read int_function"; call parse_node_write (pn)
    end if
    pn_clause => parse_node_get_sub_ptr (pn)
    pn_key   => parse_node_get_sub_ptr (pn_clause)
    pn_cond => parse_node_get_next_ptr (pn_key)
    if (associated (pn_cond)) &
        pn_arg0 => parse_node_get_sub_ptr (pn_cond, 2)
    pn_args => parse_node_get_next_ptr (pn_clause)
    pn_arg1 => parse_node_get_sub_ptr (pn_args)
    pn_arg2 => parse_node_get_next_ptr (pn_arg1)
    key = parse_node_get_key (pn_key)
    call eval_node_compile_pexpr (en1, pn_arg1, var_list)
    allocate (en)
    if (.not. associated (pn_arg2)) then
        select case (char (key))
            case ("count")
                call eval_node_init_int_fun_unary (en, en1, key, count_a)
            end select
    else
        call eval_node_compile_pexpr (en2, pn_arg2, var_list)
        select case (char (key))
            case ("count")
                call eval_node_init_int_fun_binary (en, en1, en2, key, count_pp)
            end select
    end if
    if (associated (pn_cond)) then
        call eval_node_set_observables (en, var_list)
        call eval_node_compile_lexpr (en0, pn_arg0, en%var_list)
        call eval_node_set_expr (en, en0, V_INT)
    end if
    if (debug) then
        call eval_node_write (en)
    end if
end subroutine eval_node_compile_int_function

```

```

        print *, "done int_function"
    end if
end subroutine eval_node_compile_int_function

```

PDG-code arrays

A PDG-code expression is either prefixed by `incoming` or `outgoing`, a block, or a conditional. In any case, it evaluates to a constant.

(Expressions: procedures) +≡

```

recursive subroutine eval_node_compile_prefix_cexpr (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    type(parse_node_t), pointer :: pn_avalue, pn_prt
    type(string_t) :: key
    if (debug) then
        print *, "read prefix_cexpr"; call parse_node_write (pn)
    end if
    pn_avalue => parse_node_get_sub_ptr (pn)
    key = parse_node_get_rule_key (pn_avalue)
    select case (char (key))
    case ("incoming_prt")
        pn_prt => parse_node_get_sub_ptr (pn_avalue, 2)
        call eval_node_compile_cexpr (en, pn_prt, var_list)
    case ("outgoing_prt")
        pn_prt => parse_node_get_sub_ptr (pn_avalue, 1)
        call eval_node_compile_cexpr (en, pn_prt, var_list)
    case default
        call parse_node_mismatch &
            ("incoming_prt|outgoing_prt", &
            pn_avalue)
    end select
    if (debug) then
        call eval_node_write (en)
        print *, "done prefix_cexpr"
    end if
end subroutine eval_node_compile_prefix_cexpr

```

A PDG array is a string of PDG code definitions (or aliases), concatenated by `'.'`. The code definitions may be variables which are not defined at compile time, so we have to allocate sub-nodes. This analogous to `eval_node_compile_term`.

(Expressions: procedures) +≡

```

recursive subroutine eval_node_compile_cexpr (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    type(parse_node_t), pointer :: pn_prt, pn_concatenation
    type(eval_node_t), pointer :: en1, en2
    type(pdg_array_t) :: aval
    if (debug) then
        print *, "read cexpr"; call parse_node_write (pn)
    end if

```

```

pn_prt => parse_node_get_sub_ptr (pn)
call eval_node_compile_avalue (en, pn_prt, var_list)
pn_concatenation => parse_node_get_next_ptr (pn_prt)
do while (associated (pn_concatenation))
    pn_prt => parse_node_get_sub_ptr (pn_concatenation, 2)
    en1 => en
    call eval_node_compile_avalue (en2, pn_prt, var_list)
    allocate (en)
    if (en1%type == EN_CONSTANT .and. en2%type == EN_CONSTANT) then
        call concat_cc (aval, en1, en2)
        call eval_node_init_pdg_array (en, aval)
        call eval_node_final_rec (en1)
        call eval_node_final_rec (en2)
        deallocate (en1, en2)
    else
        call eval_node_init_branch (en, var_str (":"), V_PDG, en1, en2)
        call eval_node_set_op2_pdg (en, concat_cc)
    end if
    pn_concatenation => parse_node_get_next_ptr (pn_concatenation)
end do
if (debug) then
    call eval_node_write (en)
    print *, "done cexpr"
end if
end subroutine eval_node_compile_cexpr

```

Compile a PDG-code type value. It may be either an integer expression or a variable of type PDG array, optionally quoted.

(Expressions: procedures)+≡

```

recursive subroutine eval_node_compile_avalue (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in) :: pn
    type(var_list_t), intent(in), target :: var_list
    if (debug) then
        print *, "read avalue"; call parse_node_write (pn)
    end if
    select case (char (parse_node_get_rule_key (pn)))
    case ("pdg_code")
        call eval_node_compile_pdg_code (en, pn, var_list)
    case ("cvariable", "variable", "prt_name")
        call eval_node_compile_cvariable (en, pn, var_list)
    case ("cexpr")
        call eval_node_compile_cexpr (en, pn, var_list)
    case ("block_cexpr")
        call eval_node_compile_block_expr (en, pn, var_list, V_PDG)
    case ("conditional_cexpr")
        call eval_node_compile_conditional (en, pn, var_list, V_PDG)
    case default
        call parse_node_mismatch &
            ("grouped_cexpr|block_cexpr|conditional_cexpr|" // &
             "pdg_code|cvariable|prt_name", pn)
    end select
    if (debug) then

```

```

        call eval_node_write (en)
        print *, "done avalue"
    end if
end subroutine eval_node_compile_avalue

```

Compile a PDG-code expression, which is the key PDG with an integer expression as argument. The procedure is analogous to `eval_node_compile_unary_function`.

(Expressions: procedures) +=

```

subroutine eval_node_compile_pdg_code (en, pn, var_list)
    type(eval_node_t), pointer :: en
    type(parse_node_t), intent(in), target :: pn
    type(var_list_t), intent(in), target :: var_list
    type(parse_node_t), pointer :: pn_arg
    type(eval_node_t), pointer :: en1
    type(string_t) :: key
    type(pdg_array_t) :: aval
    integer :: t
    if (debug) then
        print *, "read PDG code"; call parse_node_write (pn)
    end if
    pn_arg => parse_node_get_sub_ptr (pn, 2)
    call eval_node_compile_expr &
        (en1, parse_node_get_sub_ptr (pn_arg, tag="expr"), var_list)
    t = en1%result_type
    allocate (en)
    key = "PDG"
    if (en1%type == EN_CONSTANT) then
        select case (t)
            case (V_INT)
                call pdg_i (aval, en1)
                call eval_node_init_pdg_array (en, aval)
            case default; call eval_type_error (pn, char (key), t)
        end select
        call eval_node_final_rec (en1)
        deallocate (en1)
    else
        select case (t)
            case (V_INT); call eval_node_set_op1_pdg (en, pdg_i)
            case default; call eval_type_error (pn, char (key), t)
        end select
    end if
    if (debug) then
        call eval_node_write (en)
        print *, "done function"
    end if
end subroutine eval_node_compile_pdg_code

```

This is entirely analogous to `eval_node_compile_variable`. However, PDG-array variables occur in different contexts.

To avoid name clashes between PDG-array variables and ordinary variables, we prepend a character (*). This is not visible to the user.

(Expressions: procedures) +=

```

subroutine eval_node_compile_cvariable (en, pn, var_list)

```

```

type(eval_node_t), pointer :: en
type(parse_node_t), intent(in), target :: pn
type(var_list_t), intent(in), target :: var_list
type(parse_node_t), pointer :: pn_name
type(string_t) :: var_name
type(var_entry_t), pointer :: var
type(pdg_array_t), target, save :: no_aval
logical, target, save :: unknown = .false.
if (debug) then
    print *, "read cvariable"; call parse_node_write (pn)
end if
! select case (char (parse_node_get_rule_key (pn)))
! case ("cvariable"); pn_name => parse_node_get_sub_ptr (pn, 2)
! case default; pn_name => pn
! end select
pn_name => pn
var_name = parse_node_get_string (pn_name)
var => var_list_get_var_ptr (var_list, var_name, V_PDG)
allocate (en)
if (associated (var)) then
    call eval_node_init_pdg_array_ptr &
        (en, var_entry_get_name (var), var_entry_get_aval_ptr (var), &
        var_entry_get_known_ptr (var))
else
    call parse_node_write (pn)
    call msg_error ("This PDG-array variable is undefined at this point")
    call eval_node_init_pdg_array_ptr (en, var_name, no_aval, unknown)
end if
if (debug) then
    call eval_node_write (en)
    print *, "done cvariable"
end if
end subroutine eval_node_compile_cvariable

```

String expressions

A string expression is either a string value or a concatenation of string values.

(Expressions: procedures)+≡

```

recursive subroutine eval_node_compile_sexpr (en, pn, var_list)
type(eval_node_t), pointer :: en
type(parse_node_t), intent(in) :: pn
type(var_list_t), intent(in), target :: var_list
type(parse_node_t), pointer :: pn_svalue, pn_concatenation, pn_op, pn_arg
type(eval_node_t), pointer :: en1, en2
type(string_t) :: string
if (debug) then
    print *, "read sexpr"; call parse_node_write (pn)
end if
pn_svalue => parse_node_get_sub_ptr (pn)
call eval_node_compile_svalue (en, pn_svalue, var_list)
pn_concatenation => &
    parse_node_get_next_ptr (pn_svalue, tag="str_concatenation")
do while (associated (pn_concatenation))

```

```

pn_op => parse_node_get_sub_ptr (pn_concatenation)
pn_arg => parse_node_get_next_ptr (pn_op)
en1 => en
call eval_node_compile_svalue (en2, pn_arg, var_list)
allocate (en)
if (en1%type == EN_CONSTANT .and. en2%type == EN_CONSTANT) then
  call concat_ss (string, en1, en2)
  call eval_node_init_string (en, string)
  call eval_node_final_rec (en1)
  call eval_node_final_rec (en2)
  deallocate (en1, en2)
else
  call eval_node_init_branch &
    (en, var_str ("concat"), V_STR, en1, en2)
  call eval_node_set_op2_str (en, concat_ss)
end if
pn_concatenation => parse_node_get_next_ptr (pn_concatenation)
end do
if (debug) then
  call eval_node_write (en)
  print *, "done sexpr"
end if
end subroutine eval_node_compile_sexpr

```

A string value is a string literal, a variable, a (grouped) sexpr, a block sexpr, or a conditional.

(Expressions: procedures)+≡

```

recursive subroutine eval_node_compile_svalue (en, pn, var_list)
  type(eval_node_t), pointer :: en
  type(parse_node_t), intent(in) :: pn
  type(var_list_t), intent(in), target :: var_list
  if (debug) then
    print *, "read svalue"; call parse_node_write (pn)
  end if
  select case (char (parse_node_get_rule_key (pn)))
  case ("svariable")
    call eval_node_compile_variable (en, pn, var_list, V_STR)
  case ("sexpr")
    call eval_node_compile_sexpr (en, pn, var_list)
  case ("block_sexpr")
    call eval_node_compile_block_expr (en, pn, var_list, V_STR)
  case ("conditional_sexpr")
    call eval_node_compile_conditional (en, pn, var_list, V_STR)
  case ("string_literal")
    allocate (en)
    call eval_node_init_string (en, parse_node_get_string (pn))
  case default
    call parse_node_mismatch &
      ("svariable|" // &
        "grouped_sexpr|block_sexpr|conditional_sexpr|" // &
        "string_literal", pn)
  end select
  if (debug) then

```

```

        call eval_node_write (en)
        print *, "done svalue"
    end if
end subroutine eval_node_compile_svalue

```

5.5.5 Auxiliary functions for the compiler

Issue an error that the current node could not be compiled because of type mismatch:

```

(Expressions: procedures) +=
subroutine eval_type_error (pn, string, t)
    type(parse_node_t), intent(in) :: pn
    character(*), intent(in) :: string
    integer, intent(in) :: t
    type(string_t) :: type
    select case (t)
    case (V_NONE); type = "(none)"
    case (V_LOG); type = "'logical'"
    case (V_INT); type = "'integer'"
    case (V_REAL); type = "'real'"
    case (V_CMPLX); type = "'complex'"
    case default; type = "(unknown)"
    end select
    call parse_node_write (pn)
    call msg_fatal (" The " // string // &
        " operation is not defined for the given argument type " // &
        char (type))
end subroutine eval_type_error

```

If two numerics are combined, the result is integer if both arguments are integer, if one is integer and the other real or both are real, than its argument is real, otherwise complex.

```

(Expressions: procedures) +=
function numeric_result_type (t1, t2) result (t)
    integer, intent(in) :: t1, t2
    integer :: t
    if (t1 == V_INT .and. t2 == V_INT) then
        t = V_INT
    else if (t1 == V_INT .and. t2 == V_REAL) then
        t = V_REAL
    else if (t1 == V_REAL .and. t2 == V_INT) then
        t = V_REAL
    else if (t1 == V_REAL .and. t2 == V_REAL) then
        t = V_REAL
    else
        t = V_CMPLX
    end if
end function numeric_result_type

```

5.5.6 Evaluation

Evaluation is done recursively. For leaf nodes nothing is to be done.

Evaluating particle-list functions: First, we evaluate the particle lists. If a condition is present, we assign the particle pointers of the condition node to the allocated particle entries in the parent node, keeping in mind that the observables in the variable stack used for the evaluation of the condition also contain pointers to these entries. Then, the assigned procedure is evaluated, which sets the particle list in the parent node. If required, the procedure evaluates the condition node once for each (pair of) particles to determine the result.

(Expressions: procedures)+≡

```

recursive subroutine eval_node_evaluate (en)
  type(eval_node_t), intent(inout) :: en
  logical :: exist
  select case (en%type)
  case (EN_UNARY)
    call eval_node_evaluate (en%arg1)
    en%value_is_known = en%arg1%value_is_known
    if (en%value_is_known) then
      select case (en%result_type)
      case (V_LOG); en%lval = en% op1_log (en%arg1)
      case (V_INT); en%ival = en% op1_int (en%arg1)
      case (V_REAL); en%rval = en% op1_real (en%arg1)
      case (V_CMPLX); en%cval = en% op1_cmplx (en%arg1)
      case (V_PDG);
        call en% op1_pdg (en%aval, en%arg1)
      case (V_PTL)
        if (associated (en%arg0)) then
          call en% op1_ptl (en%pval, en%arg1, en%arg0)
        else
          call en% op1_ptl (en%pval, en%arg1)
        end if
      case (V_STR)
        call en% op1_str (en%sval, en%arg1)
      end select
    end if
  case (EN_BINARY)
    call eval_node_evaluate (en%arg1)
    call eval_node_evaluate (en%arg2)
    en%value_is_known = &
      en%arg1%value_is_known .and. en%arg2%value_is_known
    if (en%value_is_known) then
      select case (en%result_type)
      case (V_LOG); en%lval = en% op2_log (en%arg1, en%arg2)
      case (V_INT); en%ival = en% op2_int (en%arg1, en%arg2)
      case (V_REAL); en%rval = en% op2_real (en%arg1, en%arg2)
      case (V_CMPLX); en%cval = en% op2_cmplx (en%arg1, en%arg2)
      case (V_PDG)
        call en% op2_pdg (en%aval, en%arg1, en%arg2)
      case (V_PTL)
        if (associated (en%arg0)) then
          call en% op2_ptl (en%pval, en%arg1, en%arg2, en%arg0)
        else

```

```

        call en% op2_ptl (en%pval, en%arg1, en%arg2)
    end if
    case (V_STR)
        call en% op2_str (en%sval, en%arg1, en%arg2)
    end select
end if
case (EN_BLOCK)
    call eval_node_evaluate (en%arg1)
    call eval_node_evaluate (en%arg0)
    en%value_is_known = en%arg0%value_is_known
    if (en%value_is_known) then
        select case (en%result_type)
            case (V_LOG); en%lval = en%arg0%lval
            case (V_INT); en%ival = en%arg0%ival
            case (V_REAL); en%rval = en%arg0%rval
            case (V_CMPLX); en%cval = en%arg0%cval
            case (V_PDG); en%aval = en%arg0%aval
            case (V_PTL); en%pval = en%arg0%pval
            case (V_STR); en%sval = en%arg0%sval
        end select
    end if
case (EN_CONDITIONAL)
    call eval_node_evaluate (en%arg0)
    en%value_is_known = en%arg0%value_is_known
    if (en%arg0%value_is_known) then
        if (en%arg0%lval) then
            call eval_node_evaluate (en%arg1)
            en%value_is_known = en%arg1%value_is_known
            if (en%value_is_known) then
                select case (en%result_type)
                    case (V_LOG); en%lval = en%arg1%lval
                    case (V_INT); en%ival = en%arg1%ival
                    case (V_REAL); en%rval = en%arg1%rval
                    case (V_CMPLX); en%cval = en%arg1%cval
                    case (V_PDG); en%aval = en%arg1%aval
                    case (V_PTL); en%pval = en%arg1%pval
                    case (V_STR); en%sval = en%arg1%sval
                end select
            end if
        else
            call eval_node_evaluate (en%arg2)
            en%value_is_known = en%arg2%value_is_known
            if (en%value_is_known) then
                select case (en%result_type)
                    case (V_LOG); en%lval = en%arg2%lval
                    case (V_INT); en%ival = en%arg2%ival
                    case (V_REAL); en%rval = en%arg2%rval
                    case (V_CMPLX); en%cval = en%arg2%cval
                    case (V_PDG); en%aval = en%arg2%aval
                    case (V_PTL); en%pval = en%arg2%pval
                    case (V_STR); en%sval = en%arg2%sval
                end select
            end if
        end if
    end if
end if

```

```

        end if
    case (EN_RECORD_CMD)
        exist = .true.
        call eval_node_evaluate (en%arg0)
        if (en%arg0%value_is_known) then
            if (associated (en%arg1)) then
                call eval_node_evaluate (en%arg1)
                if (en%arg1%value_is_known) then
                    if (associated (en%arg2)) then
                        call eval_node_evaluate (en%arg2)
                        if (en%arg2%value_is_known) then
                            call analysis_record_data (en%arg0%sval, &
                                en%arg1%rval, en%arg2%rval, exist=exist)
                        end if
                    else
                        call analysis_record_data (en%arg0%sval, &
                            en%arg1%rval, exist=exist)
                    end if
                end if
            else
                call analysis_record_data (en%arg0%sval, 1._default, &
                    exist=exist)
            end if
        if (.not. exist) then
            call msg_error ("Analysis object '" // char (en%arg0%sval) &
                // "' is undefined")
            en%arg0%value_is_known = .false.
        end if
    end if
case (EN_OBS1_INT)
    en%ival = en% obs1_int (en%prt1)
    en%value_is_known = .true.
case (EN_OBS2_INT)
    en%ival = en% obs2_int (en%prt1, en%prt2)
    en%value_is_known = .true.
case (EN_OBS1_REAL)
    en%rval = en% obs1_real (en%prt1)
    en%value_is_known = .true.
case (EN_OBS2_REAL)
    en%rval = en% obs2_real (en%prt1, en%prt2)
    en%value_is_known = .true.
case (EN_PRT_FUN_UNARY)
    call eval_node_evaluate (en%arg1)
    en%value_is_known = en%arg1%value_is_known
    if (en%value_is_known) then
        if (associated (en%arg0)) then
            en%arg0%index => en%index
            en%arg0%prt1 => en%prt1
            call en% op1_pt1 (en%pval, en%arg1, en%arg0)
        else
            call en% op1_pt1 (en%pval, en%arg1)
        end if
    end if
case (EN_PRT_FUN_BINARY)

```

```

call eval_node_evaluate (en%arg1)
call eval_node_evaluate (en%arg2)
en%value_is_known = &
    en%arg1%value_is_known .and. en%arg2%value_is_known
if (en%value_is_known) then
    if (associated (en%arg0)) then
        en%arg0%index => en%index
        en%arg0%prt1 => en%prt1
        en%arg0%prt2 => en%prt2
        call en% op2_ptl (en%pval, en%arg1, en%arg2, en%arg0)
    else
        call en% op2_ptl (en%pval, en%arg1, en%arg2)
    end if
end if
case (EN_EVAL_FUN_UNARY)
    call eval_node_evaluate (en%arg1)
    en%value_is_known = prt_list_is_nonempty (en%arg1%pval)
    if (en%value_is_known) then
        en%arg0%index => en%index
        en%index = 1
        en%arg0%prt1 => en%prt1
        en%prt1 = prt_list_get_prt (en%arg1%pval, 1)
        call eval_node_evaluate (en%arg0)
        en%rval = en%arg0%rval
    end if
case (EN_EVAL_FUN_BINARY)
    call eval_node_evaluate (en%arg1)
    call eval_node_evaluate (en%arg2)
    en%value_is_known = &
        prt_list_is_nonempty (en%arg1%pval) .and. &
        prt_list_is_nonempty (en%arg2%pval)
    if (en%value_is_known) then
        en%arg0%index => en%index
        en%arg0%prt1 => en%prt1
        en%arg0%prt2 => en%prt2
        en%index = 1
        en%prt1 = prt_list_get_prt (en%arg1%pval, 1)
        en%prt2 = prt_list_get_prt (en%arg2%pval, 1)
        call eval_node_evaluate (en%arg0)
        en%rval = en%arg0%rval
    end if
case (EN_LOG_FUN_UNARY)
    call eval_node_evaluate (en%arg1)
    en%value_is_known = .true.
    if (en%value_is_known) then
        en%arg0%index => en%index
        en%arg0%prt1 => en%prt1
        en%lval = en% op1_cut (en%arg1, en%arg0)
    end if
case (EN_LOG_FUN_BINARY)
    call eval_node_evaluate (en%arg1)
    call eval_node_evaluate (en%arg2)
    en%value_is_known = .true.
    if (en%value_is_known) then

```

```

        en%arg0%index => en%index
        en%arg0%prt1 => en%prt1
        en%arg0%prt2 => en%prt2
        en%lval = en% op2_cut (en%arg1, en%arg2, en%arg0)
    end if
case (EN_INT_FUN_UNARY)
    call eval_node_evaluate (en%arg1)
    en%value_is_known = en%arg1%value_is_known
    if (en%value_is_known) then
        if (associated (en%arg0)) then
            en%arg0%index => en%index
            en%arg0%prt1 => en%prt1
            call en% op1_num (en%ival, en%arg1, en%arg0)
        else
            call en% op1_num (en%ival, en%arg1)
        end if
    end if
case (EN_INT_FUN_BINARY)
    call eval_node_evaluate (en%arg1)
    call eval_node_evaluate (en%arg2)
    en%value_is_known = &
        en%arg1%value_is_known .and. &
        en%arg2%value_is_known
    if (en%value_is_known) then
        if (associated (en%arg0)) then
            en%arg0%index => en%index
            en%arg0%prt1 => en%prt1
            en%arg0%prt2 => en%prt2
            call en% op2_num (en%ival, en%arg1, en%arg2, en%arg0)
        else
            call en% op2_num (en%ival, en%arg1, en%arg2)
        end if
    end if
end select
if (debug) then
    print *, "evaluated"
    call eval_node_write (en)
end if
end subroutine eval_node_evaluate

```

5.5.7 Evaluation syntax

We have two different flavors of the syntax: with and without particles.

(Expressions: variables) +=
 type(syntax_t), target, save :: syntax_expr
 type(syntax_t), target, save :: syntax_pexpr

These are for testing only and may be removed:

(Expressions: public) =
 public :: syntax_expr_init
 public :: syntax_pexpr_init

```

<Expressions: procedures>+≡
  subroutine syntax_expr_init ()
    type(ifile_t) :: ifile
    call define_expr_syntax (ifile, particles=.false., analysis=.false.)
    call syntax_init (syntax_expr, ifile)
    call ifile_final (ifile)
  end subroutine syntax_expr_init

  subroutine syntax_pexpr_init ()
    type(ifile_t) :: ifile
    call define_expr_syntax (ifile, particles=.true., analysis=.false.)
    call syntax_init (syntax_pexpr, ifile)
    call ifile_final (ifile)
  end subroutine syntax_pexpr_init

<Expressions: public>+≡
  public :: syntax_expr_final
  public :: syntax_pexpr_final

<Expressions: procedures>+≡
  subroutine syntax_expr_final ()
    call syntax_final (syntax_expr)
  end subroutine syntax_expr_final

  subroutine syntax_pexpr_final ()
    call syntax_final (syntax_pexpr)
  end subroutine syntax_pexpr_final

<Expressions: public>+≡
  public :: define_expr_syntax

Numeric expressions.

<Expressions: procedures>+≡
  subroutine define_expr_syntax (ifile, particles, analysis)
    type(ifile_t), intent(inout) :: ifile
    logical, intent(in) :: particles, analysis
    type(string_t) :: numeric_pexpr
    type(string_t) :: var_plist, var_alias
    if (particles) then
      numeric_pexpr = " | numeric_pexpr"
      var_plist = " | var_plist"
      var_alias = " | var_alias"
    else
      numeric_pexpr = ""
      var_plist = ""
      var_alias = ""
    end if
    call ifile_append (ifile, "SEQ expr = subexpr addition*")
    call ifile_append (ifile, "ALT subexpr = addition | term")
    call ifile_append (ifile, "SEQ addition = plus_or_minus term")
    call ifile_append (ifile, "SEQ term = factor multiplication*")
    call ifile_append (ifile, "SEQ multiplication = times_or_over factor")
    call ifile_append (ifile, "SEQ factor = value exponentiation?")
    call ifile_append (ifile, "SEQ exponentiation = to_the value")
  end subroutine define_expr_syntax

```

```

call ifile_append (ifile, "ALT plus_or_minus = '+' | '-'")
call ifile_append (ifile, "ALT times_or_over = '*' | '/'")
call ifile_append (ifile, "ALT to_the = '^' | '**")
call ifile_append (ifile, "KEY '+'")
call ifile_append (ifile, "KEY '-'")
call ifile_append (ifile, "KEY '*'")
call ifile_append (ifile, "KEY '/'")
call ifile_append (ifile, "KEY '^'")
call ifile_append (ifile, "KEY '**")
call ifile_append (ifile, "ALT value = signed_value | unsigned_value")
call ifile_append (ifile, "SEQ signed_value = '-' unsigned_value")
call ifile_append (ifile, "ALT unsigned_value = " // &
    "numeric_value | constant | variable | result | " // &
    "grouped_expr | block_expr | conditional_expr | " // &
    "unary_function | binary_function" // &
    numeric_pexpr)
call ifile_append (ifile, "ALT numeric_value = integer_value | " &
    // "real_value | complex_value")
call ifile_append (ifile, "SEQ integer_value = integer_literal unit_expr?")
call ifile_append (ifile, "SEQ real_value = real_literal unit_expr?")
call ifile_append (ifile, "SEQ complex_value = complex_literal unit_expr?")
call ifile_append (ifile, "INT integer_literal")
call ifile_append (ifile, "REA real_literal")
call ifile_append (ifile, "COM complex_literal")
call ifile_append (ifile, "SEQ unit_expr = unit unit_power?")
call ifile_append (ifile, "ALT unit = " // &
    "TeV | GeV | MeV | keV | eV | meV | " // &
    "nbarn | pbarn | fbarn | abarn | " // &
    "rad | mrad | degree | '%")
call ifile_append (ifile, "KEY TeV")
call ifile_append (ifile, "KEY GeV")
call ifile_append (ifile, "KEY MeV")
call ifile_append (ifile, "KEY keV")
call ifile_append (ifile, "KEY eV")
call ifile_append (ifile, "KEY meV")
call ifile_append (ifile, "KEY nbarn")
call ifile_append (ifile, "KEY pbarn")
call ifile_append (ifile, "KEY fbarn")
call ifile_append (ifile, "KEY abarn")
call ifile_append (ifile, "KEY rad")
call ifile_append (ifile, "KEY mrad")
call ifile_append (ifile, "KEY degree")
call ifile_append (ifile, "KEY '%")
call ifile_append (ifile, "SEQ unit_power = '^' frac_expr")
call ifile_append (ifile, "ALT frac_expr = frac | grouped_frac")
call ifile_append (ifile, "GRO grouped_frac = ( frac_expr )")
call ifile_append (ifile, "SEQ frac = signed_int div?")
call ifile_append (ifile, "ALT signed_int = " &
    // "neg_int | pos_int | integer_literal")
call ifile_append (ifile, "SEQ neg_int = '-' integer_literal")
call ifile_append (ifile, "SEQ pos_int = '+' integer_literal")
call ifile_append (ifile, "SEQ div = '/' integer_literal")
call ifile_append (ifile, "ALT constant = pi")
call ifile_append (ifile, "KEY pi")

```

```

call ifile_append (ifile, "IDE variable")
call ifile_append (ifile, "SEQ result = result_key result_arg")
call ifile_append (ifile, "ALT result_key = " // &
    "n_calls | integral | error | accuracy | efficiency")
call ifile_append (ifile, "KEY n_calls")
call ifile_append (ifile, "KEY integral")
call ifile_append (ifile, "KEY error")
call ifile_append (ifile, "KEY accuracy")
call ifile_append (ifile, "KEY efficiency")
call ifile_append (ifile, "GRO result_arg = ( process_id )")
call ifile_append (ifile, "IDE process_id")
call ifile_append (ifile, "SEQ unary_function = fun_unary function_arg1")
call ifile_append (ifile, "SEQ binary_function = fun_binary function_arg2")
call ifile_append (ifile, "ALT fun_unary = " // &
    "cmplx | real | int | nint | floor | ceiling | abs | sgn | " // &
    "sqrt | exp | log | log10 | " // &
    "sin | cos | tan | asin | acos | atan | " // &
    "sinh | cosh | tanh")
call ifile_append (ifile, "KEY cmplx")
call ifile_append (ifile, "KEY real")
call ifile_append (ifile, "KEY int")
call ifile_append (ifile, "KEY nint")
call ifile_append (ifile, "KEY floor")
call ifile_append (ifile, "KEY ceiling")
call ifile_append (ifile, "KEY abs")
call ifile_append (ifile, "KEY sgn")
call ifile_append (ifile, "KEY sqrt")
call ifile_append (ifile, "KEY exp")
call ifile_append (ifile, "KEY log")
call ifile_append (ifile, "KEY log10")
call ifile_append (ifile, "KEY sin")
call ifile_append (ifile, "KEY cos")
call ifile_append (ifile, "KEY tan")
call ifile_append (ifile, "KEY asin")
call ifile_append (ifile, "KEY acos")
call ifile_append (ifile, "KEY atan")
call ifile_append (ifile, "KEY sinh")
call ifile_append (ifile, "KEY cosh")
call ifile_append (ifile, "KEY tanh")
call ifile_append (ifile, "ALT fun_binary = max | min | mod | modulo")
call ifile_append (ifile, "KEY max")
call ifile_append (ifile, "KEY min")
call ifile_append (ifile, "KEY mod")
call ifile_append (ifile, "KEY modulo")
call ifile_append (ifile, "ARG function_arg1 = ( expr )")
call ifile_append (ifile, "ARG function_arg2 = ( expr, expr )")
call ifile_append (ifile, "GRO grouped_expr = ( expr )")
call ifile_append (ifile, "SEQ block_expr = let var_spec in expr")
call ifile_append (ifile, "KEY let")
call ifile_append (ifile, "ALT var_spec = " // &
    "var_num | var_int | var_real | var_cmplx | " // &
    "var_logical" // var_plist // var_alias // " | var_string")
call ifile_append (ifile, "SEQ var_num = var_name '=' expr")
call ifile_append (ifile, "SEQ var_int = int var_name '=' expr")

```

```

call ifile_append (ifile, "SEQ var_real = real var_name '=' expr")
call ifile_append (ifile, "SEQ var_cmplx = cmplx var_name '=' cmplx_expr")
call ifile_append (ifile, "ALT cmplx_expr = " // &
    "cexpr_real | cexpr_cmplx")
call ifile_append (ifile, "ARG cexpr_cmplx = ( expr, expr )")
call ifile_append (ifile, "SEQ cexpr_real = expr")
call ifile_append (ifile, "IDE var_name")
call ifile_append (ifile, "KEY '='")
call ifile_append (ifile, "KEY in")
call ifile_append (ifile, "SEQ conditional_expr = " // &
    "if lexpr then expr else expr endif")
call ifile_append (ifile, "KEY if")
call ifile_append (ifile, "KEY then")
call ifile_append (ifile, "KEY else")
call ifile_append (ifile, "KEY endif")
call define_lexpr_syntax (ifile, particles, analysis)
call define_sexpr_syntax (ifile)
if (particles) then
    call define_pexpr_syntax (ifile)
    call define_cexpr_syntax (ifile)
    call define_var_plist_syntax (ifile)
    call define_var_alias_syntax (ifile)
    call define_numeric_pexpr_syntax (ifile)
    call define_logical_pexpr_syntax (ifile)
end if

end subroutine define_expr_syntax

```

Logical expressions.

(Expressions: procedures) +=

```

subroutine define_lexpr_syntax (ifile, particles, analysis)
    type(ifile_t), intent(inout) :: ifile
    logical, intent(in) :: particles, analysis
    type(string_t) :: logical_pexpr, record_cmd
    if (particles) then
        logical_pexpr = " | logical_pexpr"
    else
        logical_pexpr = ""
    end if
    if (analysis) then
        record_cmd = " | record_cmd"
    else
        record_cmd = ""
    end if
    call ifile_append (ifile, "SEQ lexpr = lterm alternative*")
    call ifile_append (ifile, "SEQ alternative = or lterm")
    call ifile_append (ifile, "SEQ lterm = lvalue coincidence*")
    call ifile_append (ifile, "SEQ coincidence = and lvalue")
    call ifile_append (ifile, "KEY or")
    call ifile_append (ifile, "KEY and")
    call ifile_append (ifile, "ALT lvalue = " // &
        "true | false | lvariable | negation | " // &
        "grouped_lexpr | block_lexpr | conditional_lexpr | " // &
        "compared_expr | compared_sexpr" // &

```

```

        logical_pexpr // record_cmd)
call ifile_append (ifile, "KEY true")
call ifile_append (ifile, "KEY false")
call ifile_append (ifile, "SEQ lvariable = '?' variable")
call ifile_append (ifile, "KEY '?'")
call ifile_append (ifile, "SEQ negation = not lvalue")
call ifile_append (ifile, "KEY not")
call ifile_append (ifile, "GRO grouped_lexpr = ( lexpr )")
call ifile_append (ifile, "SEQ block_lexpr = let var_spec in lexpr")
call ifile_append (ifile, "SEQ var_logical = '?' var_name = lexpr")
call ifile_append (ifile, "SEQ conditional_lexpr = " // &
    "if lexpr then lexpr else lexpr endif")
call ifile_append (ifile, "SEQ compared_expr = expr comparison+")
call ifile_append (ifile, "SEQ comparison = compare expr")
call ifile_append (ifile, "ALT compare = " // &
    "'<' | '>' | '<=' | '>=' | '==' | '/=' | '~' | '/~'")
call ifile_append (ifile, "KEY '<'")
call ifile_append (ifile, "KEY '>'")
call ifile_append (ifile, "KEY '<='")
call ifile_append (ifile, "KEY '>='")
call ifile_append (ifile, "KEY '=='")
call ifile_append (ifile, "KEY '/='")
call ifile_append (ifile, "KEY '~'")
call ifile_append (ifile, "KEY '/~'")
call ifile_append (ifile, "SEQ compared_sexpr = sexpr str_comparison+")
call ifile_append (ifile, "SEQ str_comparison = str_compare sexpr")
call ifile_append (ifile, "ALT str_compare = '==' | '/='")
if (analysis) then
    call ifile_append (ifile, "SEQ record_cmd = " // &
        "record analysis_tag record_arg?")
    call ifile_append (ifile, "KEY record")
    call ifile_append (ifile, "ALT analysis_tag = analysis_id | sexpr")
    call ifile_append (ifile, "IDE analysis_id")
    call ifile_append (ifile, "ARG record_arg = ( expr, expr? )")
end if
end subroutine define_lexpr_syntax

```

String expressions.

(Expressions: procedures)+≡

```

subroutine define_sexpr_syntax (ifile)
type(ifile_t), intent(inout) :: ifile
call ifile_append (ifile, "SEQ sexpr = svalue str_concatenation*")
call ifile_append (ifile, "SEQ str_concatenation = '//' svalue")
call ifile_append (ifile, "KEY '//'")
call ifile_append (ifile, "ALT svalue = " // &
    "grouped_sexpr | block_sexpr | conditional_sexpr | " // &
    "svariable | string_literal")
call ifile_append (ifile, "GRO grouped_sexpr = ( sexpr )")
call ifile_append (ifile, "SEQ block_sexpr = let var_spec in sexpr")
call ifile_append (ifile, "SEQ conditional_sexpr = " // &
    "if lexpr then sexpr else sexpr endif")
call ifile_append (ifile, "SEQ svariable = '$' variable")
call ifile_append (ifile, "KEY '$'")
call ifile_append (ifile, "SEQ var_string = '$' var_name '=' sexpr") ! $

```

```

    call ifile_append (ifile, "QUO string_literal = '""'...'""')
end subroutine define_sexpr_syntax

```

Expressions that evaluate to particle lists.

(Expressions: procedures)+≡

```

subroutine define_pexpr_syntax (ifile)
  type(ifile_t), intent(inout) :: ifile
  call ifile_append (ifile, "SEQ pexpr = pvalue combination*")
  call ifile_append (ifile, "SEQ combination = '&' pvalue")
  call ifile_append (ifile, "KEY '&'")
  call ifile_append (ifile, "ALT pvalue = " // &
    "pexpr_src | pvariable | " // &
    "grouped_pexpr | block_pexpr | conditional_pexpr | " // &
    "prt_function")
  call ifile_append (ifile, "SEQ pexpr_src = prefix_cexpr")
  call ifile_append (ifile, "ALT prefix_cexpr = " // &
    "incoming_prt | outgoing_prt")
  call ifile_append (ifile, "SEQ incoming_prt = incoming cexpr")
  call ifile_append (ifile, "KEY incoming")
  call ifile_append (ifile, "SEQ outgoing_prt = cexpr")
  call ifile_append (ifile, "SEQ pvariable = '@' variable")
  call ifile_append (ifile, "KEY '@'")
  call ifile_append (ifile, "GRO grouped_pexpr = '[' pexpr ']'")
  call ifile_append (ifile, "SEQ block_pexpr = let var_spec in pexpr")
  call ifile_append (ifile, "SEQ conditional_pexpr = " // &
    "if lexpr then pexpr else pexpr endif")
  call ifile_append (ifile, "ALT prt_function = " // &
    "join_fun | combine_fun | collect_fun | select_fun | " // &
    "extract_fun | sort_fun")
  call ifile_append (ifile, "SEQ join_fun = join_clause pargs2")
  call ifile_append (ifile, "SEQ combine_fun = combine_clause pargs2")
  call ifile_append (ifile, "SEQ collect_fun = collect_clause pargs1")
  call ifile_append (ifile, "SEQ select_fun = select_clause pargs1")
  call ifile_append (ifile, "SEQ extract_fun = extract_clause pargs1")
  call ifile_append (ifile, "SEQ sort_fun = sort_clause pargs1")
  call ifile_append (ifile, "SEQ join_clause = join condition?")
  call ifile_append (ifile, "SEQ combine_clause = combine condition?")
  call ifile_append (ifile, "SEQ collect_clause = collect condition?")
  call ifile_append (ifile, "SEQ select_clause = select condition?")
  call ifile_append (ifile, "SEQ extract_clause = extract position?")
  call ifile_append (ifile, "SEQ sort_clause = sort criterion?")
  call ifile_append (ifile, "KEY join")
  call ifile_append (ifile, "KEY combine")
  call ifile_append (ifile, "KEY collect")
  call ifile_append (ifile, "KEY select")
  call ifile_append (ifile, "SEQ condition = if lexpr")
  call ifile_append (ifile, "KEY extract")
  call ifile_append (ifile, "SEQ position = index expr")
  call ifile_append (ifile, "KEY sort")
  call ifile_append (ifile, "SEQ criterion = by expr")
  call ifile_append (ifile, "KEY index")
  call ifile_append (ifile, "KEY by")
  call ifile_append (ifile, "ARG pargs2 = '[' pexpr, pexpr ']'")
  call ifile_append (ifile, "ARG pargs1 = '[' pexpr, pexpr? ']'")

```

```
end subroutine define_pexpr_syntax
```

Expressions that evaluate to PDG-code arrays.

(Expressions: procedures)+≡

```
subroutine define_cexpr_syntax (ifile)
  type(ifile_t), intent(inout) :: ifile
  call ifile_append (ifile, "SEQ cexpr = avalue concatenation*")
  call ifile_append (ifile, "SEQ concatenation = ':' avalue")
  call ifile_append (ifile, "KEY ':'")
  call ifile_append (ifile, "ALT avalue = " // &
    "grouped_cexpr | block_cexpr | conditional_cexpr | " // &
    "variable | pdg_code | prt_name")
  call ifile_append (ifile, "GRO grouped_cexpr = ( cexpr )")
  call ifile_append (ifile, "SEQ block_cexpr = let var_spec in cexpr")
  call ifile_append (ifile, "SEQ conditional_cexpr = " // &
    "if lexpr then cexpr else cexpr endif")
  call ifile_append (ifile, "SEQ pdg_code = pdg pdg_arg")
  call ifile_append (ifile, "KEY pdg")
  call ifile_append (ifile, "ARG pdg_arg = ( expr )")
  call ifile_append (ifile, "QUO prt_name = '""'...'""'")
end subroutine define_cexpr_syntax
```

Extra variable types.

(Expressions: procedures)+≡

```
subroutine define_var_plist_syntax (ifile)
  type(ifile_t), intent(inout) :: ifile
  call ifile_append (ifile, "SEQ var_plist = '@' var_name '=' pexpr")
end subroutine define_var_plist_syntax

subroutine define_var_alias_syntax (ifile)
  type(ifile_t), intent(inout) :: ifile
  call ifile_append (ifile, "SEQ var_alias = alias var_name '=' cexpr")
  call ifile_append (ifile, "KEY alias")
end subroutine define_var_alias_syntax
```

Particle-list expressions that evaluate to numeric values

(Expressions: procedures)+≡

```
subroutine define_numeric_pexpr_syntax (ifile)
  type(ifile_t), intent(inout) :: ifile
  call ifile_append (ifile, "ALT numeric_pexpr = eval_fun | count_fun")
  call ifile_append (ifile, "SEQ eval_fun = eval expr pargs1")
  call ifile_append (ifile, "SEQ count_fun = count_clause pargs1")
  call ifile_append (ifile, "SEQ count_clause = count condition?")
  call ifile_append (ifile, "KEY eval")
  call ifile_append (ifile, "KEY count")
end subroutine define_numeric_pexpr_syntax
```

Particle-list functions that evaluate to logical values.

(Expressions: procedures)+≡

```
subroutine define_logical_pexpr_syntax (ifile)
  type(ifile_t), intent(inout) :: ifile
  call ifile_append (ifile, "ALT logical_pexpr = " // &
```

```

    "all_fun | any_fun | no_fun")
    call ifile_append (ifile, "SEQ all_fun = all lexpr pargs1")
    call ifile_append (ifile, "SEQ any_fun = any lexpr pargs1")
    call ifile_append (ifile, "SEQ no_fun = no lexpr pargs1")
    call ifile_append (ifile, "KEY all")
    call ifile_append (ifile, "KEY any")
    call ifile_append (ifile, "KEY no")
end subroutine define_logical_pexpr_syntax

```

All characters that can occur in expressions (apart from alphanumeric).

```

(Expressions: procedures) +=
  subroutine lexer_init_eval_tree (lexer, particles)
    type(lexer_t), intent(out) :: lexer
    logical, intent(in) :: particles
    type(keyword_list_t), pointer :: keyword_list
    if (particles) then
      keyword_list => syntax_get_keyword_list_ptr (syntax_pexpr)
    else
      keyword_list => syntax_get_keyword_list_ptr (syntax_expr)
    end if
    call lexer_init (lexer, &
      comment_chars = "#!", &
      quote_chars = "'", &
      quote_match = "'", &
      single_chars = "()[],:%?$@", &
      special_class = (/ "+-*/^<>=~" /) , &
      keyword_list = keyword_list)
  end subroutine lexer_init_eval_tree

```

5.5.8 Set up appropriate parse trees

Parse an input stream as a specific flavor of expression. The appropriate expression syntax has to be available.

```

(Expressions: public) +=
  public :: parse_tree_init_expr
  public :: parse_tree_init_lexpr
  public :: parse_tree_init_pexpr
  public :: parse_tree_init_cexpr
  public :: parse_tree_init_sexpr

(Expressions: procedures) +=
  subroutine parse_tree_init_expr (parse_tree, stream, particles)
    type(parse_tree_t), intent(out) :: parse_tree
    type(stream_t), intent(inout) :: stream
    logical, intent(in) :: particles
    type(lexer_t) :: lexer
    call lexer_init_eval_tree (lexer, particles)
    if (particles) then
      call parse_tree_init &
        (parse_tree, syntax_pexpr, lexer, stream, var_str ("expr"))
    else
      call parse_tree_init &

```

```

        (parse_tree, syntax_expr, lexer, stream, var_str ("expr"))
    end if
    call lexer_final (lexer)
end subroutine parse_tree_init_expr

subroutine parse_tree_init_lexpr (parse_tree, stream, particles)
    type(parse_tree_t), intent(out) :: parse_tree
    type(stream_t), intent(inout) :: stream
    logical, intent(in) :: particles
    type(lexer_t) :: lexer
    call lexer_init_eval_tree (lexer, particles)
    if (particles) then
        call parse_tree_init &
            (parse_tree, syntax_pexpr, lexer, stream, var_str ("lexpr"))
    else
        call parse_tree_init &
            (parse_tree, syntax_expr, lexer, stream, var_str ("lexpr"))
    end if
    call lexer_final (lexer)
end subroutine parse_tree_init_lexpr

subroutine parse_tree_init_pexpr (parse_tree, stream)
    type(parse_tree_t), intent(out) :: parse_tree
    type(stream_t), intent(inout) :: stream
    type(lexer_t) :: lexer
    call lexer_init_eval_tree (lexer, .true.)
    call parse_tree_init &
        (parse_tree, syntax_pexpr, lexer, stream, var_str ("pexpr"))
    call lexer_final (lexer)
end subroutine parse_tree_init_pexpr

subroutine parse_tree_init_cexpr (parse_tree, stream)
    type(parse_tree_t), intent(out) :: parse_tree
    type(stream_t), intent(inout) :: stream
    type(lexer_t) :: lexer
    call lexer_init_eval_tree (lexer, .true.)
    call parse_tree_init &
        (parse_tree, syntax_pexpr, lexer, stream, var_str ("cexpr"))
    call lexer_final (lexer)
end subroutine parse_tree_init_cexpr

subroutine parse_tree_init_sexpr (parse_tree, stream, particles)
    type(parse_tree_t), intent(out) :: parse_tree
    type(stream_t), intent(inout) :: stream
    logical, intent(in) :: particles
    type(lexer_t) :: lexer
    call lexer_init_eval_tree (lexer, particles)
    if (particles) then
        call parse_tree_init &
            (parse_tree, syntax_pexpr, lexer, stream, var_str ("sexpr"))
    else
        call parse_tree_init &
            (parse_tree, syntax_expr, lexer, stream, var_str ("sexpr"))
    end if
end if

```

```

    call lexer_final (lexer)
end subroutine parse_tree_init_sexpr

```

5.5.9 The evaluation tree

The evaluation tree contains the initial variable list and the root node.

```

<Expressions: public>+≡
    public :: eval_tree_t

<Expressions: types>+≡
    type :: eval_tree_t
    private
        type(var_list_t) :: var_list
        type(eval_node_t), pointer :: root => null ()
    end type eval_tree_t

```

Init from stream, using a temporary parse tree.

```

<Expressions: procedures>+≡
    subroutine eval_tree_init_stream &
        (eval_tree, stream, var_list, prt_list, result_type)
        type(eval_tree_t), intent(out), target :: eval_tree
        type(stream_t), intent(inout) :: stream
        type(var_list_t), intent(in), target :: var_list
        type(prt_list_t), intent(in), target, optional :: prt_list
        integer, intent(in), optional :: result_type
        type(parse_tree_t) :: parse_tree
        type(parse_node_t), pointer :: nd_root
        integer :: type
        type = V_REAL; if (present (result_type)) type = result_type
        select case (type)
        case (V_INT, V_REAL)
            call parse_tree_init_expr (parse_tree, stream, present (prt_list))
        case (V_LOG)
            call parse_tree_init_lexpr (parse_tree, stream, present (prt_list))
        case (V_PTL)
            call parse_tree_init_pexpr (parse_tree, stream)
        case (V_PDG)
            call parse_tree_init_cexpr (parse_tree, stream)
        case (V_STR)
            call parse_tree_init_sexpr (parse_tree, stream, present (prt_list))
        end select
        call parse_tree_write (parse_tree)
        nd_root => parse_tree_get_root_ptr (parse_tree)
        if (associated (nd_root)) then
            select case (type)
            case (V_INT, V_REAL)
                call eval_tree_init_expr (eval_tree, nd_root, var_list, prt_list)
            case (V_LOG)
                call eval_tree_init_lexpr (eval_tree, nd_root, var_list, prt_list)
            case (V_PTL)
                call eval_tree_init_pexpr (eval_tree, nd_root, var_list, prt_list)
            case (V_PDG)

```

```

        call eval_tree_init_cexpr (eval_tree, nd_root, var_list, prt_list)
    case (V_STR)
        call eval_tree_init_sexpr (eval_tree, nd_root, var_list, prt_list)
    end select
end if
call parse_tree_final (parse_tree)
end subroutine eval_tree_init_stream

```

API: Init from a given parse-tree node. If we evaluate an expression that contains particle-list references, the original particle list has to be supplied. The initial variable list is optional.

(Expressions: public)+≡

```

public :: eval_tree_init_expr
public :: eval_tree_init_lexpr
public :: eval_tree_init_pexpr
public :: eval_tree_init_cexpr
public :: eval_tree_init_sexpr

```

(Expressions: procedures)+≡

```

subroutine eval_tree_init_expr (eval_tree, parse_node, var_list, prt_list)
    type(eval_tree_t), intent(out), target :: eval_tree
    type(parse_node_t), intent(in), target :: parse_node
    type(var_list_t), intent(in), target :: var_list
    type(prt_list_t), intent(in), optional, target :: prt_list
    call eval_tree_set_var_list (eval_tree, var_list, prt_list)
    call eval_node_compile_expr &
        (eval_tree%root, parse_node, eval_tree%var_list)
end subroutine eval_tree_init_expr

```

```

subroutine eval_tree_init_lexpr (eval_tree, parse_node, var_list, prt_list)
    type(eval_tree_t), intent(out), target :: eval_tree
    type(parse_node_t), intent(in), target :: parse_node
    type(var_list_t), intent(in), target :: var_list
    type(prt_list_t), intent(in), optional, target :: prt_list
    call eval_tree_set_var_list (eval_tree, var_list, prt_list)
    call eval_node_compile_lexpr &
        (eval_tree%root, parse_node, eval_tree%var_list)
end subroutine eval_tree_init_lexpr

```

```

subroutine eval_tree_init_pexpr (eval_tree, parse_node, var_list, prt_list)
    type(eval_tree_t), intent(out), target :: eval_tree
    type(parse_node_t), intent(in), target :: parse_node
    type(var_list_t), intent(in), target :: var_list
    type(prt_list_t), intent(in), optional, target :: prt_list
    call eval_tree_set_var_list (eval_tree, var_list, prt_list)
    call eval_node_compile_pexpr &
        (eval_tree%root, parse_node, eval_tree%var_list)
end subroutine eval_tree_init_pexpr

```

```

subroutine eval_tree_init_cexpr (eval_tree, parse_node, var_list, prt_list)
    type(eval_tree_t), intent(out), target :: eval_tree
    type(parse_node_t), intent(in), target :: parse_node
    type(var_list_t), intent(in), target :: var_list
    type(prt_list_t), intent(in), optional, target :: prt_list

```

```

    call eval_tree_set_var_list (eval_tree, var_list, prt_list)
    call eval_node_compile_cexpr &
        (eval_tree%root, parse_node, eval_tree%var_list)
end subroutine eval_tree_init_cexpr

subroutine eval_tree_init_sexpr (eval_tree, parse_node, var_list, prt_list)
    type(eval_tree_t), intent(out), target :: eval_tree
    type(parse_node_t), intent(in), target :: parse_node
    type(var_list_t), intent(in), target :: var_list
    type(prt_list_t), intent(in), optional, target :: prt_list
    call eval_tree_set_var_list (eval_tree, var_list, prt_list)
    call eval_node_compile_sexpr &
        (eval_tree%root, parse_node, eval_tree%var_list)
end subroutine eval_tree_init_sexpr

```

This extra API function handles numerical constant expressions only. The only nontrivial part is the optional unit.

```

<Expressions: public>+≡
    public :: eval_tree_init_numeric_value

<Expressions: procedures>+≡
    subroutine eval_tree_init_numeric_value (eval_tree, parse_node)
        type(eval_tree_t), intent(out), target :: eval_tree
        type(parse_node_t), intent(in), target :: parse_node
        call eval_node_compile_numeric_value (eval_tree%root, parse_node)
    end subroutine eval_tree_init_numeric_value

```

Initialize the variable list with the initial one; if a particle list is provided, add a pointer to this as variable @evt.

```

<Expressions: procedures>+≡
    subroutine eval_tree_set_var_list (eval_tree, var_list, prt_list)
        type(eval_tree_t), intent(inout), target :: eval_tree
        type(var_list_t), intent(in), target :: var_list
        type(prt_list_t), intent(in), optional, target :: prt_list
        logical, save, target :: known = .true.
        call var_list_link (eval_tree%var_list, var_list)
        if (present (prt_list)) call var_list_append_prt_list_ptr &
            (eval_tree%var_list, var_str ("@evt"), prt_list, known, &
                intrinsic=.true.)
    end subroutine eval_tree_set_var_list

```

```

<Expressions: public>+≡
    public :: eval_tree_final

<Expressions: procedures>+≡
    subroutine eval_tree_final (eval_tree)
        type(eval_tree_t), intent(inout) :: eval_tree
        call var_list_final (eval_tree%var_list)
        if (associated (eval_tree%root)) then
            call eval_node_final_rec (eval_tree%root)
            deallocate (eval_tree%root)
        end if
    end subroutine eval_tree_final

```

```

<Expressions: public>+≡
    public :: eval_tree_evaluate

<Expressions: procedures>+≡
    subroutine eval_tree_evaluate (eval_tree)
        type(eval_tree_t), intent(inout) :: eval_tree
        if (associated (eval_tree%root)) then
            call eval_node_evaluate (eval_tree%root)
        end if
    end subroutine eval_tree_evaluate

```

Check if the eval tree is allocated.

```

<Expressions: public>+≡
    public :: eval_tree_is_defined

<Expressions: procedures>+≡
    function eval_tree_is_defined (eval_tree) result (flag)
        logical :: flag
        type(eval_tree_t), intent(in) :: eval_tree
        flag = associated (eval_tree%root)
    end function eval_tree_is_defined

```

Check if the eval tree result is constant.

```

<Expressions: public>+≡
    public :: eval_tree_is_constant

<Expressions: procedures>+≡
    function eval_tree_is_constant (eval_tree) result (flag)
        logical :: flag
        type(eval_tree_t), intent(in) :: eval_tree
        if (associated (eval_tree%root)) then
            flag = eval_tree%root%type == EN_CONSTANT
        else
            flag = .false.
        end if
    end function eval_tree_is_constant

```

Insert a conversion node at the root, if necessary (only for real/int conversion)

```

<Expressions: public>+≡
    public :: eval_tree_convert_result

<Expressions: procedures>+≡
    subroutine eval_tree_convert_result (eval_tree, result_type)
        type(eval_tree_t), intent(inout) :: eval_tree
        integer, intent(in) :: result_type
        if (associated (eval_tree%root)) then
            call insert_conversion_node (eval_tree%root, result_type)
        end if
    end subroutine eval_tree_convert_result

```

Return the value of the top node, after evaluation. If the tree is empty, return the type of V_NONE. When extracting the value, no check for existence is done. For numeric values, the functions are safe against real/integer mismatch.

```

<Expressions: public>+≡

```

```

public :: eval_tree_get_result_type
public :: eval_tree_result_is_known
public :: eval_tree_result_is_known_ptr
public :: eval_tree_get_log
public :: eval_tree_get_int
public :: eval_tree_get_real
public :: eval_tree_get_cmplx
public :: eval_tree_get_pdg_array
public :: eval_tree_get_prt_list
public :: eval_tree_get_string

```

(Expressions: procedures)+≡

```

function eval_tree_get_result_type (eval_tree) result (type)
  integer :: type
  type(eval_tree_t), intent(in) :: eval_tree
  if (associated (eval_tree%root)) then
    type = eval_tree%root%result_type
  else
    type = V_NONE
  end if
end function eval_tree_get_result_type

```

```

function eval_tree_result_is_known (eval_tree) result (flag)
  logical :: flag
  type(eval_tree_t), intent(in) :: eval_tree
  if (associated (eval_tree%root)) then
    select case (eval_tree%root%result_type)
    case (V_LOG, V_INT, V_REAL)
      flag = eval_tree%root%value_is_known
    case default
      flag = .true.
    end select
  else
    flag = .false.
  end if
end function eval_tree_result_is_known

```

```

function eval_tree_result_is_known_ptr (eval_tree) result (ptr)
  logical, pointer :: ptr
  type(eval_tree_t), intent(in) :: eval_tree
  logical, target, save :: known = .true.
  if (associated (eval_tree%root)) then
    select case (eval_tree%root%result_type)
    case (V_LOG, V_INT, V_REAL)
      ptr => eval_tree%root%value_is_known
    case default
      ptr => known
    end select
  else
    ptr => null ()
  end if
end function eval_tree_result_is_known_ptr

```

```

function eval_tree_get_log (eval_tree) result (lval)
  logical :: lval

```

```

    type(eval_tree_t), intent(in) :: eval_tree
    if (associated (eval_tree%root)) lval = eval_tree%root%lval
end function eval_tree_get_log

function eval_tree_get_int (eval_tree) result (ival)
    integer :: ival
    type(eval_tree_t), intent(in) :: eval_tree
    if (associated (eval_tree%root)) then
        select case (eval_tree%root%result_type)
            case (V_INT); ival = eval_tree%root%ival
            case (V_REAL); ival = eval_tree%root%rval
            case (V_CMPLX); ival = eval_tree%root%cval
        end select
    end if
end function eval_tree_get_int

function eval_tree_get_real (eval_tree) result (rval)
    real(default) :: rval
    type(eval_tree_t), intent(in) :: eval_tree
    if (associated (eval_tree%root)) then
        select case (eval_tree%root%result_type)
            case (V_REAL); rval = eval_tree%root%rval
            case (V_INT); rval = eval_tree%root%ival
            case (V_CMPLX); rval = eval_tree%root%cval
        end select
    end if
end function eval_tree_get_real

function eval_tree_get_cmplx (eval_tree) result (cval)
    complex(default) :: cval
    type(eval_tree_t), intent(in) :: eval_tree
    if (associated (eval_tree%root)) then
        select case (eval_tree%root%result_type)
            case (V_CMPLX); cval = eval_tree%root%cval
            case (V_REAL); cval = eval_tree%root%rval
            case (V_INT); cval = eval_tree%root%ival
        end select
    end if
end function eval_tree_get_cmplx

function eval_tree_get_pdg_array (eval_tree) result (aval)
    type(pdg_array_t) :: aval
    type(eval_tree_t), intent(in) :: eval_tree
    if (associated (eval_tree%root)) then
        aval = eval_tree%root%aval
    end if
end function eval_tree_get_pdg_array

function eval_tree_get_prt_list (eval_tree) result (pval)
    type(prt_list_t) :: pval
    type(eval_tree_t), intent(in) :: eval_tree
    if (associated (eval_tree%root)) then
        pval = eval_tree%root%pval
    end if
end function eval_tree_get_prt_list

```

```

end function eval_tree_get_ptr_list

function eval_tree_get_string (eval_tree) result (sval)
  type(string_t) :: sval
  type(eval_tree_t), intent(in) :: eval_tree
  if (associated (eval_tree%root)) then
    sval = eval_tree%root%sval
  end if
end function eval_tree_get_string

```

Return a pointer to the value of the top node.

(Expressions: public)+≡

```

public :: eval_tree_get_log_ptr
public :: eval_tree_get_int_ptr
public :: eval_tree_get_real_ptr
public :: eval_tree_get_cmplx_ptr
public :: eval_tree_get_ptr_list_ptr
public :: eval_tree_get_pdg_array_ptr
public :: eval_tree_get_string_ptr

```

(Expressions: procedures)+≡

```

function eval_tree_get_log_ptr (eval_tree) result (lval)
  logical, pointer :: lval
  type(eval_tree_t), intent(in) :: eval_tree
  if (associated (eval_tree%root)) then
    lval => eval_tree%root%lval
  else
    lval => null ()
  end if
end function eval_tree_get_log_ptr

```

```

function eval_tree_get_int_ptr (eval_tree) result (ival)
  integer, pointer :: ival
  type(eval_tree_t), intent(in) :: eval_tree
  if (associated (eval_tree%root)) then
    ival => eval_tree%root%ival
  else
    ival => null ()
  end if
end function eval_tree_get_int_ptr

```

```

function eval_tree_get_real_ptr (eval_tree) result (rval)
  real(default), pointer :: rval
  type(eval_tree_t), intent(in) :: eval_tree
  if (associated (eval_tree%root)) then
    rval => eval_tree%root%rval
  else
    rval => null ()
  end if
end function eval_tree_get_real_ptr

```

```

function eval_tree_get_cmplx_ptr (eval_tree) result (cval)
  complex(default), pointer :: cval
  type(eval_tree_t), intent(in) :: eval_tree

```

```

    if (associated (eval_tree%root)) then
        cval => eval_tree%root%cval
    else
        cval => null ()
    end if
end function eval_tree_get_cmplx_ptr

function eval_tree_get_ptr_list_ptr (eval_tree) result (pval)
    type(ptr_list_t), pointer :: pval
    type(eval_tree_t), intent(in) :: eval_tree
    if (associated (eval_tree%root)) then
        pval => eval_tree%root%pval
    else
        pval => null ()
    end if
end function eval_tree_get_ptr_list_ptr

function eval_tree_get_pdg_array_ptr (eval_tree) result (aval)
    type(pdg_array_t), pointer :: aval
    type(eval_tree_t), intent(in) :: eval_tree
    if (associated (eval_tree%root)) then
        aval => eval_tree%root%aval
    else
        aval => null ()
    end if
end function eval_tree_get_pdg_array_ptr

function eval_tree_get_string_ptr (eval_tree) result (sval)
    type(string_t), pointer :: sval
    type(eval_tree_t), intent(in) :: eval_tree
    if (associated (eval_tree%root)) then
        sval => eval_tree%root%sval
    else
        sval => null ()
    end if
end function eval_tree_get_string_ptr

```

<Expressions: public>+≡

```
public :: eval_tree_write
```

<Expressions: procedures>+≡

```

subroutine eval_tree_write (eval_tree, unit, write_var_list)
    type(eval_tree_t), intent(in) :: eval_tree
    integer, intent(in), optional :: unit
    logical, intent(in), optional :: write_var_list
    integer :: u
    logical :: vl
    u = output_unit (unit); if (u < 0) return
    vl = .false.; if (present (write_var_list)) vl = write_var_list
    write (u, "(1x,A)") "Evaluation tree:"
    if (associated (eval_tree%root)) then
        call eval_node_write_rec (eval_tree%root, unit)
    else
        write (u, "(3x,A)") "[empty]"
    end if
end subroutine eval_tree_write

```

```

end if
if (vl) call var_list_write (eval_tree%var_list, unit)
end subroutine eval_tree_write

```

5.5.10 Test

```

(Expressions: public) +=
  public :: expressions_test

(Expressions: procedures) +=
  subroutine expressions_test ()
    call expressions_test1 ()
    !   call syntax_expr_init ()
    !   call syntax_write (syntax_expr)
    !   call expressions_test1
    !   call syntax_expr_final ()
    !   print *
    !   call expressions_test2
    !   print *
    !   call syntax_pexpr_init ()
    !   call syntax_write (syntax_pexpr)
    !   call expressions_test3
    !   call syntax_pexpr_final ()
  end subroutine expressions_test

  subroutine expressions_test1 ()
    type(var_list_t) :: var_list
    type(eval_node_t) :: node
    type(prt_t), target :: prt
    type(var_entry_t), pointer :: var
    call var_list_set_observables_unary (var_list, prt)
    call var_list_write (var_list)
    var => var_list_get_var_ptr (var_list, var_str ("PDG"))
    call eval_node_init_obs (node, var)
    call eval_node_write (node)
  end subroutine expressions_test1

  !   subroutine expressions_test1 ()
  !   !   type(ifile_t) :: ifile
  !   !   type(stream_t) :: stream
  !   !   type(eval_tree_t) :: eval_tree
  !   !   type(string_t) :: expr_text
  !   !   type(var_list_t), target :: var_list
  !   !   call var_list_append_real (var_list, var_str ("x"), -5._default)
  !   !   call var_list_append_int (var_list, var_str ("foo"), -27)
  !   !   call var_list_append_real (var_list, var_str ("mb"), 4._default)
  !   !   expr_text = &
  !   !   "let real twopi = 2 * pi in" // &
  !   !   " twopi * sqrt (25.d0 - mb^2)" // &
  !   !   " / (let int mb_or_0 = max (mb, 0) in" // &
  !   !   " 1 + (if -1 TeV <= x < mb_or_0 then abs(x) else x))"
  !   !   call ifile_append (ifile, expr_text)
  !   !   call stream_init (stream, ifile)

```

```

!      call var_list_write (var_list)
!      call eval_tree_init_stream (eval_tree, stream, var_list=var_list)
!      call eval_tree_evaluate (eval_tree)
!      call eval_tree_write (eval_tree)
!      print "(A)", "Input string:"
!      print *, char (expr_text)
!      call stream_final (stream)
!      call ifile_final (ifile)
!      call eval_tree_final (eval_tree)
! end subroutine expressions_test1

! subroutine expressions_test2 ()
!   type(prt_list_t) :: prt_list
!   call prt_list_init (prt_list)
!   call prt_list_reset (prt_list, 1)
!   call prt_list_set_incoming (prt_list, 1, &
!     22, vector4_moving (1.e3_default, 1.e3_default, 1), &
!     0._default, (/ 2 /))
!   call prt_list_write (prt_list)
!   call prt_list_reset (prt_list, 4)
!   call prt_list_reset (prt_list, 3)
!   call prt_list_set_incoming (prt_list, 1, &
!     21, vector4_moving (1.e3_default, 1.e3_default, 3), &
!     0._default, (/ 1 /))
!   call prt_list_polarize (prt_list, 1, -1)
!   call prt_list_set_outgoing (prt_list, 2, &
!     1, vector4_moving (0._default, 1.e3_default, 3), &
!     -1.e6_default, (/ 7 /))
!   call prt_list_set_composite (prt_list, 3, &
!     vector4_moving (-1.e3_default, 0._default, 3), &
!     (/ 2, 7 /))
!   call prt_list_write (prt_list)
! end subroutine expressions_test2

! subroutine expressions_test3 ()
!   type(prt_list_t), target :: prt_list
!   type(string_t) :: expr_text
!   type(ifile_t) :: ifile
!   type(stream_t) :: stream
!   type(eval_tree_t) :: eval_tree
!   type(var_list_t), target :: var_list
!   type(pdg_array_t) :: aval
!   aval = 0
!   call var_list_append_pdg_array (var_list, var_str ("particle"), aval)
!   aval = (/ 11,-11 /)
!   call var_list_append_pdg_array (var_list, var_str ("lepton"), aval)
!   aval = 22
!   call var_list_append_pdg_array (var_list, var_str ("photon"), aval)
!   aval = 1
!   call var_list_append_pdg_array (var_list, var_str ("u"), aval)
!   call prt_list_init (prt_list)
!   call prt_list_reset (prt_list, 6)
!   call prt_list_set_incoming (prt_list, 1, &
!     1, vector4_moving (1._default, 1._default, 1), 0._default)

```

```

!      call prt_list_set_incoming (prt_list, 2, &
!      -1, vector4_moving (2._default, 2._default, 1), 0._default)
!      call prt_list_set_outgoing (prt_list, 3, &
!      22, vector4_moving (3._default, 3._default, 1), 0._default)
!      call prt_list_set_outgoing (prt_list, 4, &
!      22, vector4_moving (4._default, 4._default, 1), 0._default)
!      call prt_list_set_outgoing (prt_list, 5, &
!      11, vector4_moving (5._default, 5._default, 1), 0._default)
!      call prt_list_set_outgoing (prt_list, 6, &
!      -11, vector4_moving (6._default, 6._default, 1), 0._default)
!      print *
!      print *, "Expression:"
!      expr_text = &
!      "let alias quark = pdg(1):pdg(2):pdg(3) in" // &
!      "  any E > 3 GeV " // &
!      "    (sort by - Pt " // &
!      "      (select if Index < 6 " // &
!      "        (outgoing photon:pdg(-11):pdg(3):quark " // &
!      "          & incoming particle)))" // &
!      " and" // &
!      " eval Theta (extract index -1 (outgoing photon)) > 45 degree" // &
!      " and" // &
!      " count (incoming photon) * 3 > 0"
!      print *, char (expr_text)
!      print *
!      call ifile_append (ifile, expr_text)
!      call stream_init (stream, ifile)
!      call eval_tree_init_stream (eval_tree, stream, var_list, prt_list, V_LOG)
!      print *
!      call eval_tree_write (eval_tree)
!      call eval_tree_evaluate (eval_tree)
!      print *
!      call eval_tree_write (eval_tree)
!      call stream_final (stream)
!      call ifile_final (ifile)
!      call eval_tree_final (eval_tree)
!      end subroutine expressions_test3

```

Chapter 6

Physics Models

While in previous WHIZARD versions, the physics model was partially hard-coded and injected into the main code via include files, the current version stores the accessible models in module variables. This allows for maintaining different models concurrently. Accessing the model is possible via pointers to the module variables; this is used by flavor objects, for instance.

6.1 Model module

```
<models.f90>≡  
  <File header>  
  
  module models  
  
    use iso_c_binding !NODEP!  
  <Use kinds>  
    use kinds, only: i8, i32 !NODEP!  
    use kinds, only: c_default_float !NODEP!  
  <Use strings>  
    use limits, only: VERTEX_TABLE_SCALE_FACTOR !NODEP!  
  <Use file utils>  
    use md5  
    use os_interface  
    use hashes, only: hash  
    use diagnostics !NODEP!  
    use ifiles  
    use syntax_rules  
    use lexers  
    use parser  
    use pdg_arrays  
    use variables  
    use expressions  
  
  <Standard module head>  
  
  <Models: public>  
  
  <Models: parameters>
```

```

    <Models: types>

    <Models: interfaces>

    <Models: variables>

contains

    <Models: procedures>

end module models

```

6.1.1 Physics Parameters

A parameter has a name, a value. Derived parameters also have a definition in terms of other parameters, which is stored as an `eval_tree`. External parameters are set by an external program.

```

<Models: parameters>≡
    integer, parameter :: PAR_NONE = 0
    integer, parameter :: PAR_INDEPENDENT = 1, PAR_DERIVED = 2
    integer, parameter :: PAR_EXTERNAL = 3

<Models: public>≡
    public :: parameter_t

<Models: types>≡
    type :: parameter_t
        private
        integer :: type = PAR_NONE
        type(string_t) :: name
        real(default) :: value
        type(eval_tree_t) :: eval_tree
    end type parameter_t

```

Initialization depends on parameter type. Independent parameters are initialized by a constant value or a constant numerical expression (which may contain a unit). Derived parameters are initialized by an arbitrary numerical expression, which makes use of the current variable list. The expression is evaluated by the function `parameter_reset`.

```

<Models: procedures>≡
    subroutine parameter_init_independent_value (par, name, value)
        type(parameter_t), intent(out) :: par
        type(string_t), intent(in) :: name
        real(default), intent(in) :: value
        par%type = PAR_INDEPENDENT
        par%name = name
        par%value = value
    end subroutine parameter_init_independent_value

    subroutine parameter_init_independent (par, name, pn)
        type(parameter_t), intent(out) :: par

```

```

    type(string_t), intent(in) :: name
    type(parse_node_t), intent(in), target :: pn
    par%type = PAR_INDEPENDENT
    par%name = name
    call eval_tree_init_numeric_value (par%eval_tree, pn)
    par%value = eval_tree_get_real (par%eval_tree)
end subroutine parameter_init_independent

subroutine parameter_init_derived (par, name, pn, var_list)
    type(parameter_t), intent(out) :: par
    type(string_t), intent(in) :: name
    type(parse_node_t), intent(in), target :: pn
    type(var_list_t), intent(in), target :: var_list
    par%type = PAR_DERIVED
    par%name = name
    call eval_tree_init_expr (par%eval_tree, pn, var_list=var_list)
    call parameter_reset_derived (par)
end subroutine parameter_init_derived

subroutine parameter_init_external (par, name)
    type(parameter_t), intent(out) :: par
    type(string_t), intent(in) :: name
    par%type = PAR_EXTERNAL
    par%name = name
end subroutine parameter_init_external

```

The finalizer is needed for the evaluation tree in the definition.

```

<Models: procedures>+≡
subroutine parameter_final (par)
    type(parameter_t), intent(inout) :: par
    call eval_tree_final (par%eval_tree)
end subroutine parameter_final

```

All derived parameters should be recalculated if some independent parameters have changed:

```

<Models: procedures>+≡
subroutine parameter_reset_derived (par)
    type(parameter_t), intent(inout) :: par
    select case (par%type)
    case (PAR_DERIVED)
        call eval_tree_evaluate (par%eval_tree)
        par%value = eval_tree_get_real (par%eval_tree)
    end select
end subroutine parameter_reset_derived

```

Direct access to the parameter value:

```

<Models: procedures>+≡
function parameter_get_value_ptr (par) result (val)
    real(default), pointer :: val
    type(parameter_t), intent(in), target :: par
    val => par%value
end function parameter_get_value_ptr

```

Output. [We should have a formula format for the eval tree, suitable for input and output!]

(Models: procedures)+≡

```

subroutine parameter_write (par, unit, write_defs)
  type(parameter_t), intent(in) :: par
  integer, intent(in), optional :: unit
  logical, intent(in), optional :: write_defs
  integer :: u
  u = output_unit (unit); if (u < 0) return
  write (u, "(3x,A)", advance="no") "parameter"
  write (u, "(1x,A,1x,A)", advance="no") char (par%name), "="
  write (u, "(G17.10)", advance="no") par%value
  select case (par%type)
  case (PAR_DERIVED)
    write (u, *) " ! derived"
    if (present (write_defs)) then
      if (write_defs) then
        call eval_tree_write (par%eval_tree, unit)
      end if
    end if
  case (PAR_EXTERNAL)
    write (u, *) " ! external"
  end select
end subroutine parameter_write

```

6.1.2 Particle codes

Let us define a few particle codes independent of the model.

Gauge bosons:

(Models: types)+≡

```

integer, parameter, public :: GLUON = 21
integer, parameter, public :: PHOTON = 22
integer, parameter, public :: Z_BOSON = 23
integer, parameter, public :: W_BOSON = 24

```

Hadrons:

(Models: types)+≡

```

integer, parameter, public :: PROTON = 2212
integer, parameter, public :: PION = 111
integer, parameter, public :: PIPLUS = 211
integer, parameter, public :: PIMINUS = - PIPLUS

```

Hadron remnants (internal)

(Models: types)+≡

```

integer, parameter, public :: HADRON_REMNANT = 90
integer, parameter, public :: HADRON_REMNANT_SINGLET = 91
integer, parameter, public :: HADRON_REMNANT_TRIPLET = 92
integer, parameter, public :: HADRON_REMNANT_OCTET = 93

```

Generic particles for internal use in event analysis:

```
⟨Models: types⟩+=
    integer, parameter, public :: PRT_ANY = 81
    integer, parameter, public :: PRT_VISIBLE = 82
    integer, parameter, public :: PRT_CHARGED = 83
    integer, parameter, public :: PRT_COLORED = 84
```

Further particle codes for internal use:

```
⟨Models: types⟩+=
    integer, parameter, public :: INVALID = 97
    integer, parameter, public :: KEYSTONE = 98
    integer, parameter, public :: COMPOSITE = 99
```

6.1.3 Spin codes

Somewhat redundant, but for better readability we define named constants for spin types. If the mass is nonzero, this is equal to the number of degrees of freedom.

```
⟨Models: types⟩+=
    integer, parameter, public :: UNKNOWN=0
    integer, parameter, public :: SCALAR=1, SPINOR=2, VECTOR=3, &
        VECTORSPINOR=4, TENSOR=5
```

Isospin types and charge types are counted in an analogous way, where charge type 1 is charge 0, 2 is charge 1/3, and so on. Zero always means unknown.

Color types are defined as the dimension of the representation.

6.1.4 Particle data

The particle-data type holds all information that pertains to a particular particle within a particular model. Information such as spin type, particle code etc. is stored within the object itself, while mass and width are associated to parameters, otherwise assumed zero.

```
⟨Models: public⟩+=
    public :: particle_data_t

⟨Models: types⟩+=
    type :: particle_data_t
    private
        type(string_t) :: longname
        integer :: pdg = UNDEFINED
        logical :: is_visible = .true.
        logical :: is_parton = .false.
        logical :: is_gauge = .false.
        logical :: is_left_handed = .false.
        logical :: is_right_handed = .false.
        logical :: has_antiparticle = .false.
        logical :: is_stable = .true.
        type(string_t), dimension(:), allocatable :: name, anti
        type(string_t) :: tex_name, tex_anti
        integer :: spin_type = UNDEFINED
        integer :: isospin_type = 1
```

```

integer :: charge_type = 1
integer :: color_type = 1
real(default), pointer :: mass_val => null ()
type(parameter_t), pointer :: mass_src => null ()
real(default), pointer :: width_val => null ()
type(parameter_t), pointer :: width_src => null ()
integer :: multiplicity = 1
end type particle_data_t

```

Initialize particle data with PDG long name and PDG code. \TeX names should be initialized to avoid issues with accessing unallocated string contents.

```

<Models: public>+≡
public :: particle_data_init

<Models: procedures>+≡
subroutine particle_data_init (prt, longname, pdg)
type(particle_data_t), intent(out) :: prt
type(string_t), intent(in) :: longname
integer, intent(in) :: pdg
prt%longname = longname
prt%pdg = pdg
prt%tex_name = ""
prt%tex_anti = ""
end subroutine particle_data_init

```

Copy quantum numbers from another particle

```

<Models: procedures>+≡
subroutine particle_data_copy (prt, prt_src)
type(particle_data_t), intent(inout) :: prt
type(particle_data_t), intent(in) :: prt_src
prt%is_visible = prt_src%is_visible
prt%is_parton = prt_src%is_parton
prt%is_gauge = prt_src%is_gauge
prt%is_left_handed = prt_src%is_left_handed
prt%is_right_handed = prt_src%is_right_handed
prt%spin_type = prt_src%spin_type
prt%isospin_type = prt_src%isospin_type
prt%charge_type = prt_src%charge_type
prt%color_type = prt_src%color_type
call particle_data_set_multiplicity (prt)
end subroutine particle_data_copy

```

Set particle quantum numbers.

```

<Models: public>+≡
public :: particle_data_set

<Models: procedures>+≡
subroutine particle_data_set (prt, &
is_visible, is_parton, is_gauge, is_left_handed, is_right_handed, &
is_stable, &
name, anti, tex_name, tex_anti, &
spin_type, isospin_type, charge_type, color_type, &
mass_src, width_src)

```

```

type(particle_data_t), intent(inout) :: prt
logical, intent(in), optional :: is_visible, is_parton, is_gauge
logical, intent(in), optional :: is_left_handed, is_right_handed
logical, intent(in), optional :: is_stable
type(string_t), dimension(:), intent(in), optional :: name, anti
type(string_t), intent(in), optional :: tex_name, tex_anti
integer, intent(in), optional :: spin_type, isospin_type
integer, intent(in), optional :: charge_type, color_type
type(parameter_t), intent(in), target, optional :: mass_src, width_src
if (present (is_visible)) prt%is_visible = is_visible
if (present (is_parton)) prt%is_parton = is_parton
if (present (is_gauge)) prt%is_gauge = is_gauge
if (present (is_left_handed)) prt%is_left_handed = is_left_handed
if (present (is_right_handed)) prt%is_right_handed = is_right_handed
if (present (is_stable)) prt%is_stable = is_stable
if (present (name)) then
    allocate (prt%name (size (name)))
    prt%name = name
end if
if (present (anti)) then
    allocate (prt%anti (size (anti)))
    prt%anti = anti
    prt%has_antiparticle = .true.
end if
if (present (tex_name)) prt%tex_name = tex_name
if (present (tex_anti)) prt%tex_anti = tex_anti
if (present (spin_type)) prt%spin_type = spin_type
if (present (isospin_type)) prt%isospin_type = isospin_type
if (present (charge_type)) prt%charge_type = charge_type
if (present (color_type)) prt%color_type = color_type
if (present (mass_src)) then
    prt%mass_src => mass_src
    prt%mass_val => parameter_get_value_ptr (mass_src)
end if
if (present (width_src)) then
    prt%width_src => width_src
    prt%width_val => parameter_get_value_ptr (width_src)
end if
if (present (spin_type) .or. present (mass_src)) then
    call particle_data_set_multiplicity (prt)
end if
end subroutine particle_data_set

```

Calculate the multiplicity given spin type and mass.

(Models: procedures)+≡

```

subroutine particle_data_set_multiplicity (prt)
type(particle_data_t), intent(inout) :: prt
if (prt%spin_type /= SCALAR) then
    if (associated (prt%mass_src)) then
        prt%multiplicity = prt%spin_type
    else
        prt%multiplicity = 2
    end if
end if

```

```

        end if
    end subroutine particle_data_set_multiplicity

```

Set the mass/width value (not the pointer). The mass/width pointer must be allocated.

```

<Models: procedures>+≡
subroutine particle_data_set_mass (prt, mass)
    type(particle_data_t), intent(inout) :: prt
    real(default), intent(in) :: mass
    if (associated (prt%mass_val)) prt%mass_val = mass
end subroutine particle_data_set_mass

subroutine particle_data_set_width (prt, width)
    type(particle_data_t), intent(inout) :: prt
    real(default), intent(in) :: width
    if (associated (prt%width_val)) prt%width_val = width
end subroutine particle_data_set_width

```

Loose ends

```

<Models: public>+≡
public :: particle_data_freeze

<Models: procedures>+≡
subroutine particle_data_freeze (prt)
    type(particle_data_t), intent(inout) :: prt
    if (.not. allocated (prt%name)) allocate (prt%name (0))
    if (.not. allocated (prt%anti)) allocate (prt%anti (0))
end subroutine particle_data_freeze

```

Output

```

<Models: procedures>+≡
subroutine particle_data_write (prt, unit)
    type(particle_data_t), intent(in) :: prt
    integer, intent(in), optional :: unit
    integer :: u, i
    u = output_unit (unit); if (u < 0) return
    write (u, "(3x,A,1x,A)", advance="no") "particle", char (prt%longname)
    write (u, "(1x,I7)", advance="no") prt%pdg
    if (.not. prt%is_visible) write (u, "(3x,A)", advance="no") "invisible"
    if (prt%is_parton) write (u, "(3x,A)", advance="no") "parton"
    if (prt%is_gauge) write (u, "(3x,A)", advance="no") "gauge"
    if (prt%is_left_handed) write (u, "(3x,A)", advance="no") "left"
    if (prt%is_right_handed) write (u, "(3x,A)", advance="no") "right"
    write (u, *)
    write (u, "(5x,A)", advance="no") "name"
    if (allocated (prt%name)) then
        do i = 1, size (prt%name)
            write (u, "(1x,A)", advance="no") ' ' // char (prt%name(i)) // ' '
        end do
        write (u, *)
    end if
    if (prt%has_antiparticle) then
        write (u, "(5x,A)", advance="no") "anti"
        do i = 1, size (prt%anti)

```

```

        write (u, "(1x,A)", advance="no") ' ' // char (prt%anti(i)) // ' '
    end do
    write (u, *)
end if
if (prt%tex_name /= "") then
    write (u, "(5x,A)") &
        "tex_name " // ' ' // char (prt%tex_name) // ' '
end if
if (prt%has_antiparticle .and. prt%tex_anti /= "") then
    write (u, "(5x,A)") &
        "tex_anti " // ' ' // char (prt%tex_anti) // ' '
end if
else
    write (u, "(A)") "???"
end if
write (u, "(5x,A)", advance="no") "spin "
select case (mod (prt%spin_type - 1, 2))
case (0); write (u, "(I1)", advance="no") (prt%spin_type-1) / 2
case default; write (u, "(I1,A)", advance="no") prt%spin_type-1, "/2"
end select
! write (u, "(3x,A,I1,A)") "! [multiplicity = ", prt%multiplicity, "]"
if (abs (prt%isospin_type) /= 1) then
    write (u, "(5x,A)", advance="no") "isospin "
    select case (mod (abs (prt%isospin_type) - 1, 2))
    case (0); write (u, "(I2)", advance="no") &
        sign (abs (prt%isospin_type) - 1, prt%isospin_type) / 2
    case default; write (u, "(I2,A)", advance="no") &
        sign (abs (prt%isospin_type) - 1, prt%isospin_type), "/2"
    end select
end if
if (abs (prt%charge_type) /= 1) then
    write (u, "(5x,A)", advance="no") "charge "
    select case (mod (abs (prt%charge_type) - 1, 3))
    case (0); write (u, "(I2)", advance="no") &
        sign (abs (prt%charge_type) - 1, prt%charge_type) / 3
    case default; write (u, "(I2,A)", advance="no") &
        sign (abs (prt%charge_type) - 1, prt%charge_type), "/3"
    end select
end if
if (prt%color_type /= 1) then
    write (u, "(5x,A,I2)", advance="no") "color ", prt%color_type
end if
write (u, *)
if (associated (prt%mass_src)) then
    write (u, "(5x,A)") "mass " // char (prt%mass_src%name)
    if (associated (prt%width_src)) then
        write (u, "(5x,A)") "width " // char (prt%width_src%name)
    end if
end if
end subroutine particle_data_write

```

Retrieve data:

<Models: public>+≡

public :: particle_data_get_pdg

```

public :: particle_data_get_pdg_anti
<Models: procedures>+≡
  elemental function particle_data_get_pdg (prt) result (pdg)
    integer :: pdg
    type(particle_data_t), intent(in) :: prt
    pdg = prt%pdg
  end function particle_data_get_pdg

  elemental function particle_data_get_pdg_anti (prt) result (pdg)
    integer :: pdg
    type(particle_data_t), intent(in) :: prt
    if (prt%has_antiparticle) then
      pdg = - prt%pdg
    else
      pdg = prt%pdg
    end if
  end function particle_data_get_pdg_anti

```

Predicates:

```

<Models: public>+≡
  public :: particle_data_is_visible
  public :: particle_data_is_parton
  public :: particle_data_is_gauge
  public :: particle_data_is_left_handed
  public :: particle_data_is_right_handed
  public :: particle_data_has_antiparticle
  public :: particle_data_is_stable

<Models: procedures>+≡
  elemental function particle_data_is_visible (prt) result (flag)
    logical :: flag
    type(particle_data_t), intent(in) :: prt
    flag = prt%is_visible
  end function particle_data_is_visible

  elemental function particle_data_is_parton (prt) result (flag)
    logical :: flag
    type(particle_data_t), intent(in) :: prt
    flag = prt%is_parton
  end function particle_data_is_parton

  elemental function particle_data_is_gauge (prt) result (flag)
    logical :: flag
    type(particle_data_t), intent(in) :: prt
    flag = prt%is_gauge
  end function particle_data_is_gauge

  elemental function particle_data_is_left_handed (prt) result (flag)
    logical :: flag
    type(particle_data_t), intent(in) :: prt
    flag = prt%is_left_handed
  end function particle_data_is_left_handed

  elemental function particle_data_is_right_handed (prt) result (flag)

```

```

    logical :: flag
    type(particle_data_t), intent(in) :: prt
    flag = prt%is_right_handed
end function particle_data_is_right_handed

elemental function particle_data_has_antiparticle (prt) result (flag)
    logical :: flag
    type(particle_data_t), intent(in) :: prt
    flag = prt%has_antiparticle
end function particle_data_has_antiparticle

elemental function particle_data_is_stable (prt) result (flag)
    logical :: flag
    type(particle_data_t), intent(in) :: prt
    flag = prt%is_stable
end function particle_data_is_stable

```

Names. Return the first name in the list (or the first antiparticle name)

```

⟨Models: public⟩+≡
    public :: particle_data_get_name

⟨Models: procedures⟩+≡
    elemental function particle_data_get_name &
        (prt, is_antiparticle) result (name)
        type(string_t) :: name
        type(particle_data_t), intent(in) :: prt
        logical, intent(in) :: is_antiparticle
        if (is_antiparticle) then
            if (prt%has_antiparticle) then
                name = prt%anti(1)
            else
                name = prt%name(1)
            end if
        else
            name = prt%name(1)
        end if
    end function particle_data_get_name

```

Same for the T_EX name.

```

⟨Models: public⟩+≡
    public :: particle_data_get_tex_name

⟨Models: procedures⟩+≡
    elemental function particle_data_get_tex_name &
        (prt, is_antiparticle) result (name)
        type(string_t) :: name
        type(particle_data_t), intent(in) :: prt
        logical, intent(in) :: is_antiparticle
        if (is_antiparticle) then
            if (prt%has_antiparticle) then
                name = prt%tex_anti
            else
                name = prt%tex_name
            end if
        end if
    end function particle_data_get_tex_name

```

```

    else
        name = prt%tex_name
    end if
end function particle_data_get_tex_name

```

Quantum numbers

<Models: public>+≡

```

public :: particle_data_get_spin_type
public :: particle_data_get_multiplicity
public :: particle_data_get_isospin_type
public :: particle_data_get_charge_type
public :: particle_data_get_color_type

```

<Models: procedures>+≡

```

elemental function particle_data_get_spin_type (prt) result (type)
    integer :: type
    type(particle_data_t), intent(in) :: prt
    type = prt%spin_type
end function particle_data_get_spin_type

elemental function particle_data_get_multiplicity (prt) result (type)
    integer :: type
    type(particle_data_t), intent(in) :: prt
    type = prt%multiplicity
end function particle_data_get_multiplicity

elemental function particle_data_get_isospin_type (prt) result (type)
    integer :: type
    type(particle_data_t), intent(in) :: prt
    type = prt%isospin_type
end function particle_data_get_isospin_type

elemental function particle_data_get_charge_type (prt) result (type)
    integer :: type
    type(particle_data_t), intent(in) :: prt
    type = prt%charge_type
end function particle_data_get_charge_type

elemental function particle_data_get_color_type (prt) result (type)
    integer :: type
    type(particle_data_t), intent(in) :: prt
    type = prt%color_type
end function particle_data_get_color_type

```

In the MSSM, neutralinos can have a negative mass. This is relevant for computing matrix elements. However, within the **WHIZARD** main program we are interested only in kinematics, therefore we return the absolute value of the particle mass. If desired, we can extract the sign separately.

<Models: public>+≡

```

public :: particle_data_get_charge
public :: particle_data_get_mass
public :: particle_data_get_mass_sign
public :: particle_data_get_width

```

```

<Models: procedures>+≡
  elemental function particle_data_get_charge (prt) result (charge)
    real(default) :: charge
    type(particle_data_t), intent(in) :: prt
    if (prt%charge_type /= 0) then
      charge = real (prt%charge_type - 1, default) / 3
    else
      charge = 0
    end if
  end function particle_data_get_charge

  elemental function particle_data_get_mass (prt) result (mass)
    real(default) :: mass
    type(particle_data_t), intent(in) :: prt
    if (associated (prt%mass_val)) then
      mass = abs (prt%mass_val)
    else
      mass = 0
    end if
  end function particle_data_get_mass

  elemental function particle_data_get_mass_sign (prt) result (sgn)
    integer :: sgn
    type(particle_data_t), intent(in) :: prt
    if (associated (prt%mass_val)) then
      sgn = sign (1._default, prt%mass_val)
    else
      sgn = 0
    end if
  end function particle_data_get_mass_sign

  elemental function particle_data_get_width (prt) result (width)
    real(default) :: width
    type(particle_data_t), intent(in) :: prt
    if (associated (prt%width_val)) then
      width = prt%width_val
    else
      width = 0
    end if
  end function particle_data_get_width

```

Given an array of particles, return a PDG-array object that consists of all charged particles in the array

```

<Models: procedures>+≡
  function particle_data_get_charged_pdg (prt) result (aval)
    type(pdg_array_t) :: aval
    type(particle_data_t), dimension(:), intent(in) :: prt
    aval = pack (prt%pdg, abs (prt%charge_type) > 1)
  end function particle_data_get_charged_pdg

```

The same for color.

```

<Models: procedures>+≡
  function particle_data_get_colored_pdg (prt) result (aval)

```

```

type(pdg_array_t) :: aval
type(particle_data_t), dimension(:), intent(in) :: prt
aval = pack (prt%pdg, abs (prt%color_type) > 1)
end function particle_data_get_colored_pdg

```

6.1.5 Vertex data

The vertex object contains an array of particle-data pointers, for which we need a separate type. (We could use the flavor type defined in another module.)

The program does not (yet?) make use of vertex definitions, so they are not stored here.

```

⟨Models: types⟩+≡
  type :: particle_p
    type(particle_data_t), pointer :: p => null ()
  end type particle_p

⟨Models: types⟩+≡
  type :: vertex_t
    logical :: trilinear
    integer, dimension(:), allocatable :: pdg
    type(particle_p), dimension(:), allocatable :: prt
  end type vertex_t

```

Initialize using PDG codes. The model is used for finding particle data pointers associated with the pdg codes.

```

⟨Models: procedures⟩+≡
  subroutine vertex_init (vtx, pdg, model)
    type(vertex_t), intent(out) :: vtx
    integer, dimension(:), intent(in) :: pdg
    type(model_t), intent(in), target, optional :: model
    integer :: i
    allocate (vtx%pdg (size (pdg)))
    allocate (vtx%prt (size (pdg)))
    vtx%trilinear = size (pdg) == 3
    vtx%pdg = pdg
    if (present (model)) then
      do i = 1, size (pdg)
        vtx%prt(i)%p => model_get_particle_ptr (model, pdg(i))
      end do
    end if
  end subroutine vertex_init

⟨Models: procedures⟩+≡
  subroutine vertex_write (vtx, unit)
    type(vertex_t), intent(in) :: vtx
    integer, intent(in), optional :: unit
    integer :: u, i
    u = output_unit (unit); if (u < 0) return
    write (u, "(3x,A)", advance="no") "vertex"
    do i = 1, size (vtx%prt)

```

```

        if (associated (vtx%prt(i)%p)) then
            write (u, "(1x,A)", advance="no") &
                ', ' // char (particle_data_get_name &
                            (vtx%prt(i)%p, vtx%pdg(i) < 0)) &
                // ', '
        else
            write (u, "(1x,I7)", advance="no") vtx%pdg(i)
        end if
    end do
    write (u, *)
end subroutine vertex_write

```

6.1.6 Vertex lookup table

The vertex lookup table is a hash table: given two particle codes, we check which codes are allowed for the third one.

The size of the hash table should be large enough that collisions are rare. We first select a size based on the number of vertices (multiplied by six because all permutations count), with some margin, and then choose the smallest integer power of two larger than this.

```

<Limits: public parameters>+≡
    integer, parameter, public :: VERTEX_TABLE_SCALE_FACTOR = 60

<Models: procedures>+≡
    function vertex_table_size (n_vtx) result (n)
        integer(i32) :: n
        integer, intent(in) :: n_vtx
        integer :: i, s
        s = VERTEX_TABLE_SCALE_FACTOR * n_vtx
        n = 1
        do i = 1, 31
            n = ishft (n, 1)
            s = ishft (s,-1)
            if (s == 0) exit
        end do
    end function vertex_table_size

```

The specific hash function takes two particle codes (arbitrary integers) and returns a 32-bit integer. It makes use of the universal function `hash` which operates on a byte array.

```

<Models: procedures>+≡
    function hash2 (pdg1, pdg2)
        integer(i32) :: hash2
        integer, intent(in) :: pdg1, pdg2
        integer(i8), dimension(1) :: mold
        hash2 = hash (transfer (/pdg1, pdg2/), mold)
    end function hash2

```

Each entry in the vertex table stores the two particle codes and an array of possibilities for the third code.

```

<Models: types>+≡

```

```

type :: vertex_table_entry_t
  integer :: pdg1 = 0, pdg2 = 0
  integer :: n = 0
  integer, dimension(:), allocatable :: pdg3
end type vertex_table_entry_t

```

The vertex table:

(Models: types)+≡

```

type :: vertex_table_t
  type(vertex_table_entry_t), dimension(:), allocatable :: entry
  integer :: n_collisions = 0
  integer(i32) :: mask
end type vertex_table_t

```

Initializing the vertex table: This is done in two passes. First, we scan all permutations for all vertices and count the number of entries in each bucket of the hashtable. Then, the buckets are allocated accordingly and filled.

Collision resolution is done by just incrementing the hash value until an empty bucket is found. The vertex table size is fixed, since we know from the beginning the number of entries.

(Models: procedures)+≡

```

subroutine vertex_table_init (vt, prt, vtx)
  type(vertex_table_t), intent(out) :: vt
  type(particle_data_t), dimension(:), intent(in) :: prt
  type(vertex_t), dimension(:), intent(in) :: vtx
  integer :: n_prt, n_vtx, vt_size, i, p1, p2, p3
  integer, dimension(3) :: p
  n_prt = size (prt)
  n_vtx = size (vtx)
  vt_size = vertex_table_size (count (vtx%trilinear))
  vt%mask = vt_size - 1
  allocate (vt%entry (0:vt_size-1))
  do i = 1, n_vtx
    if (vtx(i)%trilinear) then
      p = vtx(i)%pdg
      p1 = p(1); p2 = p(2)
      call create (hash2 (p1, p2))
      if (p(2) /= p(3)) then
        p2 = p(3)
        call create (hash2 (p1, p2))
      end if
      if (p(1) /= p(2)) then
        p1 = p(2); p2 = p(1)
        call create (hash2 (p1, p2))
        if (p(1) /= p(3)) then
          p2 = p(3)
          call create (hash2 (p1, p2))
        end if
      end if
      if (p(1) /= p(3)) then
        p1 = p(3); p2 = p(1)
        call create (hash2 (p1, p2))
        if (p(1) /= p(2)) then

```

```

        p2 = p(2)
        call create (hash2 (p1, p2))
    end if
end if
end if
end do
do i = 0, vt_size - 1
    allocate (vt%entry(i)%pdg3 (vt%entry(i)%n))
end do
vt%entry%n = 0
do i = 1, n_vtx
    if (vtx(i)%trilinear) then
        p = vtx(i)%pdg
        p1 = p(1); p2 = p(2); p3 = p(3)
        call register (hash2 (p1, p2))
        if (p(2) /= p(3)) then
            p2 = p(3); p3 = p(2)
            call register (hash2 (p1, p2))
        end if
        if (p(1) /= p(2)) then
            p1 = p(2); p2 = p(1); p3 = p(3)
            call register (hash2 (p1, p2))
            if (p(1) /= p(3)) then
                p2 = p(3); p3 = p(1)
                call register (hash2 (p1, p2))
            end if
        end if
        if (p(1) /= p(3)) then
            p1 = p(3); p2 = p(1); p3 = p(2)
            call register (hash2 (p1, p2))
            if (p(1) /= p(2)) then
                p2 = p(2); p3 = p(1)
                call register (hash2 (p1, p2))
            end if
        end if
    end if
end do
contains
recursive subroutine create (hashval)
    integer(i32), intent(in) :: hashval
    integer :: h
    h = iand (hashval, vt%mask)
    if (vt%entry(h)%n == 0) then
        vt%entry(h)%pdg1 = p1
        vt%entry(h)%pdg2 = p2
        vt%entry(h)%n = 1
    else if (vt%entry(h)%pdg1 == p1 .and. vt%entry(h)%pdg2 == p2) then
        vt%entry(h)%n = vt%entry(h)%n + 1
    else
        vt%n_collisions = vt%n_collisions + 1
        call create (hashval + 1)
    end if
end subroutine create
recursive subroutine register (hashval)

```

```

integer(i32), intent(in) :: hashval
integer :: h
h = iand (hashval, vt%mask)
if (vt%entry(h)%pdg1 == p1 .and. vt%entry(h)%pdg2 == p2) then
    vt%entry(h)%n = vt%entry(h)%n + 1
    vt%entry(h)%pdg3(vt%entry(h)%n) = p3
else
    call register (hashval + 1)
end if
end subroutine register
end subroutine vertex_table_init

```

Output

(Models: procedures)+≡

```

subroutine vertex_table_write (vt, unit)
    type(vertex_table_t), intent(in) :: vt
    integer, intent(in), optional :: unit
    integer :: u, i
    u = output_unit (unit); if (u < 0) return
    write (u, *) "vertex hash table:"
    write (u, *) " size = ", size (vt%entry)
    write (u, *) " used = ", count (vt%entry%n /= 0)
    write (u, *) " coll = ", vt%n_collisions
    do i = lbound (vt%entry, 1), ubound (vt%entry, 1)
        if (vt%entry(i)%n /= 0) then
            write (u, *) " ", i, ":", &
                vt%entry(i)%pdg1, vt%entry(i)%pdg2, "->", vt%entry(i)%pdg3
        end if
    end do
end subroutine vertex_table_write

```

Return the array of particle codes that match the given pair.

(Models: procedures)+≡

```

subroutine vertex_table_match (vt, pdg1, pdg2, pdg3)
    type(vertex_table_t), intent(in) :: vt
    integer, intent(in) :: pdg1, pdg2
    integer, dimension(:), allocatable, intent(out) :: pdg3
    integer :: vt_size
    vt_size = size (vt%entry)
    call match (hash2 (pdg1, pdg2))
contains
    recursive subroutine match (hashval)
        integer(i32), intent(in) :: hashval
        integer :: h
        h = iand (hashval, vt%mask)
        if (vt%entry(h)%n == 0) then
            allocate (pdg3 (0))
        else if (vt%entry(h)%pdg1 == pdg1 .and. vt%entry(h)%pdg2 == pdg2) then
            allocate (pdg3 (size (vt%entry(h)%pdg3)))
            pdg3 = vt%entry(h)%pdg3
        else
            call match (hashval + 1)
        end if
    end subroutine match
end subroutine vertex_table_match

```

```

        end subroutine match
    end subroutine vertex_table_match

```

Return true if the triplet is represented as a vertex.

(Models: procedures)+≡

```

function vertex_table_check (vt, pdg1, pdg2, pdg3) result (flag)
    type(vertex_table_t), intent(in) :: vt
    integer, intent(in) :: pdg1, pdg2, pdg3
    logical :: flag
    integer :: vt_size
    vt_size = size (vt%entry)
    flag = check (hash2 (pdg1, pdg2))
contains
    recursive function check (hashval) result (flag)
        integer(i32), intent(in) :: hashval
        integer :: h
        logical :: flag
        h = iand (hashval, vt%mask)
        if (vt%entry(h)%n == 0) then
            flag = .false.
        else if (vt%entry(h)%pdg1 == pdg1 .and. vt%entry(h)%pdg2 == pdg2) then
            flag = any (vt%entry(h)%pdg3 == pdg3)
        else
            flag = check (hashval + 1)
        end if
    end function check
end function vertex_table_check

```

6.1.7 Model data

A model object holds all information about parameters, particles, and vertices. For models that require an external program for parameter calculation, there is the pointer to a function that does this calculation, given the set of independent and derived parameters.

(Models: public)+≡

```

public :: model_t

```

(Models: types)+≡

```

type :: model_t
private
    type(string_t) :: name
    character(32) :: md5sum = ""
    type(parameter_t), dimension(:), allocatable :: par
    type(particle_data_t), dimension(:), allocatable :: prt
    type(vertex_t), dimension(:), allocatable :: vtx
    type(vertex_table_t) :: vt
    type(var_list_t) :: var_list
    type(string_t) :: dlname
    procedure(model_init_external_parameters), nopass, pointer :: &
        init_external_parameters => null ()
    type(dlaccess_t) :: dlaccess
end type model_t

```

This is the interface for a procedure that initializes the calculation of external parameters, given the array of all parameters.

(Models: interfaces)≡

```
abstract interface
  subroutine model_init_external_parameters (par) bind (C)
    import
    real(c_default_float), dimension(*), intent(inout) :: par
  end subroutine model_init_external_parameters
end interface
```

Initialization: Specify the number of parameters, particles, vertices and allocate memory. If an associated DL library is specified, load this library.

(Models: procedures)+≡

```
subroutine model_init (model, name, libname, os_data, n_par, n_prt, n_vtx)
  type(model_t), intent(out) :: model
  type(string_t), intent(in) :: name, libname
  type(os_data_t), intent(in) :: os_data
  integer, intent(in) :: n_par, n_prt, n_vtx
  type(c_funptr) :: c_fptr
  model%name = name
  allocate (model%par (n_par))
  allocate (model%prt (n_prt))
  allocate (model%vtx (n_vtx))
  if (libname /= "") then
    model%dlname = os_get_dlname &
      (os_data%whizard_models_libpath // "/" // libname, os_data)
  else
    model%dlname = ""
  end if
  if (model%dlname /= "") then
    if (.not. dlaccess_is_open (model%dlaccess)) then
      call msg_message ("Loading model auxiliary library '" &
        // char (model%dlname) // "'")
      call dlaccess_init (model%dlaccess, os_data%whizard_models_libpath, &
        model%dlname, os_data)
      if (dlaccess_has_error (model%dlaccess)) then
        call msg_message (char (dlaccess_get_error (model%dlaccess)))
        call msg_fatal ("Loading model auxiliary library '" &
          // char (model%dlname) // "' failed")
        return
      end if
      c_fptr = dlaccess_get_c_funptr (model%dlaccess, &
        var_str ("init_external_parameters"))
      if (dlaccess_has_error (model%dlaccess)) then
        call msg_message (char (dlaccess_get_error (model%dlaccess)))
        call msg_fatal ("Loading function from auxiliary library '" &
          // char (model%dlname) // "' failed")
        return
      end if
      call c_f_procpointer (c_fptr, model% init_external_parameters)
    end if
  end if
```

```
end subroutine model_init
```

Finalization: The variable list is the only part that contains pointers.

```
<Models: procedures>+≡
subroutine model_final (model)
  type(model_t), intent(inout) :: model
  call var_list_final (model%var_list)
  if (model%dlname /= "") call dlaccess_final (model%dlaccess)
end subroutine model_final
```

Output. By default, the output is in the form of an input file. If **verbose** is true, for each derived parameter the definition (eval tree) is displayed, and the vertex hash table is shown.

```
<Models: public>+≡
public :: model_write

<Models: procedures>+≡
subroutine model_write (model, unit, verbose)
  type(model_t), intent(in) :: model
  integer, intent(in), optional :: unit
  logical, intent(in), optional :: verbose
  integer :: u, i
  u = output_unit (unit); if (u < 0) return
  write (u, *) 'model "', char (model%name), '"'
  write (u, *) '! md5sum = "', model%md5sum, '"'
  do i = 1, size (model%par)
    call parameter_write (model%par(i), unit, verbose)
    write (u, *)
  end do
  do i = 1, size (model%prt)
    call particle_data_write (model%prt(i), unit)
  end do
  do i = 1, size (model%vtx)
    call vertex_write (model%vtx(i), unit)
  end do
  if (present (verbose)) then
    if (verbose) then
      call vertex_table_write (model%vt, unit)
      call var_list_write (model%var_list, unit)
    end if
  end if
end subroutine model_write
```

Accessing contents:

```
<Models: public>+≡
public :: model_get_name

<Models: procedures>+≡
function model_get_name (model) result (name)
  type(string_t) :: name
  type(model_t), intent(in) :: model
  name = model%name
end function model_get_name
```

Retrieve the MD5 sum of a model (actually, of the model file).

```

<Models: public>+≡
    public :: model_get_md5sum

<Models: procedures>+≡
    function model_get_md5sum (model) result (md5sum)
        character(32) :: md5sum
        type(model_t), intent(in) :: model
        md5sum = model%md5sum
    end function model_get_md5sum

```

Retrieve a MD5 sum for the current model parameter values. This is done by writing them to a string, using default format.

```

<Models: public>+≡
    public :: model_get_parameters_md5sum

<Models: procedures>+≡
    function model_get_parameters_md5sum (model) result (par_md5sum)
        character(32) :: par_md5sum
        type(model_t), intent(in) :: model
        real(default), dimension(:), allocatable :: par
        integer :: unit
        call model_parameters_to_array (model, par)
        unit = free_unit ()
        open (unit, status="scratch", action="readwrite")
        write (unit, *) par
        rewind (unit)
        par_md5sum = md5sum (unit)
        close (unit)
    end function model_get_parameters_md5sum

```

Parameters are defined by an expression which may be constant or arbitrary.

```

<Models: interfaces>+≡
    interface model_set_parameter
        module procedure model_set_parameter_constant
        module procedure model_set_parameter_parse_node
    end interface

<Models: procedures>+≡
    subroutine model_set_parameter_constant (model, i, name, value)
        type(model_t), intent(inout), target :: model
        integer, intent(in) :: i
        type(string_t), intent(in) :: name
        real(default), intent(in) :: value
        logical, save, target :: known = .true.
        call parameter_init_independent_value (model%par(i), name, value)
        call var_list_append_real_ptr &
            (model%var_list, name, parameter_get_value_ptr (model%par(i)), known, &
            intrinsic=.true.)
    end subroutine model_set_parameter_constant

    subroutine model_set_parameter_parse_node (model, i, name, pn, constant)
        type(model_t), intent(inout), target :: model

```

```

integer, intent(in) :: i
type(string_t), intent(in) :: name
type(parse_node_t), intent(in), target :: pn
logical, intent(in) :: constant
logical, save, target :: known = .true.
if (constant) then
    call parameter_init_independent (model%par(i), name, pn)
else
    call parameter_init_derived (model%par(i), name, pn, model%var_list)
end if
call var_list_append_real_ptr &
    (model%var_list, name, parameter_get_value_ptr (model%par(i)), &
    is_known=known, locked=.not.constant, intrinsic=.true.)
end subroutine model_set_parameter_parse_node

subroutine model_set_parameter_external (model, i, name)
    type(model_t), intent(inout), target :: model
    integer, intent(in) :: i
    type(string_t), intent(in) :: name
    logical, save, target :: known = .true.
    call parameter_init_external (model%par(i), name)
    call var_list_append_real_ptr &
        (model%var_list, name, parameter_get_value_ptr (model%par(i)), &
        is_known=known, locked=.true., intrinsic=.true.)
end subroutine model_set_parameter_external

```

Return the pointer to a parameter

<Models: procedures>+≡

```

function model_get_parameter_ptr (model, par_name) result (par)
    type(parameter_t), pointer :: par
    type(model_t), intent(in), target :: model
    type(string_t), intent(in), optional :: par_name
    integer :: i
    par => null ()
    if (present (par_name)) then
        do i = 1, size (model%par)
            if (model%par(i)%name == par_name) then
                par => model%par(i); exit
            end if
        end do
        if (.not. associated (par)) then
            call msg_fatal (" Model '" // char (model%name) // "' // &
                " has no parameter '" // char (par_name) // "'")
        end if
    end if
end function model_get_parameter_ptr

```

Return the value of a particular parameter

<Models: public>+≡

```

public :: model_get_parameter_value

```

<Models: procedures>+≡

```

function model_get_parameter_value (model, par_name) result (val)

```

```

    real(default) :: val
    type(model_t), intent(in), target :: model
    type(string_t), intent(in), optional :: par_name
    val = parameter_get_value_ptr (model_get_parameter_ptr (model, par_name))
end function model_get_parameter_value

```

Return the number of parameters

```

<Models: public>+≡
    public :: model_get_n_parameters

<Models: procedures>+≡
    function model_get_n_parameters (model) result (n)
        integer :: n
        type(model_t), intent(in) :: model
        n = size (model%par)
    end function model_get_n_parameters

```

Transform the parameters into a single real-valued array. The first version uses the Fortran default kind, the second one the C default kind. (Usually, the two will be identical).

```

<Models: public>+≡
    public :: model_parameters_to_array

<Models: procedures>+≡
    subroutine model_parameters_to_array (model, array)
        type(model_t), intent(in) :: model
        real(default), dimension(:), allocatable :: array
        integer :: i
        allocate (array (size (model%par)))
        do i = 1, size (model%par)
            array(i) = model%par(i)%value
        end do
    end subroutine model_parameters_to_array

    subroutine model_parameters_to_c_array (model, array)
        type(model_t), intent(in) :: model
        real(c_default_float), dimension(:), allocatable :: array
        allocate (array (size (model%par)))
        array = model%par%value
    end subroutine model_parameters_to_c_array

    subroutine model_parameters_from_c_array (model, array)
        type(model_t), intent(inout) :: model
        real(c_default_float), dimension(:), intent(in) :: array
        if (size (array) == size (model%par)) then
            model%par%value = array
        else
            call msg_bug ("Model '" // char (model%name) // "': size mismatch " &
                // "in parameter array")
        end if
    end subroutine model_parameters_from_c_array

```

Rcalculate all derived parameters.

```

<Models: public>+≡
    public :: model_parameters_update

<Models: procedures>+≡
    subroutine model_parameters_update (model)
        type(model_t), intent(inout) :: model
        integer :: i
        real(default), dimension(:), allocatable :: par
        do i = 1, size (model%par)
            call parameter_reset_derived (model%par(i))
        end do
        if (associated (model% init_external_parameters)) then
            call model_parameters_to_c_array (model, par)
            call model% init_external_parameters (par)
            call model_parameters_from_c_array (model, par)
        end if
    end subroutine model_parameters_update

```

Initialize particle data with PDG long name and PDG code.

```

<Models: procedures>+≡
    subroutine model_init_particle (model, i, longname, pdg)
        type(model_t), intent(inout) :: model
        integer, intent(in) :: i
        type(string_t), intent(in) :: longname
        integer, intent(in) :: pdg
        type(pdg_array_t) :: aval
        call particle_data_init (model%prt(i), longname, pdg)
        aval = pdg
        call var_list_append_pdg_array &
            (model%var_list, longname, aval, locked=.true., intrinsic=.true.)
    end subroutine model_init_particle

```

Copy quantum numbers from another particle

```

<Models: procedures>+≡
    subroutine model_copy_particle_data (model, i, name_src)
        type(model_t), intent(inout) :: model
        integer, intent(in) :: i
        type(string_t), intent(in) :: name_src
        call particle_data_copy (model%prt(i), &
            model_get_particle_ptr (model, &
                model_get_particle_pdg (model, name_src)))
    end subroutine model_copy_particle_data

```

Set particle quantum numbers individually. Names get a * prepended.

```

<Models: procedures>+≡
    subroutine model_set_particle_data (model, i, &
        is_visible, is_parton, is_gauge, is_left_handed, is_right_handed, &
        name, anti, tex_name, tex_anti, &
        spin_type, isospin_type, charge_type, color_type, &
        mass_src, width_src)
        type(model_t), intent(inout) :: model

```

```

integer, intent(in) :: i
logical, intent(in), optional :: is_visible, is_parton, is_gauge
logical, intent(in), optional :: is_left_handed, is_right_handed
type(string_t), dimension(:), intent(in), optional :: name, anti
type(string_t), intent(in), optional :: tex_name, tex_anti
integer, intent(in), optional :: spin_type, isospin_type
integer, intent(in), optional :: charge_type, color_type
type(parameter_t), intent(in), optional, target :: mass_src, width_src
integer :: j
type(pdg_array_t) :: aval
logical, parameter :: is_stable = .true.
call particle_data_set (model%prt(i), &
    is_visible, is_parton, is_gauge, is_left_handed, is_right_handed, &
    is_stable, &
    name, anti, tex_name, tex_anti, &
    spin_type, isospin_type, charge_type, color_type, &
    mass_src, width_src)
if (present (name)) then
    aval = particle_data_get_pdg (model%prt(i))
    do j = 1, size (name)
        call var_list_append_pdg_array &
            (model%var_list, name(j), aval, locked=.true., intrinsic=.true.)
    end do
end if
if (present (anti)) then
    aval = - particle_data_get_pdg (model%prt(i))
    do j = 1, size (anti)
        call var_list_append_pdg_array &
            (model%var_list, anti(j), aval, locked=.true., intrinsic=.true.)
    end do
end if
end subroutine model_set_particle_data

```

<Models: procedures>+≡

```

subroutine model_freeze_particle_data (model, i)
    type(model_t), intent(inout) :: model
    integer, intent(in) :: i
    call particle_data_freeze (model%prt(i))
end subroutine model_freeze_particle_data

```

Return a pointer to the particle-data object that belongs to the specified PDG code or name.

<Models: public>+≡

```

public :: model_get_particle_ptr

```

<Models: procedures>+≡

```

function model_get_particle_ptr (model, pdg) result (prt)
    type(particle_data_t), pointer :: prt
    type(model_t), intent(in), target :: model
    integer, intent(in) :: pdg
    integer :: i
    prt => null ()
    if (pdg /= UNDEFINED) then
        do i = 1, size (model%prt)

```

```

        if (model%prt(i)%pdg == abs (pdg)) then
            prt => model%prt(i); exit
        end if
    end do
    if (.not. associated (prt)) then
        write (msg_buffer, "(1x,A,1x,I7)") "PDG code =", pdg
        call msg_message
        call msg_fatal (" Model '" // char (model%name) // "' // &
            " has no particle with this PDG code")
    end if
end if
end function model_get_particle_ptr

```

Set the value, not the pointer. If the PDG code is not valid, do nothing.

<Models: public>+≡

```

public :: model_set_particle_mass
public :: model_set_particle_width

```

<Models: procedures>+≡

```

subroutine model_set_particle_mass (model, pdg, mass)
    type(model_t), intent(inout) :: model
    integer, intent(in) :: pdg
    real(default), intent(in) :: mass
    type(particle_data_t), pointer :: prt
    prt => model_get_particle_ptr (model, pdg)
    if (associated (prt)) call particle_data_set_mass (prt, mass)
end subroutine model_set_particle_mass

subroutine model_set_particle_width (model, pdg, width)
    type(model_t), intent(inout) :: model
    integer, intent(in) :: pdg
    real(default), intent(in) :: width
    type(particle_data_t), pointer :: prt
    prt => model_get_particle_ptr (model, pdg)
    if (associated (prt)) call particle_data_set_width (prt, width)
end subroutine model_set_particle_width

```

Return the PDG code that matches a particle name.

<Models: public>+≡

```

public :: model_get_particle_pdg

```

<Models: procedures>+≡

```

function model_get_particle_pdg (model, name) result (pdg)
    integer :: pdg
    type(model_t), intent(in), target :: model
    type(string_t), intent(in) :: name
    integer :: i
    pdg = UNDEFINED
    do i = 1, size (model%prt)
        if (model%prt(i)%longname == name) then
            pdg = particle_data_get_pdg (model%prt(i)); exit
        else if (any (model%prt(i)%name == name)) then
            pdg = particle_data_get_pdg (model%prt(i)); exit
        else if (any (model%prt(i)%anti == name)) then

```

```

        pdg = - particle_data_get_pdg (model%prt(i)); exit
    end if
end do
if (pdg == UNDEFINED) then
    write (msg_buffer, "(ix,A,ix,A)" "Particle name =", char (name)
    call msg_message
    call msg_fatal (" Model '" // char (model%name) // "' // &
        " has no particle with this name")
    end if
end function model_get_particle_pdg

```

Return a pointer to the variable list.

```

<Models: public>+≡
    public :: model_get_var_list_ptr

<Models: procedures>+≡
    function model_get_var_list_ptr (model) result (var_list)
        type(var_list_t), pointer :: var_list
        type(model_t), intent(in), target :: model
        var_list => model%var_list
    end function model_get_var_list_ptr

```

Vertex definition.

```

<Models: interfaces>+≡
    interface model_set_vertex
        module procedure model_set_vertex_pdg
        module procedure model_set_vertex_names
    end interface

<Models: procedures>+≡
    subroutine model_set_vertex_pdg (model, i, pdg)
        type(model_t), intent(inout), target :: model
        integer, intent(in) :: i
        integer, dimension(:), intent(in) :: pdg
        call vertex_init (model%vtx(i), pdg, model)
    end subroutine model_set_vertex_pdg

    subroutine model_set_vertex_names (model, i, name)
        type(model_t), intent(inout), target :: model
        integer, intent(in) :: i
        type(string_t), dimension(:), intent(in) :: name
        integer, dimension(size(name)) :: pdg
        integer :: j
        do j = 1, size (name)
            pdg(j) = model_get_particle_pdg (model, name(j))
        end do
        call vertex_init (model%vtx(i), pdg, model)
    end subroutine model_set_vertex_names

```

Lookup functions

```

<Models: public>+≡
    public :: model_match_vertex

```

```

<Models: procedures>+≡
  subroutine model_match_vertex (model, pdg1, pdg2, pdg3)
    type(model_t), intent(in) :: model
    integer, intent(in) :: pdg1, pdg2
    integer, dimension(:), allocatable, intent(out) :: pdg3
    call vertex_table_match (model%vt, pdg1, pdg2, pdg3)
  end subroutine model_match_vertex

<Models: public>+≡
  public :: model_check_vertex

<Models: procedures>+≡
  function model_check_vertex (model, pdg1, pdg2, pdg3) result (flag)
    logical :: flag
    type(model_t), intent(in) :: model
    integer, intent(in) :: pdg1, pdg2, pdg3
    flag = vertex_table_check (model%vt, pdg1, pdg2, pdg3)
  end function model_check_vertex

```

6.1.8 Reading models from file

This procedure defines the model-file syntax for the parser, returning an internal file (ifile).

Note that arithmetic operators are defined as keywords in the expression syntax, so we exclude them here.

```

<Models: procedures>+≡
  subroutine define_model_file_syntax (ifile)
    type(ifile_t), intent(inout) :: ifile
    call ifile_append (ifile, "SEQ model_def = model_name_def " // &
      "parameters derived_pars external_pars particles vertices")
    call ifile_append (ifile, "SEQ model_name_def = model model_name")
    call ifile_append (ifile, "KEY model")
    call ifile_append (ifile, "QUO model_name = '...'" // "'")
    call ifile_append (ifile, "SEQ parameters = parameter_def*")
    call ifile_append (ifile, "SEQ parameter_def = parameter par_name " // &
      "'=' any_real_value")
    call ifile_append (ifile, "ALT any_real_value = " // &
      "// "neg_real_value | pos_real_value | real_value")
    call ifile_append (ifile, "SEQ neg_real_value = '-' real_value")
    call ifile_append (ifile, "SEQ pos_real_value = '+' real_value")
    call ifile_append (ifile, "KEY parameter")
    call ifile_append (ifile, "IDE par_name")
    ! call ifile_append (ifile, "KEY '='")
    ! call ifile_append (ifile, "REA par_value")
    call ifile_append (ifile, "SEQ derived_pars = derived_def*")
    call ifile_append (ifile, "SEQ derived_def = derived par_name " // &
      "'=' expr")
    call ifile_append (ifile, "KEY derived")
    call ifile_append (ifile, "SEQ external_pars = external_def*")
    call ifile_append (ifile, "SEQ external_def = external par_name")
    call ifile_append (ifile, "KEY external")
    call ifile_append (ifile, "SEQ particles = particle_def*")
  end subroutine define_model_file_syntax

```

```

call ifile_append (ifile, "SEQ particle_def = particle prt_longname " // &
"prt_pdg prt_details")
call ifile_append (ifile, "KEY particle")
call ifile_append (ifile, "IDE prt_longname")
call ifile_append (ifile, "INT prt_pdg")
call ifile_append (ifile, "ALT prt_details = prt_src | prt_properties")
call ifile_append (ifile, "SEQ prt_src = like prt_longname prt_properties")
call ifile_append (ifile, "KEY like")
call ifile_append (ifile, "SEQ prt_properties = prt_property*")
call ifile_append (ifile, "ALT prt_property = " // &
"parton | invisible | gauge | left | right | " // &
"prt_name | prt_anti | prt_tex_name | prt_tex_anti | " // &
"prt_spin | prt_isospin | prt_charge | " // &
"prt_color | prt_mass | prt_width")
call ifile_append (ifile, "KEY parton")
call ifile_append (ifile, "KEY invisible")
call ifile_append (ifile, "KEY gauge")
call ifile_append (ifile, "KEY left")
call ifile_append (ifile, "KEY right")
call ifile_append (ifile, "SEQ prt_name = name name_def+")
call ifile_append (ifile, "SEQ prt_anti = anti name_def+")
call ifile_append (ifile, "SEQ prt_tex_name = tex_name name_def")
call ifile_append (ifile, "SEQ prt_tex_anti = tex_anti name_def")
call ifile_append (ifile, "KEY name")
call ifile_append (ifile, "KEY anti")
call ifile_append (ifile, "KEY tex_name")
call ifile_append (ifile, "KEY tex_anti")
call ifile_append (ifile, "ALT name_def = name_string | name_id")
call ifile_append (ifile, "QUO name_string = '""'...'""'")
call ifile_append (ifile, "IDE name_id")
call ifile_append (ifile, "SEQ prt_spin = spin frac")
call ifile_append (ifile, "KEY spin")
!   call ifile_append (ifile, "SEQ frac = signed_int div?")
!   call ifile_append (ifile, "ALT signed_int = " &
!       // "neg_int | pos_int | integer_literal")
!   call ifile_append (ifile, "SEQ neg_int = '-' integer_literal")
!   call ifile_append (ifile, "SEQ pos_int = '+' integer_literal")
!   call ifile_append (ifile, "KEY '-'")
!   call ifile_append (ifile, "KEY '+'")
!   call ifile_append (ifile, "INT int")
!   call ifile_append (ifile, "SEQ div = '/' integer_literal")
!   call ifile_append (ifile, "KEY '/'")
call ifile_append (ifile, "SEQ prt_isospin = isospin frac")
call ifile_append (ifile, "KEY isospin")
call ifile_append (ifile, "SEQ prt_charge = charge frac")
call ifile_append (ifile, "KEY charge")
call ifile_append (ifile, "SEQ prt_color = color integer_literal")
call ifile_append (ifile, "KEY color")
call ifile_append (ifile, "SEQ prt_mass = mass par_name")
call ifile_append (ifile, "KEY mass")
call ifile_append (ifile, "SEQ prt_width = width par_name")
call ifile_append (ifile, "KEY width")
call ifile_append (ifile, "SEQ vertices = vertex_def*")
call ifile_append (ifile, "SEQ vertex_def = vertex name_def+")

```

```

        call ifile_append (ifile, "KEY vertex")
        call define_expr_syntax (ifile, particles=.false., analysis=.false.)
    end subroutine define_model_file_syntax

```

The model-file syntax and lexer are fixed, therefore stored as module variables:

<Models: variables>+≡

```

    type(syntax_t), target, save :: syntax_model_file

```

<Models: public>+≡

```

    public :: syntax_model_file_init

```

<Models: procedures>+≡

```

    subroutine syntax_model_file_init ()
        type(ifile_t) :: ifile
        call define_model_file_syntax (ifile)
        call syntax_init (syntax_model_file, ifile)
        call ifile_final (ifile)
    end subroutine syntax_model_file_init

```

<Models: procedures>+≡

```

    subroutine lexer_init_model_file (lexer)
        type(lexer_t), intent(out) :: lexer
        call lexer_init (lexer, &
            comment_chars = "#!", &
            quote_chars = '"{', &
            quote_match = '"}', &
            single_chars = ":()", &
            special_class = (/ "+-*/^<>=" /) , &
            keyword_list = syntax_get_keyword_list_ptr (syntax_model_file))
    end subroutine lexer_init_model_file

```

<Models: public>+≡

```

    public :: syntax_model_file_final

```

<Models: procedures>+≡

```

    subroutine syntax_model_file_final ()
        call syntax_final (syntax_model_file)
    end subroutine syntax_model_file_final

```

<Models: procedures>+≡

```

    subroutine model_read (model, filename, os_data, exist)
        type(model_t), intent(out), target :: model
        type(string_t), intent(in) :: filename
        type(os_data_t), intent(in) :: os_data
        logical, intent(out) :: exist
        type(string_t) :: file
        type(stream_t) :: stream
        type(lexer_t) :: lexer
        integer :: unit
        character(32) :: model_md5sum
        type(parse_tree_t) :: parse_tree
        type(parse_node_t), pointer :: nd_model_def, nd_model_name_def
        type(parse_node_t), pointer :: nd_model_arg
    end subroutine model_read

```

```

type(parse_node_t), pointer :: nd_parameters, nd_derived_pars
type(parse_node_t), pointer :: nd_external_pars
type(parse_node_t), pointer :: nd_particles, nd_vertices
type(string_t) :: model_name, lib_name
integer :: n_par, n_der, n_ext, n_prt, n_vtx
real(c_default_float), dimension(:), allocatable :: par
integer :: i
type(parse_node_t), pointer :: nd_par_def
type(parse_node_t), pointer :: nd_der_def
type(parse_node_t), pointer :: nd_ext_def
type(parse_node_t), pointer :: nd_prt
type(parse_node_t), pointer :: nd_vtx
type(pdg_array_t) :: prt_undefined
file = filename
inquire (file=char(file), exist=exist)
if (.not. exist) then
    file = os_data%whizard_modelpath // "/" // filename
    inquire (file = char (file), exist = exist)
    if (.not. exist) then
        call msg_fatal ("Model file '" // char (filename) // "' not found")
        return
    end if
end if
call msg_message ("Reading model file '" // char (filename) // "'")
call lexer_init_model_file (lexer)
unit = free_unit ()
open (file=char(file), unit=unit, action="read", status="old")
model_md5sum = md5sum (unit)
rewind (unit)
call stream_init (stream, unit)
call parse_tree_init (parse_tree, syntax_model_file, lexer, stream)
call stream_final (stream)
close (unit)
call lexer_final (lexer)
! call parse_tree_write (parse_tree)
nd_model_def => parse_tree_get_root_ptr (parse_tree)
nd_model_name_def => parse_node_get_sub_ptr (nd_model_def)
model_name = parse_node_get_string &
    (parse_node_get_sub_ptr (nd_model_name_def, 2))
nd_parameters => parse_node_get_next_ptr (nd_model_name_def)
if (associated (nd_parameters)) then
    if (parse_node_get_rule_key (nd_parameters) == "parameters") then
        n_par = parse_node_get_n_sub (nd_parameters)
        nd_par_def => parse_node_get_sub_ptr (nd_parameters)
        nd_derived_pars => parse_node_get_next_ptr (nd_parameters)
    else
        n_par = 0
        nd_derived_pars => nd_parameters
        nd_parameters => null ()
    end if
else
    n_par = 0
    nd_derived_pars => null ()
end if
end if

```

```

if (associated (nd_derived_pars)) then
  if (parse_node_get_rule_key (nd_derived_pars) == "derived_pars") then
    n_der = parse_node_get_n_sub (nd_derived_pars)
    nd_der_def => parse_node_get_sub_ptr (nd_derived_pars)
    nd_external_pars => parse_node_get_next_ptr (nd_derived_pars)
  else
    n_der = 0
    nd_external_pars => nd_derived_pars
    nd_derived_pars => null ()
  end if
else
  n_der = 0
  nd_external_pars => null ()
end if
if (associated (nd_external_pars)) then
  if (parse_node_get_rule_key (nd_external_pars) == "external_pars") then
    n_ext = parse_node_get_n_sub (nd_external_pars)
    lib_name = "external." // model_name
    nd_ext_def => parse_node_get_sub_ptr (nd_external_pars)
    nd_particles => parse_node_get_next_ptr (nd_external_pars)
  else
    n_ext = 0
    lib_name = ""
    nd_particles => nd_external_pars
    nd_external_pars => null ()
  end if
else
  n_ext = 0
  lib_name = ""
  nd_particles => null ()
end if
if (associated (nd_particles)) then
  if (parse_node_get_rule_key (nd_particles) == "particles") then
    n_prt = parse_node_get_n_sub (nd_particles)
    nd_prt => parse_node_get_sub_ptr (nd_particles)
    nd_vertices => parse_node_get_next_ptr (nd_particles)
  else
    n_prt = 0
    nd_vertices => nd_particles
    nd_particles => null ()
  end if
else
  n_prt = 0
  nd_vertices => null ()
end if
if (associated (nd_vertices)) then
  n_vtx = parse_node_get_n_sub (nd_vertices)
  nd_vtx => parse_node_get_sub_ptr (nd_vertices)
else
  n_vtx = 0
end if
call model_init (model, model_name, lib_name, os_data, &
  n_par + n_der + n_ext, n_prt, n_vtx)
model%md5sum = model_md5sum

```

```

do i = 1, n_par
  call model_read_parameter (model, i, nd_par_def)
  nd_par_def => parse_node_get_next_ptr (nd_par_def)
end do
do i = n_par + 1, n_par + n_der
  call model_read_derived (model, i, nd_der_def)
  nd_der_def => parse_node_get_next_ptr (nd_der_def)
end do
do i = n_par + n_der + 1, n_par + n_der + n_ext
  call model_read_external (model, i, nd_ext_def)
  nd_ext_def => parse_node_get_next_ptr (nd_ext_def)
end do
if (associated (model% init_external_parameters)) then
  call model_parameters_to_c_array (model, par)
  call model% init_external_parameters (par)
  call model_parameters_from_c_array (model, par)
end if
prt_undefined = UNDEFINED
call var_list_append_pdg_array &
  (model%var_list, var_str ("particle"), &
  prt_undefined, locked = .true., intrinsic=.true.)
do i = 1, n_prt
  call model_read_particle (model, i, nd_prt)
  nd_prt => parse_node_get_next_ptr (nd_prt)
end do
do i = 1, n_vtx
  call model_read_vertex (model, i, nd_vtx)
  nd_vtx => parse_node_get_next_ptr (nd_vtx)
end do
call parse_tree_final (parse_tree)
call var_list_append_pdg_array &
  (model%var_list, var_str ("charged"), &
  particle_data_get_charged_pdg (model%prt), locked = .true., &
  intrinsic=.true.)
call var_list_append_pdg_array &
  (model%var_list, var_str ("colored"), &
  particle_data_get_colored_pdg (model%prt), locked = .true., &
  intrinsic=.true.)
end subroutine model_read

```

Parameters are real values (literal) with an optional unit.

(Models: procedures)+≡

```

subroutine model_read_parameter (model, i, node)
  type(model_t), intent(inout), target :: model
  integer, intent(in) :: i
  type(parse_node_t), intent(in), target :: node
  type(parse_node_t), pointer :: node_name, node_val
  type(string_t) :: name
  node_name => parse_node_get_sub_ptr (node, 2)
  name = parse_node_get_string (node_name)
  node_val => parse_node_get_next_ptr (node_name, 2)
  call model_set_parameter (model, i, name, node_val, constant=.true.)
end subroutine model_read_parameter

```

Derived parameters have any numeric expression as their definition.

(Models: procedures)+≡

```

subroutine model_read_derived (model, i, node)
  type(model_t), intent(inout), target :: model
  integer, intent(in) :: i
  type(parse_node_t), intent(in), target :: node
  type(string_t) :: name
  type(parse_node_t), pointer :: pn_expr
  name = parse_node_get_string (parse_node_get_sub_ptr (node, 2))
  pn_expr => parse_node_get_sub_ptr (node, 4)
  call model_set_parameter (model, i, name, pn_expr, constant=.false.)
end subroutine model_read_derived

```

External parameters have no definition; they are handled by an external library.

(Models: procedures)+≡

```

subroutine model_read_external (model, i, node)
  type(model_t), intent(inout), target :: model
  integer, intent(in) :: i
  type(parse_node_t), intent(in), target :: node
  type(string_t) :: name
  name = parse_node_get_string (parse_node_get_sub_ptr (node, 2))
  call model_set_parameter_external (model, i, name)
end subroutine model_read_external

```

(Models: procedures)+≡

```

subroutine model_read_particle (model, i, node)
  type(model_t), intent(inout) :: model
  integer, intent(in) :: i
  type(parse_node_t), intent(in) :: node
  type(parse_node_t), pointer :: nd_src, nd_props, nd_prop
  type(string_t) :: longname
  integer :: pdg
  type(string_t) :: name_src
  type(string_t), dimension(:), allocatable :: name
  longname = parse_node_get_string (parse_node_get_sub_ptr (node, 2))
  pdg = parse_node_get_integer (parse_node_get_sub_ptr (node, 3))
  call model_init_particle (model, i, longname, pdg)
  nd_src => parse_node_get_sub_ptr (node, 4)
  if (associated (nd_src)) then
    if (parse_node_get_rule_key (nd_src) == "prt_src") then
      name_src = parse_node_get_string (parse_node_get_sub_ptr (nd_src, 2))
      call model_copy_particle_data (model, i, name_src)
      nd_props => parse_node_get_sub_ptr (nd_src, 3)
    else
      nd_props => nd_src
    end if
  end if
  nd_prop => parse_node_get_sub_ptr (nd_props)
  do while (associated (nd_prop))
    select case (char (parse_node_get_rule_key (nd_prop)))
    case ("invisible")
      call model_set_particle_data (model, i, is_visible=.false.)
    case ("parton")

```

```

        call model_set_particle_data (model, i, is_parton=.true.)
case ("gauge")
    call model_set_particle_data (model, i, is_gauge=.true.)
case ("left")
    call model_set_particle_data (model, i, is_left_handed=.true.)
case ("right")
    call model_set_particle_data (model, i, is_right_handed=.true.)
case ("prt_name")
    call read_names (nd_prop, name)
    call model_set_particle_data (model, i, name=name)
case ("prt_anti")
    call read_names (nd_prop, name)
    call model_set_particle_data (model, i, anti=name)
case ("prt_tex_name")
    call model_set_particle_data (model, i, &
        tex_name = parse_node_get_string &
        (parse_node_get_sub_ptr (nd_prop, 2)))
case ("prt_tex_anti")
    call model_set_particle_data (model, i, &
        tex_anti = parse_node_get_string &
        (parse_node_get_sub_ptr (nd_prop, 2)))
case ("prt_spin")
    call model_set_particle_data (model, i, &
        spin_type = read_frac &
        (parse_node_get_sub_ptr (nd_prop, 2), 2))
case ("prt_isospin")
    call model_set_particle_data (model, i, &
        isospin_type = read_frac &
        (parse_node_get_sub_ptr (nd_prop, 2), 2))
case ("prt_charge")
    call model_set_particle_data (model, i, &
        charge_type = read_frac &
        (parse_node_get_sub_ptr (nd_prop, 2), 3))
case ("prt_color")
    call model_set_particle_data (model, i, &
        color_type = parse_node_get_integer &
        (parse_node_get_sub_ptr (nd_prop, 2)))
case ("prt_mass")
    call model_set_particle_data (model, i, &
        mass_src = model_get_parameter_ptr &
        (model, parse_node_get_string &
        (parse_node_get_sub_ptr (nd_prop, 2))))
case ("prt_width")
    call model_set_particle_data (model, i, &
        width_src = model_get_parameter_ptr &
        (model, parse_node_get_string &
        (parse_node_get_sub_ptr (nd_prop, 2))))
case default
    call msg_bug (" Unknown particle property '" &
        // char (parse_node_get_rule_key (nd_prop)) // "'")
end select
if (allocated (name)) deallocate (name)
nd_prop => parse_node_get_next_ptr (nd_prop)
end do

```

```

end if
call model_freeze_particle_data (model, i)
end subroutine model_read_particle

```

(Models: procedures)+≡

```

subroutine model_read_vertex (model, i, node)
  type(model_t), intent(inout) :: model
  integer, intent(in) :: i
  type(parse_node_t), intent(in) :: node
  type(string_t), dimension(:), allocatable :: name
  call read_names (node, name)
  call model_set_vertex (model, i, name)
end subroutine model_read_vertex

```

(Models: procedures)+≡

```

subroutine read_names (node, name)
  type(parse_node_t), intent(in) :: node
  type(string_t), dimension(:), allocatable, intent(inout) :: name
  type(parse_node_t), pointer :: nd_name
  integer :: n_names, i
  n_names = parse_node_get_n_sub (node) - 1
  allocate (name (n_names))
  nd_name => parse_node_get_sub_ptr (node, 2)
  do i = 1, n_names
    name(i) = parse_node_get_string (nd_name)
    nd_name => parse_node_get_next_ptr (nd_name)
  end do
end subroutine read_names

```

(Models: procedures)+≡

```

function read_frac (nd_frac, base) result (qn_type)
  integer :: qn_type
  type(parse_node_t), intent(in) :: nd_frac
  integer, intent(in) :: base
  type(parse_node_t), pointer :: nd_num, nd_den
  integer :: num, den
  nd_num => parse_node_get_sub_ptr (nd_frac)
  nd_den => parse_node_get_next_ptr (nd_num)
  select case (char (parse_node_get_rule_key (nd_num)))
  case ("integer_literal")
    num = parse_node_get_integer (nd_num)
  case ("neg_int")
    num = - parse_node_get_integer (parse_node_get_sub_ptr (nd_num, 2))
  case ("pos_int")
    num = parse_node_get_integer (parse_node_get_sub_ptr (nd_num, 2))
  case default
    call parse_tree_bug (nd_num, "int|neg_int|pos_int")
  end select
  if (associated (nd_den)) then
    den = parse_node_get_integer (parse_node_get_sub_ptr (nd_den, 2))
  else
    den = 1
  end if
end function

```

```

if (den == 1) then
  qn_type = sign (1 + abs (num) * base, num)
else if (den == base) then
  qn_type = sign (abs (num) + 1, num)
else
  call parse_node_write_rec (nd_frac)
  call msg_fatal (" Fractional quantum number: wrong denominator")
end if
end function read_frac

```

6.1.9 Model list

List of currently active models

```

⟨Models: types⟩+≡
  type :: model_entry_t
  type(model_t) :: model
  type(model_entry_t), pointer :: next => null ()
end type model_entry_t

```

```

⟨Models: types⟩+≡
  type :: model_list_t
  type(model_entry_t), pointer :: first => null ()
  type(model_entry_t), pointer :: last => null ()
end type model_list_t

```

The model list is stored as a module variable. Thus, the operations acting on the list do not have the model list as an argument.

```

⟨Models: variables⟩+≡
  type(model_list_t), target, save :: model_list

```

Write an account of the model list.

```

⟨Models: public⟩+≡
  public :: model_list_write

⟨Models: procedures⟩+≡
  subroutine model_list_write (unit, verbose)
    integer, intent(in), optional :: unit
    logical, intent(in), optional :: verbose
    type(model_entry_t), pointer :: current
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write (u, *) "List of models:"
    current => model_list%first
    if (associated (current)) then
      do while (associated (current))
        write (u, *)
        call model_write (current%model, unit, verbose)
        current => current%next
      end do
    else
      write (u, *) " [empty]"
    end if
  end subroutine model_list_write

```

```

        end if
    end subroutine model_list_write

```

Add a new model with given name to the list, if it does not yet exist. If successful, return a pointer to the new model.

(Models: procedures)+≡

```

subroutine model_list_add (name, os_data, n_par, n_prt, n_vtx, model)
    type(string_t), intent(in) :: name
    type(os_data_t), intent(in) :: os_data
    integer, intent(in) :: n_par, n_prt, n_vtx
    type(model_t), pointer :: model
    type(model_entry_t), pointer :: current
    if (model_list_model_exists (name)) then
        model => null ()
    else
        allocate (current)
        if (associated (model_list%first)) then
            model_list%last%next => current
        else
            model_list%first => current
        end if
        model_list%last => current
        model => current%model
        call model_init (model, name, var_str (""), os_data, &
            n_par, n_prt, n_vtx)
    end if
end subroutine model_list_add

```

Read a new model from file and add to the list, if it does not yet exist. Finalize the model by allocating the vertex table. Return a pointer to the new model. If unsuccessful, return the original pointer.

(Models: public)+≡

```

    public :: model_list_read_model

```

(Models: procedures)+≡

```

subroutine model_list_read_model (name, filename, os_data, model)
    type(string_t), intent(in) :: name, filename
    type(os_data_t), intent(in) :: os_data
    type(model_t), pointer :: model
    type(model_entry_t), pointer :: current
    logical :: exist
    if (.not. model_list_model_exists (name)) then
        allocate (current)
        call model_read (current%model, filename, os_data, exist)
        if (.not. exist) return
        if (current%model%name /= name) then
            call msg_fatal ("Model file '" // char (filename) // &
                "' contains model '" // char (current%model%name) // &
                "' instead of '" // char (name) // "'")
            call model_final (current%model); deallocate (current)
            return
        end if
        if (associated (model_list%first)) then

```

```

        model_list%last%next => current
    else
        model_list%first => current
    end if
    model_list%last => current
    call vertex_table_init &
        (current%model%vt, current%model%prt, current%model%vtx)
    model => current%model
else
    model => model_list_get_model_ptr (name)
end if
end subroutine model_list_read_model

```

Check if a model exists by examining the list

<Models: public>+≡

```
public :: model_list_model_exists
```

<Models: procedures>+≡

```

function model_list_model_exists (name) result (exists)
    logical :: exists
    type(string_t), intent(in) :: name
    type(model_entry_t), pointer :: current
    current => model_list%first
    do while (associated (current))
        if (current%model%name == name) then
            exists = .true.
            return
        end if
        current => current%next
    end do
    exists = .false.
end function model_list_model_exists

```

Return a pointer to a named model

<Models: public>+≡

```
public :: model_list_get_model_ptr
```

<Models: procedures>+≡

```

function model_list_get_model_ptr (name) result (model)
    type(model_t), pointer :: model
    type(string_t), intent(in) :: name
    type(model_entry_t), pointer :: current
    current => model_list%first
    do while (associated (current))
        if (current%model%name == name) then
            model => current%model
            return
        end if
        current => current%next
    end do
    model => null ()
end function model_list_get_model_ptr

```

Delete the list of models

```
<Models: public>+≡
    public :: model_list_final

<Models: procedures>+≡
    subroutine model_list_final ()
        type(model_entry_t), pointer :: current
        model_list%last => null ()
        do while (associated (model_list%first))
            current => model_list%first
            model_list%first => model_list%first%next
            call model_final (current%model)
            deallocate (current)
        end do
    end subroutine model_list_final
```

6.1.10 Test

```
<Models: public>+≡
    public :: models_test

<Models: procedures>+≡
    subroutine models_test ()
        type(os_data_t) :: os_data
        call syntax_model_file_init ()
        call syntax_write (syntax_model_file)
        print *
        call models_test1 (os_data)
        call models_test2 (os_data)
        call models_test2 (os_data)
        call model_list_write (verbose=.true.)
!       call model_list_write ()
        call model_list_final ()
        call syntax_model_file_final ()
    end subroutine models_test

    subroutine models_test1 (os_data)
        type(os_data_t), intent(in) :: os_data
        type(model_t), pointer :: model
        type(string_t) :: model_name
        type(string_t) :: x_longname
        type(string_t), dimension(2) :: parname
        type(string_t), dimension(2) :: x_name
        type(string_t), dimension(1) :: x_anti
        type(string_t) :: x_tex_name, x_tex_anti
        type(string_t) :: y_longname
        type(string_t), dimension(2) :: y_name
        type(string_t) :: y_tex_name
        model_name = "Test model"
        call model_list_add (model_name, os_data, 2, 2, 3, model)
        parname(1) = "mx"
        parname(2) = "coup"
        call model_set_parameter (model, 1, parname(1), 10._default)
        call model_set_parameter (model, 2, parname(2), 1.3_default)
```

```

print *
x_longname = "X_LEPTON"
x_name(1) = "X"
x_name(2) = "x"
x_anti(1) = "Xbar"
x_tex_name = "X^+"
x_tex_anti = "X^- "
call model_init_particle (model, 1, x_longname, 99)
call model_set_particle_data (model, 1, &
    .true., .false., .false., .false., .false., &
    x_name, x_anti, x_tex_name, x_tex_anti, &
    SPINOR, -3, 2, 1, model_get_parameter_ptr (model, parname(1)))
y_longname = "Y_COLORON"
y_name(1) = "Y"
y_name(2) = "yc"
y_tex_name = "Y^0"
call model_init_particle (model, 2, y_longname, 97)
call model_set_particle_data (model, 2, &
    .false., .false., .true., .false., .false., &
    name=y_name, tex_name=y_tex_name, &
    spin_type=SCALAR, isospin_type=2, charge_type=1, color_type=8)
call model_set_vertex (model, 1, (/ 99, 99, 99 /))
call model_set_vertex (model, 2, (/ 99, 99, 99, 99 /))
call model_set_vertex (model, 3, (/ 99, 97, 99 /))
end subroutine models_test1

subroutine models_test2 (os_data)
    type(os_data_t), intent(in) :: os_data
    type(string_t) :: name, filename
    type(model_t), pointer :: model
    name = "QCD"
    filename = "test.mdl"
    call model_list_read_model (name, filename, os_data, model)
end subroutine models_test2

```

Chapter 7

Quantum Numbers

We introduce separate types and modules for particle quantum numbers and use them for defining independent particles and entangled states.

helicities Types and methods for spin density matrices.

colors Dealing with colored particles, using the color-flow representation.

flavors PDG codes and particle properties, depends on the model.

quantum_states Quantum numbers and density matrices for entangled particle systems.

7.1 Helicities

This module defines types and tools for dealing with helicity information.

```
<helicities.f90>≡  
  <File header>  
  
  module helicities  
  
    <Use file utils>  
  
    <Standard module head>  
  
    <Helicities: public>  
  
    <Helicities: types>  
  
    <Helicities: interfaces>  
  
    contains  
  
    <Helicities: procedures>  
  
  end module helicities
```

7.1.1 Helicity types

Helicities may be defined or undefined, corresponding to a polarized or unpolarized state. Each helicity is actually a pair of helicities, corresponding to an entry in the spin density matrix. Obviously, diagonal entries are distinguished. In addition, we have a ghost flag that would apply to FP ghosts in particular.

```
<Helicities: public>≡  
  public :: helicity_t  
  
<Helicities: types>≡  
  type :: helicity_t  
    private  
    logical :: defined = .false.  
    integer :: h1, h2  
    logical :: ghost = .false.  
  end type helicity_t
```

Initializers:

```
<Helicities: public>+≡  
  public :: helicity_init  
  
<Helicities: interfaces>≡  
  interface helicity_init  
    module procedure helicity_init0, helicity_init0g  
    module procedure helicity_init1, helicity_init1g  
    module procedure helicity_init2, helicity_init2g  
  end interface
```

```

<Helicities: procedures>+≡
  elemental subroutine helicity_init0 (hel)
    type(helicity_t), intent(out) :: hel
  end subroutine helicity_init0

  elemental subroutine helicity_init0g (hel, ghost)
    type(helicity_t), intent(out) :: hel
    logical, intent(in) :: ghost
    hel%ghost = ghost
  end subroutine helicity_init0g

  elemental subroutine helicity_init1 (hel, h)
    type(helicity_t), intent(out) :: hel
    integer, intent(in) :: h
    hel%defined = .true.
    hel%h1 = h
    hel%h2 = h
  end subroutine helicity_init1

  elemental subroutine helicity_init1g (hel, h, ghost)
    type(helicity_t), intent(out) :: hel
    integer, intent(in) :: h
    logical, intent(in) :: ghost
    call helicity_init1 (hel, h)
    hel%ghost = ghost
  end subroutine helicity_init1g

  elemental subroutine helicity_init2 (hel, h2, h1)
    type(helicity_t), intent(out) :: hel
    integer, intent(in) :: h1, h2
    hel%defined = .true.
    hel%h2 = h2
    hel%h1 = h1
  end subroutine helicity_init2

  elemental subroutine helicity_init2g (hel, h2, h1, ghost)
    type(helicity_t), intent(out) :: hel
    integer, intent(in) :: h1, h2
    logical, intent(in) :: ghost
    call helicity_init2 (hel, h2, h1)
    hel%ghost = ghost
  end subroutine helicity_init2g

```

Set the ghost property separately:

```

<Helicities: public>+≡
  public :: helicity_set_ghost

<Helicities: procedures>+≡
  elemental subroutine helicity_set_ghost (hel, ghost)
    type(helicity_t), intent(inout) :: hel
    logical, intent(in) :: ghost
    hel%ghost = ghost
  end subroutine helicity_set_ghost

```

Undefine:

```
<Helicities: public>+≡
  public :: helicity_undefine

<Helicities: procedures>+≡
  elemental subroutine helicity_undefine (hel)
    type(helicity_t), intent(inout) :: hel
    hel%defined = .false.
    hel%ghost = .false.
  end subroutine helicity_undefine
```

Diagonalize by removing the second entry (use with care!)

```
<Helicities: public>+≡
  public :: helicity_diagonalize

<Helicities: procedures>+≡
  elemental subroutine helicity_diagonalize (hel)
    type(helicity_t), intent(inout) :: hel
    hel%h2 = hel%h1
  end subroutine helicity_diagonalize
```

Output (no linebreak). No output if undefined.

```
<Helicities: public>+≡
  public :: helicity_write

<Helicities: procedures>+≡
  subroutine helicity_write (hel, unit)
    type(helicity_t), intent(in) :: hel
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    if (hel%defined) then
      if (hel%ghost) then
        write (u, "(A)", advance="no") "h*"
      else
        write (u, "(A)", advance="no") "h("
      end if
      write (u, "(IO)", advance="no") hel%h1
      if (hel%h1 /= hel%h2) then
        write (u, "(A)", advance="no") "|"
        write (u, "(IO)", advance="no") hel%h2
      end if
      write (u, "(A)", advance="no") ")"
    else if (hel%ghost) then
      write (u, "(A)", advance="no") "h*"
    end if
  end subroutine helicity_write
```

Binary I/O. Write contents only if defined.

```
<Helicities: public>+≡
  public :: helicity_write_raw
  public :: helicity_read_raw
```

```

<Helicities: procedures>+≡
  subroutine helicity_write_raw (hel, u)
    type(helicity_t), intent(in) :: hel
    integer, intent(in) :: u
    write (u) hel%defined
    if (hel%defined) then
      write (u) hel%h1, hel%h2
      write (u) hel%ghost
    end if
  end subroutine helicity_write_raw

  subroutine helicity_read_raw (hel, u, iostat)
    type(helicity_t), intent(out) :: hel
    integer, intent(in) :: u
    integer, intent(out), optional :: iostat
    read (u, iostat=iostat) hel%defined
    if (hel%defined) then
      read (u, iostat=iostat) hel%h1, hel%h2
      read (u, iostat=iostat) hel%ghost
    end if
  end subroutine helicity_read_raw

```

7.1.2 Predicates

Check if the helicity is defined:

```

<Helicities: public>+≡
  public :: helicity_is_defined

<Helicities: procedures>+≡
  elemental function helicity_is_defined (hel) result (defined)
    logical :: defined
    type(helicity_t), intent(in) :: hel
    defined = hel%defined
  end function helicity_is_defined

```

Return true if the two helicities are equal or the particle is unpolarized:

```

<Helicities: public>+≡
  public :: helicity_is_diagonal

<Helicities: procedures>+≡
  elemental function helicity_is_diagonal (hel) result (diagonal)
    logical :: diagonal
    type(helicity_t), intent(in) :: hel
    if (hel%defined) then
      diagonal = hel%h1 == hel%h2
    else
      diagonal = .true.
    end if
  end function helicity_is_diagonal

```

Return the ghost flag

```

<Helicities: public>+≡
  public :: helicity_is_ghost

```

```

<Helicities: procedures>+≡
  elemental function helicity_is_ghost (hel) result (ghost)
    logical :: ghost
    type(helicity_t), intent(in) :: hel
    ghost = hel%ghost
  end function helicity_is_ghost

```

7.1.3 Accessing contents

This returns a two-element array and thus cannot be elemental. The result is unpredictable if the helicity is undefined.

```

<Helicities: public>+≡
  public :: helicity_get

<Helicities: procedures>+≡
  pure function helicity_get (hel) result (h)
    integer, dimension(2) :: h
    type(helicity_t), intent(in) :: hel
    h(1) = hel%h2
    h(2) = hel%h1
  end function helicity_get

```

7.1.4 Comparisons

When comparing helicities, if either one is undefined, they are considered to match. In other words, an unpolarized particle matches any polarization. In the `dmatch` variant, it matches only diagonal helicity.

The ghost flag is ignored when matching, but matters when testing for equality.

```

<Helicities: public>+≡
  public :: operator(.match.)
  public :: operator(.dmatch.)
  public :: operator(==)
  public :: operator(/=)

<Helicities: interfaces>+≡
  interface operator(.match.)
    module procedure helicity_match
  end interface
  interface operator(.dmatch.)
    module procedure helicity_match_diagonal
  end interface
  interface operator(==)
    module procedure helicity_eq
  end interface
  interface operator(/=)
    module procedure helicity_neq
  end interface

```

```

<Helicities: procedures>+=
  elemental function helicity_match (hel1, hel2) result (eq)
    logical :: eq
    type(helicity_t), intent(in) :: hel1, hel2
    if (hel1%defined .and. hel2%defined) then
      eq = (hel1%h1 == hel2%h1) .and. (hel1%h2 == hel2%h2)
    else
      eq = .true.
    end if
  end function helicity_match

  elemental function helicity_match_diagonal (hel1, hel2) result (eq)
    logical :: eq
    type(helicity_t), intent(in) :: hel1, hel2
    if (hel1%defined .and. hel2%defined) then
      eq = (hel1%h1 == hel2%h1) .and. (hel1%h2 == hel2%h2)
    else if (hel1%defined) then
      eq = hel1%h1 == hel1%h2
    else if (hel2%defined) then
      eq = hel2%h1 == hel2%h2
    else
      eq = .true.
    end if
  end function helicity_match_diagonal

<Helicities: procedures>+=
  elemental function helicity_eq (hel1, hel2) result (eq)
    logical :: eq
    type(helicity_t), intent(in) :: hel1, hel2
    if (hel1%defined .and. hel2%defined) then
      eq = (hel1%h1 == hel2%h1) .and. (hel1%h2 == hel2%h2) &
        .and. (hel1%ghost .eqv. hel2%ghost)
    else if (.not. hel1%defined .and. .not. hel2%defined) then
      eq = hel1%ghost .eqv. hel2%ghost
    else
      eq = .false.
    end if
  end function helicity_eq

<Helicities: procedures>+=
  elemental function helicity_neq (hel1, hel2) result (neq)
    logical :: neq
    type(helicity_t), intent(in) :: hel1, hel2
    if (hel1%defined .and. hel2%defined) then
      neq = (hel1%h1 /= hel2%h1) .or. (hel1%h2 /= hel2%h2) &
        .or. (hel1%ghost .neqv. hel2%ghost)
    else if (.not. hel1%defined .and. .not. hel2%defined) then
      neq = hel1%ghost .neqv. hel2%ghost
    else
      neq = .true.
    end if
  end function helicity_neq

```

7.1.5 Tools

Merge two helicity objects by taking the first entry from the first and the second entry from the second argument. Makes sense only if the input helicities were defined and diagonal. The handling of ghost flags is not well-defined; one should verify beforehand that they match.

```
<Helicities: public>+≡
    public :: operator(.merge.)

<Helicities: interfaces>+≡
    interface operator(.merge.)
        module procedure merge_helicities
    end interface

<Helicities: procedures>+≡
    elemental function merge_helicities (hel1, hel2) result (hel)
        type(helicity_t) :: hel
        type(helicity_t), intent(in) :: hel1, hel2
        if (helicity_is_defined (hel1) .and. helicity_is_defined (hel2)) then
            call helicity_init2g (hel, hel2%h1, hel1%h1, hel1%ghost)
        else if (helicity_is_defined (hel1)) then
            hel = hel1
        else if (helicity_is_defined (hel2)) then
            hel = hel2
        end if
    end function merge_helicities
```

7.2 Colors

This module defines a type and tools for dealing with color information.

Each particle can have zero or more (in practice, usually not more than two) color indices. Color indices are positive; flow direction can be determined from the particle nature.

While parton shower matrix elements are diagonal in color, some special applications (e.g., subtractions for NLO matrix elements) require non-diagonal color matrices.

```
<colors.f90>≡  
  <File header>  
  
  module colors  
  
    <Use file utils>  
    use diagnostics !NODEP!  
  
    <Standard module head>  
  
    <Colors: public>  
  
    <Colors: types>  
  
    <Colors: interfaces>  
  
    contains  
  
    <Colors: procedures>  
  
  end module colors
```

7.2.1 The color type

A particle may have an arbitrary number of color indices (in practice, from zero to two, but more are possible). This object acts as a container.

The fact that color comes as an array prohibits elemental procedures in some places. (May add interfaces and multi versions where necessary.)

The color may be undefined; this corresponds to unallocated arrays.

NOTE: Due to a compiler bug in nagfor 5.2, we do not use allocatable but fixed-size arrays with dimension 2. Only nonzero entries count. This may be more efficient anyway, but gives up some flexibility. However, the squaring algorithm currently works only for singlets, (anti)triplets and octets anyway, so two components are enough.

```
<Colors: public>≡  
  public :: color_t  
  
<Colors: types>≡  
  type :: color_t  
    private  
    !   integer, dimension(:), allocatable :: c1, c2  
    integer, dimension(2) :: c1 = 0, c2 = 0  
    logical :: ghost = .false.
```

```
end type color_t
```

Initializers:

```
<Colors: public>+≡
```

```
public :: color_init
```

```
<Colors: interfaces>≡
```

```
interface color_init
```

```
module procedure color_init_undefined, color_init_undefined_ghost
```

```
module procedure color_init_array, color_init_array_ghost
```

```
module procedure color_init_arrays, color_init_arrays_ghost
```

```
end interface
```

Undefined color: array remains unallocated

```
<Colors: procedures>≡
```

```
pure subroutine color_init_undefined (col)
```

```
type(color_t), intent(out) :: col
```

```
end subroutine color_init_undefined
```

```
pure subroutine color_init_undefined_ghost (col, ghost)
```

```
type(color_t), intent(out) :: col
```

```
logical, intent(in) :: ghost
```

```
col%ghost = ghost
```

```
end subroutine color_init_undefined_ghost
```

This defines color from an arbitrary length color array, suitable for any representation. We may have two color arrays (non-diagonal matrix elements). This cannot be elemental. The third version assigns an array of colors, using a two-dimensional array as input.

```
<Colors: procedures>+≡
```

```
pure subroutine color_init_array (col, c1)
```

```
type(color_t), intent(out) :: col
```

```
integer, dimension(:), intent(in) :: c1
```

```
! allocate (col%c1 (size (c1)))
```

```
! allocate (col%c2 (size (c1)))
```

```
col%c1 = pack (c1, c1 /= 0, col%c1)
```

```
col%c2 = col%c1
```

```
end subroutine color_init_array
```

```
pure subroutine color_init_array_ghost (col, c1, ghost)
```

```
type(color_t), intent(out) :: col
```

```
integer, dimension(:), intent(in) :: c1
```

```
logical, intent(in) :: ghost
```

```
call color_init_array (col, c1)
```

```
col%ghost = ghost
```

```
end subroutine color_init_array_ghost
```

```
pure subroutine color_init_arrays (col, c1, c2)
```

```
type(color_t), intent(out) :: col
```

```
integer, dimension(:), intent(in) :: c1, c2
```

```
if (size (c1) == size (c2)) then
```

```
! allocate (col%c1 (size (c1)))
```

```

!      allocate (col%c2 (size (c2)))
      col%c1 = pack (c1, c1 /= 0, col%c1)
      col%c2 = pack (c2, c2 /= 0, col%c2)
    else if (size (c1) /= 0) then
!      allocate (col%c1 (size (c1)))
!      allocate (col%c2 (size (c1)))
      col%c1 = pack (c1, c1 /= 0, col%c1)
      col%c2 = col%c1
    else if (size (c2) /= 0) then
!      allocate (col%c1 (size (c2)))
!      allocate (col%c2 (size (c2)))
      col%c1 = pack (c2, c2 /= 0, col%c2)
      col%c2 = col%c1
    end if
end subroutine color_init_arrays

pure subroutine color_init_arrays_ghost (col, c1, c2, ghost)
  type(color_t), intent(out) :: col
  integer, dimension(:), intent(in) :: c1, c2
  logical, intent(in) :: ghost
  call color_init_arrays (col, c1, c2)
  col%ghost = ghost
end subroutine color_init_arrays_ghost

```

This version is restricted to singlets, triplets, antitriplets, and octets: The input contains the color and anticolor index, each of the may be zero.

<Colors: public>+≡

```
public :: color_init_col_acl
```

<Colors: procedures>+≡

```

elemental subroutine color_init_col_acl (col, col_in, acl_in)
  type(color_t), intent(out) :: col
  integer, intent(in) :: col_in, acl_in
  integer, dimension(0) :: null_array
  select case (col_in)
  case (0)
    select case (acl_in)
    case (0)
      call color_init_array (col, null_array)
    case default
      call color_init_array (col, (/ -acl_in /))
    end select
  case default
    select case (acl_in)
    case (0)
      call color_init_array (col, (/ col_in /))
    case default
      call color_init_array (col, (/ col_in, -acl_in /))
    end select
  end select
end subroutine color_init_col_acl

```

This version is used for the external interface. We convert a fixed-size array of colors (for each particle) to the internal form by packing only the nonzero

entries.

<Colors: public>+≡

public :: color_init_from_array

<Colors: interfaces>+≡

interface color_init_from_array

module procedure color_init_from_array1, color_init_from_array1g

module procedure color_init_from_array2, color_init_from_array2g

end interface

<Colors: procedures>+≡

pure subroutine color_init_from_array1 (col, c1)

type(color_t), intent(out) :: col

integer, dimension(:), intent(in) :: c1

logical, dimension(size(c1)) :: mask

mask = c1 /= 0

! allocate (col%c1 (count (mask)))

! allocate (col%c2 (size (col%c1)))

col%c1 = pack (c1, mask, col%c1)

col%c2 = col%c1

end subroutine color_init_from_array1

pure subroutine color_init_from_array1g (col, c1, ghost)

type(color_t), intent(out) :: col

integer, dimension(:), intent(in) :: c1

logical, intent(in) :: ghost

call color_init_from_array1 (col, c1)

col%ghost = ghost

end subroutine color_init_from_array1g

pure subroutine color_init_from_array2 (col, c1)

integer, dimension(:,:), intent(in) :: c1

type(color_t), dimension(size(c1,2)), intent(out) :: col

integer :: i

do i = 1, size (c1,2)

call color_init_from_array1 (col(i), c1(:,i))

end do

end subroutine color_init_from_array2

pure subroutine color_init_from_array2g (col, c1, ghost)

integer, dimension(:,:), intent(in) :: c1

type(color_t), dimension(size(c1,2)), intent(out) :: col

logical, intent(in), dimension(:) :: ghost

call color_init_from_array2 (col, c1)

col%ghost = ghost

end subroutine color_init_from_array2g

Set the ghost property

<Colors: public>+≡

public :: color_set_ghost

<Colors: procedures>+≡

elemental subroutine color_set_ghost (col, ghost)

type(color_t), intent(inout) :: col

```

        logical, intent(in) :: ghost
        col%ghost = ghost
    end subroutine color_set_ghost

```

Undefine the color state:

```

<Colors: public>+≡
    public :: color_undefine

<Colors: procedures>+≡
    elemental subroutine color_undefine (col, undefine_ghost)
        type(color_t), intent(inout) :: col
        logical, intent(in), optional :: undefine_ghost
    !     if (allocated (col%c1)) deallocate (col%c1)
    !     if (allocated (col%c2)) deallocate (col%c2)
        col%c1 = 0
        col%c2 = 0
        if (present (undefine_ghost)) then
            if (undefine_ghost) col%ghost = .false.
        else
            col%ghost = .false.
        end if
    end subroutine color_undefine

```

Output. As dense as possible, no linebreak. If color is undefined, no output.

```

<Colors: public>+≡
    public :: color_write

<Colors: interfaces>+≡
    interface color_write
        module procedure color_write_single
        module procedure color_write_array
    end interface

<Colors: procedures>+≡
    subroutine color_write_single (col, unit)
        type(color_t), intent(in) :: col
        integer, intent(in), optional :: unit
        integer :: u
        u = output_unit (unit); if (u < 0) return
        if (color_is_defined (col)) then
            write (u, "(A)", advance="no") "c("
            if (col%c1(1) /= 0) write (u, "(I0)", advance="no") col%c1(1)
            if (any (col%c1 /= 0)) write (u, "(1x)", advance="no")
            if (col%c1(2) /= 0) write (u, "(I0)", advance="no") col%c1(2)
            if (.not. color_is_diagonal (col)) then
                write (u, "(A)", advance="no") "|"
                if (col%c2(1) /= 0) write (u, "(I0)", advance="no") col%c2(1)
                if (any (col%c2 /= 0)) write (u, "(1x)", advance="no")
                if (col%c2(2) /= 0) write (u, "(I0)", advance="no") col%c2(2)
            end if
            write (u, "(A)", advance="no") ")"
        else if (col%ghost) then
            write (u, "(A)", advance="no") "c*"
        end if
    end subroutine color_write_single

```

```

end subroutine color_write_single

subroutine color_write_array (col, unit)
  type(color_t), dimension(:), intent(in) :: col
  integer, intent(in), optional :: unit
  integer :: u
  integer :: i
  u = output_unit (unit); if (u < 0) return
  write (u, "(A)", advance="no") "["
  do i = 1, size (col)
    if (i > 1) write (u, "(1x)", advance="no")
    call color_write_single (col(i), u)
  end do
  write (u, "(A)", advance="no") "]"
end subroutine color_write_array

```

Binary I/O. For allocatable colors, this would have to be modified.

```

<Colors: public>+≡
  public :: color_write_raw
  public :: color_read_raw

<Colors: procedures>+≡
  subroutine color_write_raw (col, u)
    type(color_t), intent(in) :: col
    integer, intent(in) :: u
    logical :: defined
    defined = color_is_defined (col) .or. color_is_ghost (col)
    write (u) defined
    if (defined) then
      write (u) col%c1, col%c2
      write (u) col%ghost
    end if
  end subroutine color_write_raw

  subroutine color_read_raw (col, u, iostat)
    type(color_t), intent(out) :: col
    integer, intent(in) :: u
    integer, intent(out), optional :: iostat
    logical :: defined
    read (u, iostat=iostat) defined
    if (defined) then
      read (u, iostat=iostat) col%c1, col%c2
      read (u, iostat=iostat) col%ghost
    end if
  end subroutine color_read_raw

```

7.2.2 Predicates

Return the definition status

```

<Colors: public>+≡
  public :: color_is_defined

```

```

<Colors: procedures>+≡
  elemental function color_is_defined (col) result (defined)
    logical :: defined
    type(color_t), intent(in) :: col
    !   defined = allocated (col%c1)
    defined = any (col%c1 /= 0)
  end function color_is_defined

```

Diagonal color objects have only one array allocated:

```

<Colors: public>+≡
  public :: color_is_diagonal

<Colors: procedures>+≡
  elemental function color_is_diagonal (col) result (diagonal)
    logical :: diagonal
    type(color_t), intent(in) :: col
    if (color_is_defined (col)) then
      diagonal = all (col%c1 == col%c2)
    else
      diagonal = .true.
    end if
  end function color_is_diagonal

```

Return the ghost flag

```

<Colors: public>+≡
  public :: color_is_ghost

<Colors: procedures>+≡
  elemental function color_is_ghost (col) result (ghost)
    logical :: ghost
    type(color_t), intent(in) :: col
    ghost = col%ghost
  end function color_is_ghost

```

7.2.3 Accessing contents

Return the number of color indices. We assume that it is identical for both arrays.

```

<Colors: procedures>+≡
  elemental function color_number (col) result (n)
    integer :: n
    type(color_t), intent(in) :: col
    !   n = size (col%c1)
    n = count (col%c1 /= 0)
  end function color_number

```

Return the (first) color/anticolor entry (assuming that color is diagonal). The result is a positive color index.

```

<Colors: public>+≡
  public :: color_get_col
  public :: color_get_acl

```

```

<Colors: procedures>+≡
function color_get_col (col) result (c)
  integer :: c
  type(color_t), intent(in) :: col
  integer :: i
  do i = 1, size (col%c1)
    if (col%c1(i) > 0) then
      c = col%c1(i)
      return
    end if
  end do
  c = 0
end function color_get_col

function color_get_acl (col) result (c)
  integer :: c
  type(color_t), intent(in) :: col
  integer :: i
  do i = 1, size (col%c1)
    if (col%c1(i) < 0) then
      c = - col%c1(i)
      return
    end if
  end do
  c = 0
end function color_get_acl

```

Return the color index with highest absolute value

```

<Colors: public>+≡
public :: color_get_max_value

<Colors: interfaces>+≡
interface color_get_max_value
  module procedure color_get_max_value0
  module procedure color_get_max_value1
  module procedure color_get_max_value2
end interface

<Colors: procedures>+≡
elemental function color_get_max_value0 (col) result (cmax)
  integer :: cmax
  type(color_t), intent(in) :: col
  cmax = maxval (abs (col%c1))
end function color_get_max_value0

pure function color_get_max_value1 (col) result (cmax)
  integer :: cmax
  type(color_t), dimension(:), intent(in) :: col
  cmax = maxval (color_get_max_value0 (col))
end function color_get_max_value1

function color_get_max_value2 (col) result (cmax)
  integer :: cmax
  type(color_t), dimension(:,:), intent(in) :: col

```

```

integer, dimension(size(col, 2)) :: cm
integer :: i
forall (i = 1:size(col, 2))
    cm(i) = color_get_max_value1 (col(:,i))
end forall
cm = maxval (cm)
end function color_get_max_value2

```

7.2.4 Comparisons

Similar to helicities, colors match if they are equal, or if either one is undefined.

<Colors: public>+≡

```

public :: operator(.match.)
public :: operator(==)
public :: operator(/=)

```

<Colors: interfaces>+≡

```

interface operator(.match.)
    module procedure color_match
end interface
interface operator(==)
    module procedure color_eq
end interface
interface operator(/=)
    module procedure color_neq
end interface

```

<Colors: procedures>+≡

```

elemental function color_match (col1, col2) result (eq)
    logical :: eq
    type(color_t), intent(in) :: col1, col2
    if (color_is_defined (col1) .and. color_is_defined (col2)) then
!       if (size (col1%c1) == size (col2%c1)) then
!           eq = all (col1%c1 == col2%c1) .and. all (col1%c2 == col2%c2)
!       else
!           eq = .false.
!       end if
    else
        eq = .true.
    end if
end function color_match

elemental function color_eq (col1, col2) result (eq)
    logical :: eq
    type(color_t), intent(in) :: col1, col2
    if (color_is_defined (col1) .and. color_is_defined (col2)) then
!       if (size (col1%c1) == size (col2%c1)) then
!           eq = all (col1%c1 == col2%c1) .and. all (col1%c2 == col2%c2) &
!               .and. (col1%ghost .eqv. col2%ghost)
!       else
!           eq = .false.
!       end if
    else if (.not. color_is_defined (col1) &

```

```

        .and. .not. color_is_defined (col2)) then
            eq = col1%ghost .eqv. col2%ghost
        else
            eq = .false.
        end if
    end function color_eq

```

<Colors: procedures>+≡

```

    elemental function color_neq (col1, col2) result (neq)
        logical :: neq
        type(color_t), intent(in) :: col1, col2
        if (color_is_defined (col1) .and. color_is_defined (col2)) then
!           if (size (col1%c1) == size (col2%c1)) then
!               neq = any (col1%c1 /= col2%c1) .or. any (col1%c2 /= col2%c2) &
!                   .or. (col1%ghost .neqv. col2%ghost)
!           else
!               neq = .true.
!           end if
        else if (.not. color_is_defined (col1) &
            .and. .not. color_is_defined (col2)) then
            neq = col1%ghost .neqv. col2%ghost
        else
            neq = .true.
        end if
    end function color_neq

```

7.2.5 Tools

Shift color indices by a common offset.

<Colors: public>+≡

```

    public :: color_add_offset

```

<Colors: procedures>+≡

```

    elemental subroutine color_add_offset (col, offset)
        type(color_t), intent(inout) :: col
        integer, intent(in) :: offset
        where (col%c1 /= 0) col%c1 = col%c1 + sign (offset, col%c1)
        where (col%c2 /= 0) col%c2 = col%c2 + sign (offset, col%c2)
!       if (allocated (col%c1)) then
!           col%c1 = col%c1 + sign (offset, col%c1)
!           col%c2 = col%c2 + sign (offset, col%c2)
!       end if
    end subroutine color_add_offset

```

Reassign color indices for an array of colored particle in canonical order. The allocated size of the color map is such that two colors per particle can be accommodated.

<Colors: public>+≡

```

    public :: color_canonicalize

```

```

<Colors: procedures>+=
subroutine color_canonicalize (col)
  type(color_t), dimension(:), intent(inout) :: col
  integer, dimension(2*size(col)) :: map
  integer :: n_col, i, j, k
  n_col = 0
  do i = 1, size (col)
    do j = 1, size (col(i)%c1)
      if (col(i)%c1(j) /= 0) then
        k = find (abs (col(i)%c1(j)), map(:n_col))
        if (k == 0) then
          n_col = n_col + 1
          map(n_col) = abs (col(i)%c1(j))
          k = n_col
        end if
        col(i)%c1(j) = sign (k, col(i)%c1(j))
      end if
      if (col(i)%c2(j) /= 0) then
        k = find (abs (col(i)%c2(j)), map(:n_col))
        if (k == 0) then
          n_col = n_col + 1
          map(n_col) = abs (col(i)%c2(j))
          k = n_col
        end if
        col(i)%c2(j) = sign (k, col(i)%c2(j))
      end if
    end do
  end do
contains
  function find (c, array) result (k)
    integer :: k
    integer, intent(in) :: c
    integer, dimension(:), intent(in) :: array
    integer :: i
    k = 0
    do i = 1, size (array)
      if (c == array (i)) then
        k = i
        return
      end if
    end do
  end function find
end subroutine color_canonicalize

```

Return an array of different color indices from an array of colors. The last argument is a pseudo-color array, where the color entries correspond to the position of the corresponding index entry in the index array. The colors are assumed to be diagonal.

```

<Colors: procedures>+=
subroutine extract_color_line_indices (col, c_index, col_pos)
  type(color_t), dimension(:), intent(in) :: col
  integer, dimension(:), intent(out), allocatable :: c_index
  type(color_t), dimension(size(col)), intent(out) :: col_pos

```

```

integer, dimension(:), allocatable :: c_tmp
integer :: i, j, k, n, c
allocate (c_tmp (sum (color_number (col))))
n = 0
SCAN1: do i = 1, size (col)
  SCAN2: do j = 1, 2
    c = abs (col(i)%c1(j))
    if (c /= 0) then
      do k = 1, n
        if (c_tmp(k) == c) then
          col_pos(i)%c1(j) = k
          cycle SCAN2
        end if
      end do
      n = n + 1
      c_tmp(n) = c
      col_pos(i)%c1(j) = n
    end if
  end do SCAN2
end do SCAN1
allocate (c_index (n))
c_index = c_tmp(1:n)
end subroutine extract_color_line_indices

```

Given a color array, pairwise contract the color lines in all possible ways and return the resulting array of arrays. The input color array must be diagonal, and each color should occur exactly twice, once as color and once as anticolor.

Gluon entries with equal color and anticolor are explicitly excluded.

This algorithm is generic, but for long arrays it is neither efficient, nor does it avoid duplicates. It is intended for small arrays, in particular for the state matrix of a structure-function pair.

<Colors: public>+≡

```
public :: color_array_make_contractions
```

<Colors: procedures>+≡

```

subroutine color_array_make_contractions (col_in, col_out)
  type(color_t), dimension(:), intent(in) :: col_in
  type(color_t), dimension(:,:), intent(out), allocatable :: col_out
  type :: entry_t
    integer, dimension(:), allocatable :: map
    type(color_t), dimension(:), allocatable :: col
    type(entry_t), pointer :: next => null ()
  end type entry_t
  type :: list_t
    integer :: n = 0
    type(entry_t), pointer :: first => null ()
    type(entry_t), pointer :: last => null ()
  end type list_t
  type(list_t) :: list
  type(entry_t), pointer :: entry
  integer, dimension(:), allocatable :: c_index
  type(color_t), dimension(size(col_in)) :: col_pos
  integer :: n_prt, n_c_index
  integer, dimension(:), allocatable :: map

```

```

integer :: i, j, c
n_prt = size (col_in)
call extract_color_line_indices (col_in, c_index, col_pos)
! print *, c_index
n_c_index = size (c_index)
allocate (map (n_c_index))
map = 0
call list_append_if_valid (list, map)
entry => list%first
do while (associated (entry))
  do i = 1, n_c_index
    if (entry%map(i) == 0) then
      c = c_index(i)
      do j = i + 1, n_c_index
        if (entry%map(j) == 0) then
          map = entry%map
          map(i) = c
          map(j) = c
          call list_append_if_valid (list, map)
        end if
      end do
    end if
  end do
  entry => entry%next
end do
call list_to_array (list, col_out)
contains
subroutine list_append_if_valid (list, map)
  type(list_t), intent(inout) :: list
  integer, dimension(:), intent(in) :: map
  type(entry_t), pointer :: entry
  integer :: i, j, c, p
  entry => list%first
  do while (associated (entry))
    if (all (map == entry%map)) return
    entry => entry%next
  end do
  allocate (entry)
  allocate (entry%map (n_c_index))
  entry%map = map
  allocate (entry%col (n_prt))
  do i = 1, n_prt
    do j = 1, 2
      c = col_in(i)%c1(j)
      if (c /= 0) then
        p = col_pos(i)%c1(j)
        if (map(p) /= 0) then
          entry%col(i)%c1(j) = sign (map(p), c)
        else
          entry%col(i)%c1(j) = c
        endif
        entry%col(i)%c2(j) = entry%col(i)%c1(j)
      end if
    end do
  end do
end do

```

```

        if (any (entry%col(i)%c1 /= 0) .and. &
            entry%col(i)%c1(1) == - entry%col(i)%c1(2)) return
    end do
    ! call color_write (entry%col); print *, map
    if (associated (list%last)) then
        list%last%next => entry
    else
        list%first => entry
    end if
    list%last => entry
    list%n = list%n + 1
end subroutine list_append_if_valid
subroutine list_to_array (list, col)
    type(list_t), intent(inout) :: list
    type(color_t), dimension(:,:), intent(out), allocatable :: col
    type(entry_t), pointer :: entry
    integer :: i
    allocate (col (n_prt, list%n - 1))
    do i = 0, list%n - 1
        entry => list%first
        list%first => list%first%next
        if (i /= 0) col(:,i) = entry%col
        deallocate (entry)
    end do
    list%last => null ()
end subroutine list_to_array
end subroutine color_array_make_contractions

```

Invert the color index, switching from particle to antiparticle.

```

<Colors: public>+≡
    public :: color_invert

<Colors: procedures>+≡
    elemental subroutine color_invert (col)
        type(color_t), intent(inout) :: col
        col%c1 = - col%c1
        col%c2 = - col%c2
    end subroutine color_invert

```

Make a color map for two matching color arrays. The result is an array of integer pairs.

```

<Colors: public>+≡
    public :: set_color_map

<Colors: procedures>+≡
    subroutine set_color_map (map, col1, col2)
        integer, dimension(:,:), intent(out), allocatable :: map
        type(color_t), dimension(:), intent(in) :: col1, col2
        integer, dimension(:,:), allocatable :: map1
        integer :: i, j, k
        allocate (map1 (2, 2 * sum (color_number (col1))))
        k = 0
        do i = 1, size (col1)
            do j = 1, size (col1(i)%c1)

```

```

        if (col1(i)%c1(j) /= 0 &
            .and. all (map1(1,:k) /= abs (col1(i)%c1(j)))) then
            k = k + 1
            map1(1,k) = abs (col1(i)%c1(j))
            map1(2,k) = abs (col2(i)%c1(j))
        end if
        if (col1(i)%c2(j) /= 0 &
            .and. all (map1(1,:k) /= abs (col1(i)%c2(j)))) then
            k = k + 1
            map1(1,k) = abs (col1(i)%c2(j))
            map1(2,k) = abs (col2(i)%c2(j))
        end if
    end do
end do
allocate (map (2, k))
map(:, :) = map1(:, :k)
end subroutine set_color_map

```

Translate colors which have a match in the translation table (an array of integer pairs). Color that do not match an entry are simply transferred; this is done by first transferring all components, then modifying entries where appropriate.

```

<Colors: public>+≡
    public :: color_translate

<Colors: interfaces>+≡
    interface color_translate
        module procedure color_translate0
        module procedure color_translate0_offset
        module procedure color_translate1
    end interface

<Colors: procedures>+≡
    subroutine color_translate0 (col, map)
        type(color_t), intent(inout) :: col
        integer, dimension(:, :), intent(in) :: map
        integer :: i
        do i = 1, size (map, 2)
            where (abs (col%c1) == map(1, i))
                col%c1 = sign (map(2, i), col%c1)
            end where
            where (abs (col%c2) == map(1, i))
                col%c2 = sign (map(2, i), col%c2)
            end where
        end do
    end subroutine color_translate0

    subroutine color_translate0_offset (col, map, offset)
        type(color_t), intent(inout) :: col
        integer, dimension(:, :), intent(in) :: map
        integer, intent(in) :: offset
        logical, dimension(size(col%c1)) :: mask1, mask2
        integer :: i
        mask1 = col%c1 /= 0

```

```

mask2 = col%c2 /= 0
do i = 1, size (map,2)
  where (abs (col%c1) == map(1,i))
    col%c1 = sign (map(2,i), col%c1)
    mask1 = .false.
  end where
  where (abs (col%c2) == map(1,i))
    col%c2 = sign (map(2,i), col%c2)
    mask2 = .false.
  end where
end do
where (mask1) col%c1 = sign (abs (col%c1) + offset, col%c1)
where (mask2) col%c2 = sign (abs (col%c2) + offset, col%c2)
end subroutine color_translate0_offset

subroutine color_translate1 (col, map, offset)
  type(color_t), dimension(:), intent(inout) :: col
  integer, dimension(:,,:), intent(in) :: map
  integer, intent(in), optional :: offset
  integer :: i
  if (present (offset)) then
    do i = 1, size (col)
      call color_translate0_offset (col(i), map, offset)
    end do
  else
    do i = 1, size (col)
      call color_translate0 (col(i), map)
    end do
  end if
end subroutine color_translate1

```

Merge two color objects by taking the first entry from the first and the second entry from the second argument. Makes sense only if the input colors are defined (and diagonal). If either one is undefined, transfer the defined one.

For a color ghost, color is not defined. These have to be treated separately.

```

<Colors: public>+≡
  public :: operator(.merge.)

<Colors: interfaces>+≡
  interface operator(.merge.)
    module procedure merge_colors
  end interface

<Colors: procedures>+≡
  elemental function merge_colors (col1, col2) result (col)
    type(color_t) :: col
    type(color_t), intent(in) :: col1, col2
    if (color_is_defined (col1) .and. color_is_defined (col2)) then
      call color_init_arrays (col, col1%c1, col2%c1)
    else if (color_is_defined (col1)) then
      col = col1
    else if (color_is_defined (col2)) then
      col = col2
    else if (color_is_ghost (col1)) then

```

```

        col = col1
    else if (color_is_ghost (col2)) then
        col = col2
    end if
end function merge_colors

```

7.2.6 Compute color flow coefficients

We have a pair of color index arrays which corresponds to a squared matrix element. We want to determine the number of color loops in this square matrix element. So we first copy the colors (stored in a single color array with a pair of color lists in each entry) to a temporary where the color indices are shifted by some offset. We then recursively follow each loop, starting at the first color that has the offset, resetting the first color index to the loop index and each further index to zero as we go. We check that (a) each color index occurs twice within the left (right) color array, (b) the loops are closed, so we always come back to a line which has the loop index.

In order for the algorithm to work we have to conjugate the colors of initial state particles (one for decays, two for scatterings) into their corresponding anticolors of outgoing particles.

```

<Colors: public>+≡
    public :: count_color_loops

<Colors: procedures>+≡
    function count_color_loops (col) result (count)
        integer :: count
        type(color_t), dimension(:), intent(in) :: col
        type(color_t), dimension(size(col)) :: cc
        integer :: i, n, offset
    !     print *, "Count color loops:"
    !     call color_write (col); print *
        cc = col
        n = size (cc)
        offset = n
        call color_add_offset (cc, offset)
    !     print *, offset
    !     call color_write (cc); print *
        count = 0
        SCAN_LOOPS: do
            do i = 1, n
    !                 print *, i, ':', cc(i)%c1
                if (color_is_defined (cc(i))) then
                    if (any (cc(i)%c1 > offset)) then
    !                         print *, 'start', i
                            count = count + 1
                            call follow_line1 (pick_new_line (cc(i)%c1, count, 1))
                            cycle SCAN_LOOPS
                        end if
                    end if
                end do
            exit SCAN_LOOPS
        end do SCAN_LOOPS
    end function count_color_loops

```

```

contains
function pick_new_line (c, reset_val, sgn) result (line)
  integer :: line
  integer, dimension(:), intent(inout) :: c
  integer, intent(in) :: reset_val
  integer, intent(in) :: sgn
  integer :: i
  if (any (c == count)) then
    line = count
  else
    do i = 1, size (c)
      if (sign (1, c(i)) == sgn .and. abs (c(i)) > offset) then
        line = c(i)
        c(i) = reset_val
        return
      end if
    end do
    call color_mismatch
  end if
end function pick_new_line
subroutine reset_line (c, line)
  integer, dimension(:), intent(inout) :: c
  integer, intent(in) :: line
  integer :: i
  do i = 1, size (c)
    if (c(i) == line) then
      c(i) = 0
      return
    end if
  end do
end subroutine reset_line
recursive subroutine follow_line1 (line)
  integer, intent(in) :: line
  integer :: i
!   print *, 'follow line 1:', line
  if (line == count) then
!     print *, 'loop closed'
    return
  end if
  do i = 1, n
    if (any (cc(i)%c1 == -line)) then
      call reset_line (cc(i)%c1, -line)
!       print *, 'found', -line, ' resetting c1:'
!       call color_write (cc); print *
      call follow_line2 (pick_new_line (cc(i)%c2, 0, sign (1, -line)))
      return
    end if
  end do
  call color_mismatch ()
end subroutine follow_line1
recursive subroutine follow_line2 (line)
  integer, intent(in) :: line
  integer :: i
!   print *, 'follow line 2:', line

```

```

do i = 1, n
  if (any (cc(i)%c2 == -line)) then
    call reset_line (cc(i)%c2, -line)
    print *, 'found', -line, ' resetting c2:'
    call color_write (cc); print *
    call follow_line1 (pick_new_line (cc(i)%c1, 0, sign (1, -line)))
    return
  end if
end do
call color_mismatch ()
end subroutine follow_line2
subroutine color_mismatch ()
  call color_write (col)
  print *
  call msg_bug (" Color flow mismatch (color loops should be closed)")
end subroutine color_mismatch
end function count_color_loops

```

7.2.7 Color counting test

<Colors: public>+≡

public :: color_test

<Colors: procedures>+≡

```

subroutine color_test ()
  type(color_t), dimension(4) :: col1, col2, col
  type(color_t), dimension(:), allocatable :: col3
  type(color_t), dimension(:,:), allocatable :: col_array
  integer :: count, i
  call color_init_col_acl (col1, (/ 1, 0, 2, 3 /), (/ 0, 1, 3, 2 /))
  col2 = col1
  call color_write (col1); print *
  call color_write (col2); print *
  col = col1 .merge. col2
  call color_write (col); print *
  count = count_color_loops (col)
  print *, "Number of color loops (3): ", count
  call color_init_col_acl (col2, (/ 1, 0, 2, 3 /), (/ 0, 2, 3, 1 /))
  call color_write (col1); print *
  call color_write (col2); print *
  col = col1 .merge. col2
  call color_write (col); print *
  count = count_color_loops (col)
  print *, "Number of color loops (2): ", count
  print *
  allocate (col3 (4))
  call color_init_from_array (col3, &
    reshape ((/ 1, 0, 0, -1, 2, -3, 3, -2 /), &
      (/ 2, 4 /)))
  call color_write (col3); print *
  call color_array_make_contractions (col3, col_array)
  print *, "Contractions:"
  do i = 1, size (col_array, 2)

```

```

      call color_write (col_array(:,i)); print *
end do
deallocate (col3)
print *
allocate (col3 (6))
call color_init_from_array (col3, &
      reshape ((/ 1, -2, 3, 0, 0, -1, 2, -4, -3, 0, 4, 0 /), &
      (/ 2, 6 /)))
call color_write (col3); print *
call color_array_make_contractions (col3, col_array)
print *, "Contractions:"
do i = 1, size (col_array, 2)
      call color_write (col_array(:,i)); print *
end do
end subroutine color_test

```

7.2.8 The Madgraph color model

This section describes the method for matrix element and color flow calculation within Madgraph.

For each Feynman diagram, the colorless amplitude for a specified helicity and momentum configuration (in- and out- combined) is computed:

$$A_d(p, h) \quad (7.1)$$

Inserting color, the squared matrix element for definite helicity and momentum is

$$M^2(p, h) = \sum_{dd'} A_d(p, h) C_{dd'} A_{d'}^*(p, h) \quad (7.2)$$

where $C_{dd'}$ describes the color interference of the two diagrams A_d and $A_{d'}$, which is independent of momentum and helicity and can be calculated for each Feynman diagram pair by reducing it to the corresponding color graph. Obviously, one could combine all diagrams with identical color structure, such that the index d runs only over different color graphs. For colorless diagrams all elements of $C_{dd'}$ are equal to unity.

The hermitian matrix $C_{dd'}$ is diagonalized once and for all, such that it can be written in the form

$$C_{dd'} = \sum_{\lambda} c_d^{\lambda} \lambda c_{d'}^{\lambda*}, \quad (7.3)$$

where the eigenvectors c_d are normalized,

$$\sum_d |c_d^{\lambda}|^2 = 1, \quad (7.4)$$

and the λ values are the corresponding eigenvalues. In the colorless case, this means $c_d = 1/\sqrt{N_d}$ for all diagrams (N_d = number of diagrams), and $\lambda = N_d$ is the only nonzero eigenvalue.

Consequently, the squared matrix element for definite helicity and momentum can also be written as

$$M^2(p, h) = \sum_{\lambda} A_{\lambda}(p, h) \lambda A_{\lambda}^*(p, h) \quad (7.5)$$

with

$$A_\lambda(p, h) = \sum_d c_d^\lambda A_d(p, h). \quad (7.6)$$

For generic spin density matrices, this is easily generalized to

$$M^2(p, h, h') = \sum_\lambda A_\lambda(p, h) \lambda A_\lambda(p, h')^* \quad (7.7)$$

To determine the color flow probabilities of a given momentum-helicity configuration, the color flow amplitudes are calculated as

$$a_f(p, h) = \sum_d \beta_d^f A_d(p, h), \quad (7.8)$$

where the coefficients β_d^f describe the amplitude for a given Feynman diagram (or color graph) d to correspond to a definite color flow f . They are computed from $C_{dd'}$ by transforming this matrix into the color flow basis and neglecting all off-diagonal elements. Again, these coefficients do not depend on momentum or helicity and can therefore be calculated in advance. This gives the color flow transition matrix

$$F^f(p, h, h') = a_f(p, h) a_f^*(p, h') \quad (7.9)$$

which is assumed diagonal in color flow space and is separate from the color-summed transition matrix M^2 . They are, however, equivalent (up to a factor) to leading order in $1/N_c$, and using the color flow transition matrix is appropriate for matching to hadronization.

Note that the color flow transition matrix is not normalized at this stage. To make use of it, we have to fold it with the in-state density matrix to get a pseudo density matrix

$$\hat{\rho}_{\text{out}}^f(p, h_{\text{out}}, h'_{\text{out}}) = \sum_{h_{\text{in}} h'_{\text{in}}} F^f(p, h, h') \rho_{\text{in}}(p, h_{\text{in}}, h'_{\text{in}}) \quad (7.10)$$

which gets a meaning only after contracted with projections on the outgoing helicity states k_{out} , given as linear combinations of helicity states with the unitary coefficient matrix $c(k_{\text{out}}, h_{\text{out}})$. Then the probability of finding color flow f when the helicity state k_{out} is measured is given by

$$P^f(p, k_{\text{out}}) = Q^f(p, k_{\text{out}}) / \sum_f Q^f(p, k_{\text{out}}) \quad (7.11)$$

where

$$Q^f(p, k_{\text{out}}) = \sum_{h_{\text{out}} h'_{\text{out}}} c(k_{\text{out}}, h_{\text{out}}) \hat{\rho}_{\text{out}}^f(p, h_{\text{out}}, h'_{\text{out}}) c^*(k_{\text{out}}, h'_{\text{out}}) \quad (7.12)$$

However, if we can assume that the out-state helicity basis is the canonical one, we can throw away the off diagonal elements in the color flow density matrix and normalize the ones on the diagonal to obtain

$$P^f(p, h_{\text{out}}) = \hat{\rho}_{\text{out}}^f(p, h_{\text{out}}, h_{\text{out}}) / \sum_f \hat{\rho}_{\text{out}}^f(p, h_{\text{out}}, h_{\text{out}}) \quad (7.13)$$

Finally, the color-summed out-state density matrix is computed by the scattering formula

$$\rho_{\text{out}}(p, h_{\text{out}}, h'_{\text{out}}) = \sum_{h_{\text{in}} h'_{\text{in}}} M^2(p, h, h') \rho_{\text{in}}(p, h_{\text{in}}, h'_{\text{in}}) \quad (7.14)$$

$$= \sum_{h_{\text{in}} h'_{\text{in}} \lambda} A_{\lambda}(p, h) \lambda A_{\lambda}(p, h')^* \rho_{\text{in}}(p, h_{\text{in}}, h'_{\text{in}}), \quad (7.15)$$

The trace of ρ_{out} is the squared matrix element, summed over all internal degrees of freedom. To get the squared matrix element for a definite helicity k_{out} and color flow f , one has to project the density matrix onto the given helicity state and multiply with $P^f(p, k_{\text{out}})$.

For diagonal helicities the out-state density reduces to

$$\rho_{\text{out}}(p, h_{\text{out}}) = \sum_{h_{\text{in}} \lambda} \lambda |A_{\lambda}(p, h)|^2 \rho_{\text{in}}(p, h_{\text{in}}). \quad (7.16)$$

Since no basis transformation is involved, we can use the normalized color flow probability $P^f(p, h_{\text{out}})$ and express the result as

$$\rho_{\text{out}}^f(p, h_{\text{out}}) = \rho_{\text{out}}(p, h_{\text{out}}) P^f(p, h_{\text{out}}) \quad (7.17)$$

$$= \sum_{h_{\text{in}} \lambda} \frac{|a^f(p, h)|^2}{\sum_f |a^f(p, h)|^2} \lambda |A_{\lambda}(p, h)|^2 \rho_{\text{in}}(p, h_{\text{in}}). \quad (7.18)$$

From these considerations, the following calculation strategy can be derived:

- Before the first event is generated, the color interference matrix $C_{dd'}$ is computed and diagonalized, so the eigenvectors c_d^{λ} , eigenvalues λ and color flow coefficients β_d^f are obtained. In practice, these calculations are done when the matrix element code is generated, and the results are hardcoded in the matrix element subroutine as **DATA** statements.
- For each event, one loops over helicities once and stores the matrices $A_{\lambda}(p, h)$ and $a^f(p, h)$. The allowed color flows, helicity combinations and eigenvalues are each labeled by integer indices, so one has to store complex matrices of dimension $N_{\lambda} \times N_h$ and $N_f \times N_h$, respectively.
- The further strategy depends on the requested information.
 1. If colorless diagonal helicity amplitudes are required, the eigenvalues $A_{\lambda}(p, h)$ are squared, summed with weight λ , and the result contracted with the in-state probability vector $\rho_{\text{in}}(p, h_{\text{in}})$. The result is a probability vector $\rho_{\text{out}}(p, h_{\text{out}})$.
 2. For colored diagonal helicity amplitudes, the color coefficients $a^f(p, h)$ are also squared and used as weights to obtain the color-flow probability vector $\rho_{\text{out}}^f(p, h_{\text{out}})$.
 3. For colorless non-diagonal helicity amplitudes, we contract the tensor product of $A_{\lambda}(p, h)$ with $A_{\lambda}(p, h')$, weighted with λ , with the correlated in-state density matrix, to obtain a correlated out-state density matrix.

4. In the general (colored, non-diagonal) case, we do the same as in the colorless case, but return the un-normalized color flow density matrix $\hat{\rho}_{\text{out}}^f(p, h_{\text{out}}, h'_{\text{out}})$ in addition. When the relevant helicity basis is known, the latter can be used by the caller program to determine flow probabilities. (In reality, we assume the canonical basis and reduce the correlated out-state density to its diagonal immediately.)

7.3 Flavors: Particle properties

This module contains a type for holding the flavor code, and all functions that depend on the model, i.e., that determine particle properties.

The PDG code is packed in a special **flavor** type. (This prohibits meaningless operations, and it allows for a different implementation, e.g., some non-PDG scheme internally, if appropriate at some point.) In addition, the flavor object holds a pointer to a **particle_data** object which is centrally stored (as part of a physics model). In this way, all particle data can be accessed using just the **flv** object without having to carry them around.

The pointer component imposes a technical restriction: Assignment of flavor objects cannot be used, directly or indirectly, in pure, and thus in elemental procedures.

```
<flavors.f90>≡  
  <File header>  
  
  module flavors  
  
    <Use kinds>  
    <Use strings>  
    <Use file utils>  
    use pdg_arrays  
    use colors, only: color_t, color_init  
    use models  
  
    <Standard module head>  
  
    <Flavors: public>  
  
    <Flavors: types>  
  
    <Flavors: interfaces>  
  
    contains  
  
    <Flavors: procedures>  
  
  end module flavors
```

7.3.1 The flavor type

The flavor type is an integer representing the PDG code, or undefined (zero). Negative codes represent antiparticles.

For full generality, and analogy with helicity and color, we allow for non-diagonal flavor indices in density matrices. This is probably academic; an obscure application is the definition of proper isospin states.

Further properties of the given flavor can be retrieved via the particle-data pointer, if it is associated.

```
<Flavors: public>≡  
  public :: flavor_t
```

```

<Flavors: types>≡
  type :: flavor_t
  private
    integer :: f = UNDEFINED
    type(particle_data_t), pointer :: prt => null ()
  end type flavor_t

```

Initializer form. If the model is assigned, the procedure is impure, therefore we have to define a separate array version.

```

<Flavors: public>+≡
  public :: flavor_init

<Flavors: interfaces>≡
  interface flavor_init
    module procedure flavor_init0_empty
    module procedure flavor_init0
    module procedure flavor_init0_particle_data
    module procedure flavor_init0_model
    module procedure flavor_init0_name_model
    module procedure flavor_init1_model
    module procedure flavor_init1_name_model
    module procedure flavor_init2_model
    module procedure flavor_init_aval_model
  end interface

<Flavors: procedures>≡
  elemental subroutine flavor_init0_empty (flv)
    type(flavor_t), intent(out) :: flv
  end subroutine flavor_init0_empty

  elemental subroutine flavor_init0 (flv, f)
    type(flavor_t), intent(out) :: flv
    integer, intent(in) :: f
    flv%f = f
  end subroutine flavor_init0

  subroutine flavor_init0_particle_data (flv, particle_data)
    type(flavor_t), intent(out) :: flv
    type(particle_data_t), intent(in), target :: particle_data
    flv%f = particle_data_get_pdg (particle_data)
    flv%prt => particle_data
  end subroutine flavor_init0_particle_data

  subroutine flavor_init0_model (flv, f, model)
    type(flavor_t), intent(out) :: flv
    integer, intent(in) :: f
    type(model_t), intent(in), target :: model
    flv%f = f
    flv%prt => model_get_particle_ptr (model, f)
  end subroutine flavor_init0_model

  subroutine flavor_init1_model (flv, f, model)
    type(flavor_t), dimension(:), intent(out) :: flv
    integer, dimension(:), intent(in) :: f
    type(model_t), intent(in), target :: model

```

```

integer :: i
do i = 1, size (f)
    call flavor_init0_model (flv(i), f(i), model)
end do
end subroutine flavor_init1_model

subroutine flavor_init2_model (flv, f, model)
    type(flavor_t), dimension(:,:), intent(out) :: flv
    integer, dimension(:,:), intent(in) :: f
    type(model_t), intent(in), target :: model
    integer :: i
    do i = 1, size (f, 2)
        call flavor_init1_model (flv(:,i), f(:,i), model)
    end do
end subroutine flavor_init2_model

subroutine flavor_init0_name_model (flv, name, model)
    type(flavor_t), intent(out) :: flv
    type(string_t), intent(in) :: name
    type(model_t), intent(in), target :: model
    flv%f = model_get_particle_pdg (model, name)
    flv%prt => model_get_particle_ptr (model, flv%f)
end subroutine flavor_init0_name_model

subroutine flavor_init1_name_model (flv, name, model)
    type(flavor_t), dimension(:), intent(out) :: flv
    type(string_t), dimension(:), intent(in) :: name
    type(model_t), intent(in), target :: model
    integer :: i
    do i = 1, size (name)
        call flavor_init0_name_model (flv(i), name(i), model)
    end do
end subroutine flavor_init1_name_model

```

This version transforms a PDG array value into a flavor array. The flavor array must be allocatable.

```

<Flavors: procedures>+≡
subroutine flavor_init_aval_model (flv, aval, model)
    type(flavor_t), dimension(:), intent(out), allocatable :: flv
    type(pdg_array_t), intent(in) :: aval
    type(model_t), intent(in), target :: model
    integer, dimension(:), allocatable :: pdg
    pdg = aval
    allocate (flv (size (pdg)))
    call flavor_init (flv, pdg, model)
end subroutine flavor_init_aval_model

```

Undefine the flavor state:

```

<Flavors: public>+≡
public :: flavor_undefine

<Flavors: procedures>+≡
elemental subroutine flavor_undefine (flv)

```

```

    type(flavor_t), intent(inout) :: flv
    flv%f = UNDEFINED
end subroutine flavor_undefine

```

Output: dense, no linebreak

<Flavors: public>+≡

```

    public :: flavor_write

```

<Flavors: procedures>+≡

```

subroutine flavor_write (flv, unit)
    type(flavor_t), intent(in) :: flv
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    if (associated (flv%prt)) then
        write (u, "(A)", advance="no") "f("
    else
        write (u, "(A)", advance="no") "p("
    end if
    write (u, "(I0)", advance="no") flv%f
    write (u, "(A)", advance="no") ")"
end subroutine flavor_write

```

Binary I/O. Currently, the model information is not written/read, so after reading the particle-data pointer is empty.

<Flavors: public>+≡

```

    public :: flavor_write_raw
    public :: flavor_read_raw

```

<Flavors: procedures>+≡

```

subroutine flavor_write_raw (flv, u)
    type(flavor_t), intent(in) :: flv
    integer, intent(in) :: u
    write (u) flv%f
end subroutine flavor_write_raw

subroutine flavor_read_raw (flv, u, iostat)
    type(flavor_t), intent(out) :: flv
    integer, intent(in) :: u
    integer, intent(out), optional :: iostat
    read (u, iostat=iostat) flv%f
end subroutine flavor_read_raw

```

Assignment

Default assignment of flavor objects is possible, but cannot be used in pure procedures, because a pointer assignment is involved.

Assign the particle pointer separately. This cannot be elemental, so we define a scalar and an array version explicitly. We refer to an array of flavors, not an array of models.

<Flavors: public>+≡

```

    public :: flavor_set_model

```

```

<Flavors: interfaces>+≡
  interface flavor_set_model
    module procedure flavor_set_model_single
    module procedure flavor_set_model_array
  end interface

<Flavors: procedures>+≡
  subroutine flavor_set_model_single (flv, model)
    type(flavor_t), intent(inout) :: flv
    type(model_t), intent(in), target :: model
    if (flv%f /= UNDEFINED) &
      flv%prt => model_get_particle_ptr (model, flv%f)
  end subroutine flavor_set_model_single

  subroutine flavor_set_model_array (flv, model)
    type(flavor_t), dimension(:), intent(inout) :: flv
    type(model_t), intent(in), target :: model
    integer :: i
    do i = 1, size (flv)
      if (flv(i)%f /= UNDEFINED) &
        flv(i)%prt => model_get_particle_ptr (model, flv(i)%f)
    end do
  end subroutine flavor_set_model_array

```

Predicates

Return the definition status

```

<Flavors: public>+≡
  public :: flavor_is_defined

<Flavors: procedures>+≡
  elemental function flavor_is_defined (flv) result (defined)
    logical :: defined
    type(flavor_t), intent(in) :: flv
    defined = flv%f /= UNDEFINED
  end function flavor_is_defined

```

Check for valid flavor (including undefined):

```

<Flavors: public>+≡
  public :: flavor_is_valid

<Flavors: procedures>+≡
  elemental function flavor_is_valid (flv) result (valid)
    logical :: valid
    type(flavor_t), intent(in) :: flv
    valid = flv%f /= INVALID
  end function flavor_is_valid

```

Return true if the particle-data pointer is associated. (Debugging aid)

```

<Flavors: public>+≡
  public :: flavor_is_associated

```

```

<Flavors: procedures>+≡
  elemental function flavor_is_associated (flv) result (flag)
    logical :: flag
    type(flavor_t), intent(in) :: flv
    flag = associated (flv%prt)
  end function flavor_is_associated

```

Accessing contents

With the exception of the PDG code, all particle properties are accessible only via the `prt` pointer. If this is unassigned, some access function will crash.

Return the flavor as an integer

```

<Flavors: public>+≡
  public :: flavor_get_pdg

<Flavors: procedures>+≡
  elemental function flavor_get_pdg (flv) result (f)
    integer :: f
    type(flavor_t), intent(in) :: flv
    f = flv%f
  end function flavor_get_pdg

```

Return the flavor of the antiparticle

```

<Flavors: public>+≡
  public :: flavor_get_pdg_anti

<Flavors: procedures>+≡
  elemental function flavor_get_pdg_anti (flv) result (f)
    integer :: f
    type(flavor_t), intent(in) :: flv
    if (particle_data_has_antiparticle (flv%prt)) then
      f = -flv%f
    else
      f = flv%f
    end if
  end function flavor_get_pdg_anti

```

Absolute value:

```

<Flavors: public>+≡
  public :: flavor_get_pdg_abs

<Flavors: procedures>+≡
  elemental function flavor_get_pdg_abs (flv) result (f)
    integer :: f
    type(flavor_t), intent(in) :: flv
    f = abs (flv%f)
  end function flavor_get_pdg_abs

```

Generic properties

```

<Flavors: public>+≡
  public :: flavor_is_visible
  public :: flavor_is_parton

```

```

public :: flavor_is_gauge
public :: flavor_is_left_handed
public :: flavor_is_right_handed
public :: flavor_is_antiparticle
public :: flavor_has_antiparticle
public :: flavor_is_stable

(Flavors: procedures) +=
  elemental function flavor_is_visible (flv) result (flag)
    logical :: flag
    type(flavor_t), intent(in) :: flv
    flag = particle_data_is_visible (flv%prt)
  end function flavor_is_visible

  elemental function flavor_is_parton (flv) result (flag)
    logical :: flag
    type(flavor_t), intent(in) :: flv
    flag = particle_data_is_parton (flv%prt)
  end function flavor_is_parton

  elemental function flavor_is_gauge (flv) result (flag)
    logical :: flag
    type(flavor_t), intent(in) :: flv
    flag = particle_data_is_gauge (flv%prt)
  end function flavor_is_gauge

  elemental function flavor_is_left_handed (flv) result (flag)
    logical :: flag
    type(flavor_t), intent(in) :: flv
    if (flv%f > 0) then
      flag = particle_data_is_left_handed (flv%prt)
    else
      flag = particle_data_is_right_handed (flv%prt)
    end if
  end function flavor_is_left_handed

  elemental function flavor_is_right_handed (flv) result (flag)
    logical :: flag
    type(flavor_t), intent(in) :: flv
    if (flv%f > 0) then
      flag = particle_data_is_right_handed (flv%prt)
    else
      flag = particle_data_is_left_handed (flv%prt)
    end if
  end function flavor_is_right_handed

  elemental function flavor_is_antiparticle (flv) result (flag)
    logical :: flag
    type(flavor_t), intent(in) :: flv
    flag = flv%f < 0
  end function flavor_is_antiparticle

  elemental function flavor_has_antiparticle (flv) result (flag)
    logical :: flag
    type(flavor_t), intent(in) :: flv

```

```

        flag = particle_data_has_antiparticle (flv%prt)
    end function flavor_has_antiparticle

    elemental function flavor_is_stable (flv) result (flag)
        logical :: flag
        type(flavor_t), intent(in) :: flv
        flag = particle_data_is_stable (flv%prt)
    end function flavor_is_stable

```

Names:

(Flavors: public)+≡

```

    public :: flavor_get_name
    public :: flavor_get_tex_name

```

(Flavors: procedures)+≡

```

    elemental function flavor_get_name (flv) result (name)
        type(string_t) :: name
        type(flavor_t), intent(in) :: flv
        if (associated (flv%prt)) then
            name = particle_data_get_name (flv%prt, flv%f < 0)
        else
            name = "?"
        end if
    end function flavor_get_name

    elemental function flavor_get_tex_name (flv) result (name)
        type(string_t) :: name
        type(flavor_t), intent(in) :: flv
        if (associated (flv%prt)) then
            name = particle_data_get_tex_name (flv%prt, flv%f < 0)
        else
            name = "?"
        end if
    end function flavor_get_tex_name

```

(Flavors: public)+≡

```

    public :: flavor_get_spin_type
    public :: flavor_get_multiplicity
    public :: flavor_get_isospin_type
    public :: flavor_get_charge_type
    public :: flavor_get_color_type

```

(Flavors: procedures)+≡

```

    elemental function flavor_get_spin_type (flv) result (type)
        integer :: type
        type(flavor_t), intent(in) :: flv
        type = particle_data_get_spin_type (flv%prt)
    end function flavor_get_spin_type

    elemental function flavor_get_multiplicity (flv) result (type)
        integer :: type
        type(flavor_t), intent(in) :: flv
        type = particle_data_get_multiplicity (flv%prt)
    end function flavor_get_multiplicity

```

```

elemental function flavor_get_isospin_type (flv) result (type)
  integer :: type
  type(flavor_t), intent(in) :: flv
  type = particle_data_get_isospin_type (flv%prt)
end function flavor_get_isospin_type

elemental function flavor_get_charge_type (flv) result (type)
  integer :: type
  type(flavor_t), intent(in) :: flv
  if (flavor_is_antiparticle (flv)) then
    type = - particle_data_get_charge_type (flv%prt)
  else
    type = particle_data_get_charge_type (flv%prt)
  end if
end function flavor_get_charge_type

elemental function flavor_get_color_type (flv) result (type)
  integer :: type
  type(flavor_t), intent(in) :: flv
  if (flavor_is_antiparticle (flv)) then
    type = - particle_data_get_color_type (flv%prt)
  else
    type = particle_data_get_color_type (flv%prt)
  end if
end function flavor_get_color_type

```

These functions return real values:

(Flavors: public)+≡

```

public :: flavor_get_charge
public :: flavor_get_mass
public :: flavor_get_width

```

(Flavors: procedures)+≡

```

elemental function flavor_get_charge (flv) result (charge)
  real(default) :: charge
  type(flavor_t), intent(in) :: flv
  if (associated (flv%prt)) then
    if (flavor_is_antiparticle (flv)) then
      charge = particle_data_get_charge (flv%prt)
    else
      charge = - particle_data_get_charge (flv%prt)
    end if
  else
    charge = 0
  end if
end function flavor_get_charge

elemental function flavor_get_mass (flv) result (mass)
  real(default) :: mass
  type(flavor_t), intent(in) :: flv
  if (associated (flv%prt)) then
    mass = particle_data_get_mass (flv%prt)
  else

```

```

        mass = 0
    end if
end function flavor_get_mass

elemental function flavor_get_width (flv) result (width)
    real(default) :: width
    type(flavor_t), intent(in) :: flv
    if (associated (flv%prt)) then
        width = particle_data_get_width (flv%prt)
    else
        width = 0
    end if
end function flavor_get_width

```

Comparisons

If one of the flavors is undefined, the other defined, they match.

```

<Flavors: public>+≡
    public :: operator(.match.)
    public :: operator(==)
    public :: operator(/=)

<Flavors: interfaces>+≡
    interface operator(.match.)
        module procedure flavor_match
    end interface
    interface operator(==)
        module procedure flavor_eq
    end interface
    interface operator(/=)
        module procedure flavor_neq
    end interface

<Flavors: procedures>+≡
    elemental function flavor_match (flv1, flv2) result (eq)
        logical :: eq
        type(flavor_t), intent(in) :: flv1, flv2
        if (flv1%f /= UNDEFINED .and. flv2%f /= UNDEFINED) then
            eq = flv1%f == flv2%f
        else
            eq = .true.
        end if
    end function flavor_match

    elemental function flavor_eq (flv1, flv2) result (eq)
        logical :: eq
        type(flavor_t), intent(in) :: flv1, flv2
        if (flv1%f /= UNDEFINED .and. flv2%f /= UNDEFINED) then
            eq = flv1%f == flv2%f
        else if (flv1%f == UNDEFINED .and. flv2%f == UNDEFINED) then
            eq = .true.
        else
            eq = .false.
        end if
    end function flavor_eq

```

```
end function flavor_eq
```

```
<Flavors: procedures>+≡
  elemental function flavor_neq (flv1, flv2) result (neq)
    logical :: neq
    type(flavor_t), intent(in) :: flv1, flv2
    if (flv1%f /= UNDEFINED .and. flv2%f /= UNDEFINED) then
      neq = flv1%f /= flv2%f
    else if (flv1%f == UNDEFINED .and. flv2%f == UNDEFINED) then
      neq = .false.
    else
      neq = .true.
    end if
  end function flavor_neq
```

Tools

Merge two flavor indices. This works only if both are equal or either one is undefined, because we have no off-diagonal flavor entries. Otherwise, generate an invalid flavor.

We cannot use elemental procedures because of the pointer component.

```
<Flavors: public>+≡
  public :: operator(.merge.)

<Flavors: interfaces>+≡
  interface operator(.merge.)
    module procedure merge_flavors0
    module procedure merge_flavors1
  end interface

<Flavors: procedures>+≡
  function merge_flavors0 (flv1, flv2) result (flv)
    type(flavor_t) :: flv
    type(flavor_t), intent(in) :: flv1, flv2
    if (flavor_is_defined (flv1) .and. flavor_is_defined (flv2)) then
      if (flv1 == flv2) then
        flv = flv1
      else
        flv%f = INVALID
      end if
    else if (flavor_is_defined (flv1)) then
      flv = flv1
    else if (flavor_is_defined (flv2)) then
      flv = flv2
    end if
  end function merge_flavors0

  function merge_flavors1 (flv1, flv2) result (flv)
    type(flavor_t), dimension(:), intent(in) :: flv1, flv2
    type(flavor_t), dimension(size(flv1)) :: flv
    integer :: i
    do i = 1, size (flv1)
```

```

        flv(i) = flv1(i) .merge. flv2(i)
    end do
end function merge_flavors1

```

Generate consecutive color indices for a given flavor. The indices are counted starting with the stored value of `c`, so new indices are created each time this (impure) function is called. The counter can be reset by the optional argument `c_seed` if desired. The optional flag `reverse` is used only for octets. If set, the color and anticolor entries of the octet particle are exchanged.

```

<Flavors: public>+≡
    public :: color_from_flavor

<Flavors: interfaces>+≡
    interface color_from_flavor
        module procedure color_from_flavor0
        module procedure color_from_flavor1
    end interface

<Flavors: procedures>+≡
    function color_from_flavor0 (flv, c_seed, reverse) result (col)
        type(color_t) :: col
        type(flavor_t), intent(in) :: flv
        integer, intent(in), optional :: c_seed
        logical, intent(in), optional :: reverse
        integer, save :: c = 1
        logical :: rev
        if (present (c_seed)) c = c_seed
        rev = .false.; if (present (reverse)) rev = reverse
        select case (flavor_get_color_type (flv))
        case (1)
        case (3)
            call color_init (col, (/ c /)); c = c + 1
        case (-3)
            call color_init (col, (/ -c /)); c = c + 1
        case (8)
            if (rev) then
                call color_init (col, (/ c+1, -c /)); c = c + 2
            else
                call color_init (col, (/ c, -(c+1) /)); c = c + 2
            end if
        end select
    end function color_from_flavor0

    function color_from_flavor1 (flv, c_seed, reverse) result (col)
        type(flavor_t), dimension(:), intent(in) :: flv
        integer, intent(in), optional :: c_seed
        logical, intent(in), optional :: reverse
        type(color_t), dimension(size(flv)) :: col
        integer :: i
        col(1) = color_from_flavor0 (flv(1), c_seed, reverse)
        do i = 2, size (flv)
            col(i) = color_from_flavor0 (flv(i), reverse=reverse)
        end do
    end function color_from_flavor1

```

This procedure returns the flavor object for the antiparticle. The antiparticle code may either be the same code or its negative.

```

<Flavors: public>+≡
    public :: flavor_anti

<Flavors: procedures>+≡
    function flavor_anti (flv) result (aflv)
        type(flavor_t) :: aflv
        type(flavor_t), intent(in) :: flv
        if (flavor_has_antiparticle (flv)) then
            aflv%f = - flv%f
        else
            aflv%f = flv%f
        end if
        aflv%prt => flv%prt
    end function flavor_anti

```

7.4 Quantum numbers

This module collects helicity, color, and flavor in a single type and defines procedures

```
<quantum_numbers.f90>≡  
  <File header>  
  
  module quantum_numbers  
  
    <Use file utils>  
    use models  
    use flavors  
    use colors  
    use helicities  
  
    <Standard module head>  
  
    <Quantum numbers: public>  
  
    <Quantum numbers: types>  
  
    <Quantum numbers: interfaces>  
  
    contains  
  
    <Quantum numbers: procedures>  
  
  end module quantum_numbers
```

7.4.1 The quantum number type

```
<Quantum numbers: public>≡  
  public :: quantum_numbers_t  
  
<Quantum numbers: types>≡  
  type :: quantum_numbers_t  
    private  
    type(flavor_t) :: f  
    type(color_t) :: c  
    type(helicity_t) :: h  
  end type quantum_numbers_t
```

Define quantum numbers: Initializer form. All arguments may be present or absent.

```
<Quantum numbers: public>+≡  
  public :: quantum_numbers_init  
  
<Quantum numbers: interfaces>≡  
  interface quantum_numbers_init  
    module procedure quantum_numbers_init0_f  
    module procedure quantum_numbers_init0_c  
    module procedure quantum_numbers_init0_h  
    module procedure quantum_numbers_init0_fc  
    module procedure quantum_numbers_init0_fh
```

```

module procedure quantum_numbers_init0_ch
module procedure quantum_numbers_init0_fch
module procedure quantum_numbers_init1_f
module procedure quantum_numbers_init1_c
module procedure quantum_numbers_init1_h
module procedure quantum_numbers_init1_fc
module procedure quantum_numbers_init1_fh
module procedure quantum_numbers_init1_ch
module procedure quantum_numbers_init1_fch
end interface

```

(Quantum numbers: procedures)≡

```

subroutine quantum_numbers_init0_f (qn, flv)
  type(quantum_numbers_t), intent(out) :: qn
  type(flavor_t), intent(in) :: flv
  qn%f = flv
end subroutine quantum_numbers_init0_f

subroutine quantum_numbers_init0_c (qn, col)
  type(quantum_numbers_t), intent(out) :: qn
  type(color_t), intent(in) :: col
  qn%c = col
end subroutine quantum_numbers_init0_c

subroutine quantum_numbers_init0_h (qn, hel)
  type(quantum_numbers_t), intent(out) :: qn
  type(helicity_t), intent(in) :: hel
  qn%h = hel
end subroutine quantum_numbers_init0_h

subroutine quantum_numbers_init0_fc (qn, flv, col)
  type(quantum_numbers_t), intent(out) :: qn
  type(flavor_t), intent(in) :: flv
  type(color_t), intent(in) :: col
  qn%f = flv
  qn%c = col
end subroutine quantum_numbers_init0_fc

subroutine quantum_numbers_init0_fh (qn, flv, hel)
  type(quantum_numbers_t), intent(out) :: qn
  type(flavor_t), intent(in) :: flv
  type(helicity_t), intent(in) :: hel
  qn%f = flv
  qn%h = hel
end subroutine quantum_numbers_init0_fh

subroutine quantum_numbers_init0_ch (qn, col, hel)
  type(quantum_numbers_t), intent(out) :: qn
  type(color_t), intent(in) :: col
  type(helicity_t), intent(in) :: hel
  qn%c = col
  qn%h = hel
end subroutine quantum_numbers_init0_ch

```

```

subroutine quantum_numbers_init0_fch (qn, flv, col, hel)
  type(quantum_numbers_t), intent(out) :: qn
  type(flavor_t), intent(in) :: flv
  type(color_t), intent(in) :: col
  type(helicity_t), intent(in) :: hel
  qn%f = flv
  qn%c = col
  qn%h = hel
end subroutine quantum_numbers_init0_fch

subroutine quantum_numbers_init1_f (qn, flv)
  type(quantum_numbers_t), dimension(:), intent(out) :: qn
  type(flavor_t), dimension(:), intent(in) :: flv
  integer :: i
  do i = 1, size (qn)
    call quantum_numbers_init0_f (qn(i), flv(i))
  end do
end subroutine quantum_numbers_init1_f

subroutine quantum_numbers_init1_c (qn, col)
  type(quantum_numbers_t), dimension(:), intent(out) :: qn
  type(color_t), dimension(:), intent(in) :: col
  integer :: i
  do i = 1, size (qn)
    call quantum_numbers_init0_c (qn(i), col(i))
  end do
end subroutine quantum_numbers_init1_c

subroutine quantum_numbers_init1_h (qn, hel)
  type(quantum_numbers_t), dimension(:), intent(out) :: qn
  type(helicity_t), dimension(:), intent(in) :: hel
  integer :: i
  do i = 1, size (qn)
    call quantum_numbers_init0_h (qn(i), hel(i))
  end do
end subroutine quantum_numbers_init1_h

subroutine quantum_numbers_init1_fc (qn, flv, col)
  type(quantum_numbers_t), dimension(:), intent(out) :: qn
  type(flavor_t), dimension(:), intent(in) :: flv
  type(color_t), dimension(:), intent(in) :: col
  integer :: i
  do i = 1, size (qn)
    call quantum_numbers_init0_fc (qn(i), flv(i), col(i))
  end do
end subroutine quantum_numbers_init1_fc

subroutine quantum_numbers_init1_fh (qn, flv, hel)
  type(quantum_numbers_t), dimension(:), intent(out) :: qn
  type(flavor_t), dimension(:), intent(in) :: flv
  type(helicity_t), dimension(:), intent(in) :: hel
  integer :: i
  do i = 1, size (qn)
    call quantum_numbers_init0_fh (qn(i), flv(i), hel(i))
  end do
end subroutine quantum_numbers_init1_fh

```

```

        end do
    end subroutine quantum_numbers_init1_fh

    subroutine quantum_numbers_init1_ch (qn, col, hel)
        type(quantum_numbers_t), dimension(:), intent(out) :: qn
        type(color_t), dimension(:), intent(in) :: col
        type(helicity_t), dimension(:), intent(in) :: hel
        integer :: i
        do i = 1, size (qn)
            call quantum_numbers_init0_ch (qn(i), col(i), hel(i))
        end do
    end subroutine quantum_numbers_init1_ch

    subroutine quantum_numbers_init1_fch (qn, flv, col, hel)
        type(quantum_numbers_t), dimension(:), intent(out) :: qn
        type(flavor_t), dimension(:), intent(in) :: flv
        type(color_t), dimension(:), intent(in) :: col
        type(helicity_t), dimension(:), intent(in) :: hel
        integer :: i
        do i = 1, size (qn)
            call quantum_numbers_init0_fch (qn(i), flv(i), col(i), hel(i))
        end do
    end subroutine quantum_numbers_init1_fch

```

7.4.2 I/O

Write the quantum numbers in condensed form, enclosed by square brackets. For convenience, introduce also an array version.

```

<Quantum numbers: public>+≡
    public :: quantum_numbers_write

<Quantum numbers: interfaces>+≡
    interface quantum_numbers_write
        module procedure quantum_numbers_write_single
        module procedure quantum_numbers_write_array
    end interface

<Quantum numbers: procedures>+≡
    subroutine quantum_numbers_write_single (qn, unit)
        type(quantum_numbers_t), intent(in) :: qn
        integer, intent(in), optional :: unit
        integer :: u
        u = output_unit (unit); if (u < 0) return
        write (u, "(A)", advance="no") "["
        if (flavor_is_defined (qn%f)) then
            call flavor_write (qn%f, u)
            if (color_is_defined (qn%c) .or. helicity_is_defined (qn%h)) &
                write (u, "(1x)", advance="no")
        end if
        if (color_is_defined (qn%c) .or. color_is_ghost (qn%c)) then
            call color_write (qn%c, u)
            if (helicity_is_defined (qn%h)) write (u, "(1x)", advance="no")
        end if
    end subroutine

```

```

        if (helicity_is_defined (qn%h)) then
            call helicity_write (qn%h, u)
        end if
        write (u, "(A)", advance="no") "]"
    end subroutine quantum_numbers_write_single

    subroutine quantum_numbers_write_array (qn, unit)
        type(quantum_numbers_t), dimension(:), intent(in) :: qn
        integer, intent(in), optional :: unit
        integer :: i
        integer :: u
        u = output_unit (unit); if (u < 0) return
        write (u, "(A)", advance="no") "["
        do i = 1, size (qn)
            if (i > 1) write (u, "(A)", advance="no") " / "
            if (flavor_is_defined (qn(i)%f)) then
                call flavor_write (qn(i)%f, u)
                if (color_is_defined (qn(i)%c) .or. helicity_is_defined (qn(i)%h)) &
                    write (u, "(1x)", advance="no")
            end if
            if (color_is_defined (qn(i)%c) .or. color_is_ghost (qn(i)%c)) then
                call color_write (qn(i)%c, u)
                if (helicity_is_defined (qn(i)%h)) write (u, "(1x)", advance="no")
            end if
            if (helicity_is_defined (qn(i)%h)) then
                call helicity_write (qn(i)%h, u)
            end if
        end do
        write (u, "(A)", advance="no") "]"
    end subroutine quantum_numbers_write_array

```

Binary I/O.

```

<Quantum numbers: public>+≡
    public :: quantum_numbers_write_raw
    public :: quantum_numbers_read_raw

<Quantum numbers: procedures>+≡
    subroutine quantum_numbers_write_raw (qn, u)
        type(quantum_numbers_t), intent(in) :: qn
        integer, intent(in) :: u
        call flavor_write_raw (qn%f, u)
        call color_write_raw (qn%c, u)
        call helicity_write_raw (qn%h, u)
    end subroutine quantum_numbers_write_raw

    subroutine quantum_numbers_read_raw (qn, u, iostat)
        type(quantum_numbers_t), intent(out) :: qn
        integer, intent(in) :: u
        integer, intent(out), optional :: iostat
        call flavor_read_raw (qn%f, u, iostat=iostat)
        call color_read_raw (qn%c, u, iostat=iostat)
        call helicity_read_raw (qn%h, u, iostat=iostat)
    end subroutine quantum_numbers_read_raw

```

7.4.3 Accessing contents

Color and helicity can be done by elemental functions. Flavor needs explicit specifics because of the pointer assignment.

```
<Quantum numbers: public>+≡
  public :: quantum_numbers_get_flavor
  public :: quantum_numbers_get_color
  public :: quantum_numbers_get_helicity

<Quantum numbers: interfaces>+≡
  interface quantum_numbers_get_flavor
    module procedure quantum_numbers_get_flavor0
    module procedure quantum_numbers_get_flavor1
  end interface

<Quantum numbers: procedures>+≡
  function quantum_numbers_get_flavor0 (qn) result (flv)
    type(flavor_t) :: flv
    type(quantum_numbers_t), intent(in) :: qn
    flv = qn%f
  end function quantum_numbers_get_flavor0

  function quantum_numbers_get_flavor1 (qn) result (flv)
    type(quantum_numbers_t), dimension(:), intent(in) :: qn
    type(flavor_t), dimension(size(qn)) :: flv
    integer :: i
    do i = 1, size (qn)
      flv(i) = qn(i)%f
    end do
  end function quantum_numbers_get_flavor1

  elemental function quantum_numbers_get_color (qn) result (col)
    type(color_t) :: col
    type(quantum_numbers_t), intent(in) :: qn
    col = qn%c
  end function quantum_numbers_get_color

  elemental function quantum_numbers_get_helicity (qn) result (hel)
    type(helicity_t) :: hel
    type(quantum_numbers_t), intent(in) :: qn
    hel = qn%h
  end function quantum_numbers_get_helicity

<Quantum numbers: public>+≡
  public :: quantum_numbers_set_flavor
  public :: quantum_numbers_set_color
  public :: quantum_numbers_set_helicity

<Quantum numbers: interfaces>+≡
  interface quantum_numbers_set_flavor
    module procedure quantum_numbers_set_flavor0
    module procedure quantum_numbers_set_flavor1
  end interface
```

```

<Quantum numbers: procedures>+≡
  subroutine quantum_numbers_set_flavor0 (qn, flv)
    type(quantum_numbers_t), intent(inout) :: qn
    type(flavor_t), intent(in) :: flv
    qn%f = flv
  end subroutine quantum_numbers_set_flavor0

  subroutine quantum_numbers_set_flavor1 (qn, flv)
    type(quantum_numbers_t), dimension(:), intent(inout) :: qn
    type(flavor_t), dimension(:), intent(in) :: flv
    integer :: i
    do i = 1, size (flv)
      qn(i)%f = flv(i)
    end do
  end subroutine quantum_numbers_set_flavor1

  elemental subroutine quantum_numbers_set_color (qn, col)
    type(quantum_numbers_t), intent(inout) :: qn
    type(color_t), intent(in) :: col
    qn%c = col
  end subroutine quantum_numbers_set_color

  elemental subroutine quantum_numbers_set_helicity (qn, hel)
    type(quantum_numbers_t), intent(inout) :: qn
    type(helicity_t), intent(in) :: hel
    qn%h = hel
  end subroutine quantum_numbers_set_helicity

```

This just resets the ghost property of the color/helicity part:

```

<Quantum numbers: public>+≡
  public :: quantum_numbers_set_color_ghost
  public :: quantum_numbers_set_helicity_ghost

<Quantum numbers: procedures>+≡
  elemental subroutine quantum_numbers_set_color_ghost (qn, ghost)
    type(quantum_numbers_t), intent(inout) :: qn
    logical, intent(in) :: ghost
    call color_set_ghost (qn%c, ghost)
  end subroutine quantum_numbers_set_color_ghost

  elemental subroutine quantum_numbers_set_helicity_ghost (qn, ghost)
    type(quantum_numbers_t), intent(inout) :: qn
    logical, intent(in) :: ghost
    call helicity_set_ghost (qn%h, ghost)
  end subroutine quantum_numbers_set_helicity_ghost

```

Assign a model to the flavor part of quantum numbers.

```

<Quantum numbers: public>+≡
  public :: quantum_numbers_set_model

<Quantum numbers: interfaces>+≡
  interface quantum_numbers_set_model
    module procedure quantum_numbers_set_model_single
    module procedure quantum_numbers_set_model_array
  end interface

```

```

end interface

<Quantum numbers: procedures>+≡
  subroutine quantum_numbers_set_model_single (qn, model)
    type(quantum_numbers_t), intent(inout) :: qn
    type(model_t), intent(in), target :: model
    call flavor_set_model (qn%f, model)
  end subroutine quantum_numbers_set_model_single

  subroutine quantum_numbers_set_model_array (qn, model)
    type(quantum_numbers_t), dimension(:), intent(inout) :: qn
    type(model_t), intent(in), target :: model
    call flavor_set_model (qn%f, model)
  end subroutine quantum_numbers_set_model_array

```

This is a convenience function: return the color type for the flavor (array).

```

<Quantum numbers: public>+≡
  public :: quantum_numbers_get_color_type

<Quantum numbers: procedures>+≡
  elemental function quantum_numbers_get_color_type (qn) result (color_type)
    integer :: color_type
    type(quantum_numbers_t), intent(in) :: qn
    color_type = flavor_get_color_type (qn%f)
  end function quantum_numbers_get_color_type

```

7.4.4 Predicates

Check if the flavor index is valid (including UNDEFINED).

```

<Quantum numbers: public>+≡
  public :: quantum_numbers_are_valid

<Quantum numbers: procedures>+≡
  elemental function quantum_numbers_are_valid (qn) result (valid)
    logical :: valid
    type(quantum_numbers_t), intent(in) :: qn
    valid = flavor_is_valid (qn%f)
  end function quantum_numbers_are_valid

```

Check if the flavor part has its particle-data pointer associated (debugging aid).

```

<Quantum numbers: public>+≡
  public :: quantum_numbers_are_associated

<Quantum numbers: procedures>+≡
  elemental function quantum_numbers_are_associated (qn) result (flag)
    logical :: flag
    type(quantum_numbers_t), intent(in) :: qn
    flag = flavor_is_associated (qn%f)
  end function quantum_numbers_are_associated

```

Check if the helicity and color quantum numbers are diagonal. (Unpolarized/colorless also counts as diagonal.) Flavor is diagonal by definition.

```

<Quantum numbers: public>+≡
    public :: quantum_numbers_are_diagonal

<Quantum numbers: procedures>+≡
    elemental function quantum_numbers_are_diagonal (qn) result (diagonal)
        logical :: diagonal
        type(quantum_numbers_t), intent(in) :: qn
        diagonal = helicity_is_diagonal (qn%h) .and. color_is_diagonal (qn%c)
    end function quantum_numbers_are_diagonal

```

Check if the color and/or helicity part has the ghost property.

```

<Quantum numbers: public>+≡
    public :: quantum_numbers_is_color_ghost
    public :: quantum_numbers_is_helicity_ghost

<Quantum numbers: procedures>+≡
    elemental function quantum_numbers_is_color_ghost (qn) result (ghost)
        logical :: ghost
        type(quantum_numbers_t), intent(in) :: qn
        ghost = color_is_ghost (qn%c)
    end function quantum_numbers_is_color_ghost

    elemental function quantum_numbers_is_helicity_ghost (qn) result (ghost)
        logical :: ghost
        type(quantum_numbers_t), intent(in) :: qn
        ghost = helicity_is_ghost (qn%h)
    end function quantum_numbers_is_helicity_ghost

```

The reverse:

```

<Quantum numbers: public>+≡
    public :: quantum_numbers_are_physical

<Quantum numbers: procedures>+≡
    elemental function quantum_numbers_are_physical (qn) result (physical)
        logical :: physical
        type(quantum_numbers_t), intent(in) :: qn
        physical = (.not. color_is_ghost (qn%c)) &
            .and. (.not. helicity_is_ghost (qn%h))
    end function quantum_numbers_are_physical

```

The ghost parity: false if no or both ghost flags are set.

```

<Quantum numbers: public>+≡
    public :: quantum_numbers_ghost_parity

<Quantum numbers: interfaces>+≡
    interface quantum_numbers_ghost_parity
        module procedure quantum_numbers_ghost_parity0
        module procedure quantum_numbers_ghost_parity1
    end interface

```

```

<Quantum numbers: procedures>+≡
pure function quantum_numbers_ghost_parity0 (qn) result (parity)
  type(quantum_numbers_t), intent(in) :: qn
  logical :: parity
  parity = color_is_ghost (qn%c) .neqv. helicity_is_ghost (qn%h)
end function quantum_numbers_ghost_parity0

pure function quantum_numbers_ghost_parity1 (qn) result (parity)
  type(quantum_numbers_t), dimension(:), intent(in) :: qn
  logical :: parity
  logical, dimension(size(qn)) :: p
  integer :: i
  forall (i = 1:size(qn))
    p(i) = quantum_numbers_ghost_parity0 (qn(i))
  end forall
  parity = mod (count (p), 2) == 1
end function quantum_numbers_ghost_parity1

```

7.4.5 Comparisons

Matching and equality is derived from the individual quantum numbers. The variant `fhmatch` matches only flavor and helicity. The variant `dhmatch` matches only diagonal helicity, if the matching helicity is undefined.

```

<Quantum numbers: public>+≡
public :: operator(.match.)
public :: operator(.fhmatch.)
public :: operator(.dhmatch.)
public :: operator(==)
public :: operator(/=)

<Quantum numbers: interfaces>+≡
interface operator(.match.)
  module procedure quantum_numbers_match
end interface
interface operator(.fhmatch.)
  module procedure quantum_numbers_match_fh
end interface
interface operator(.dhmatch.)
  module procedure quantum_numbers_match_hel_diag
end interface
interface operator(==)
  module procedure quantum_numbers_eq
end interface
interface operator(/=)
  module procedure quantum_numbers_neq
end interface

<Quantum numbers: procedures>+≡
elemental function quantum_numbers_match (qn1, qn2) result (match)
  logical :: match
  type(quantum_numbers_t), intent(in) :: qn1, qn2
  match = (qn1%f .match. qn2%f) .and. &
    (qn1%c .match. qn2%c) .and. &

```

```

        (qn1%h .match. qn2%h)
end function quantum_numbers_match

elemental function quantum_numbers_match_fh (qn1, qn2) result (match)
    logical :: match
    type(quantum_numbers_t), intent(in) :: qn1, qn2
    match = (qn1%f .match. qn2%f) .and. &
            (qn1%h .match. qn2%h)
end function quantum_numbers_match_fh

elemental function quantum_numbers_match_hel_diag (qn1, qn2) result (match)
    logical :: match
    type(quantum_numbers_t), intent(in) :: qn1, qn2
    match = (qn1%f .match. qn2%f) .and. &
            (qn1%c .match. qn2%c) .and. &
            (qn1%h .dmatch. qn2%h)
end function quantum_numbers_match_hel_diag

elemental function quantum_numbers_eq (qn1, qn2) result (eq)
    logical :: eq
    type(quantum_numbers_t), intent(in) :: qn1, qn2
    eq = (qn1%f == qn2%f) .and. &
        (qn1%c == qn2%c) .and. &
        (qn1%h == qn2%h)
end function quantum_numbers_eq

elemental function quantum_numbers_neq (qn1, qn2) result (neq)
    logical :: neq
    type(quantum_numbers_t), intent(in) :: qn1, qn2
    neq = (qn1%f /= qn2%f) .or. &
        (qn1%c /= qn2%c) .or. &
        (qn1%h /= qn2%h)
end function quantum_numbers_neq

```

7.4.6 Operations

Inherited from the color component: reassign color indices in canonical order.

```

<Quantum numbers: public>+≡
    public :: quantum_numbers_canonicalize_color

<Quantum numbers: procedures>+≡
    subroutine quantum_numbers_canonicalize_color (qn)
        type(quantum_numbers_t), dimension(:), intent(inout) :: qn
        call color_canonicalize (qn%c)
    end subroutine quantum_numbers_canonicalize_color

```

Inherited from the color component: make a color map for two matching quantum-number arrays.

```

<Quantum numbers: public>+≡
    public :: quantum_numbers_set_color_map

```

```

<Quantum numbers: procedures>+≡
  subroutine quantum_numbers_set_color_map (map, qn1, qn2)
    integer, dimension(:,:), intent(out), allocatable :: map
    type(quantum_numbers_t), dimension(:), intent(in) :: qn1, qn2
    call set_color_map (map, qn1%c, qn2%c)
  end subroutine quantum_numbers_set_color_map

```

Inherited from the color component: translate the color part using a color-map array

```

<Quantum numbers: public>+≡
  public :: quantum_numbers_translate_color

<Quantum numbers: interfaces>+≡
  interface quantum_numbers_translate_color
    module procedure quantum_numbers_translate_color0
    module procedure quantum_numbers_translate_color1
  end interface

<Quantum numbers: procedures>+≡
  subroutine quantum_numbers_translate_color0 (qn, map, offset)
    type(quantum_numbers_t), intent(inout) :: qn
    integer, dimension(:,:), intent(in) :: map
    integer, intent(in), optional :: offset
    call color_translate (qn%c, map, offset)
  end subroutine quantum_numbers_translate_color0

  subroutine quantum_numbers_translate_color1 (qn, map, offset)
    type(quantum_numbers_t), dimension(:), intent(inout) :: qn
    integer, dimension(:,:), intent(in) :: map
    integer, intent(in), optional :: offset
    call color_translate (qn%c, map, offset)
  end subroutine quantum_numbers_translate_color1

```

Inherited from the color component: return the color index with highest absolute value

```

<Quantum numbers: public>+≡
  public :: quantum_numbers_get_max_color_value

<Quantum numbers: interfaces>+≡
  interface quantum_numbers_get_max_color_value
    module procedure quantum_numbers_get_max_color_value0
    module procedure quantum_numbers_get_max_color_value1
    module procedure quantum_numbers_get_max_color_value2
  end interface

<Quantum numbers: procedures>+≡
  function quantum_numbers_get_max_color_value0 (qn) result (cmax)
    integer :: cmax
    type(quantum_numbers_t), intent(in) :: qn
    cmax = color_get_max_value (qn%c)
  end function quantum_numbers_get_max_color_value0

  function quantum_numbers_get_max_color_value1 (qn) result (cmax)

```

```

integer :: cmax
type(quantum_numbers_t), dimension(:), intent(in) :: qn
cmax = color_get_max_value (qn%c)
end function quantum_numbers_get_max_color_value1

function quantum_numbers_get_max_color_value2 (qn) result (cmax)
integer :: cmax
type(quantum_numbers_t), dimension(:,:), intent(in) :: qn
cmax = color_get_max_value (qn%c)
end function quantum_numbers_get_max_color_value2

```

Inherited from the color component: add an offset to the indices of the color part

```

<Quantum numbers: public>+≡
public :: quantum_numbers_add_color_offset

<Quantum numbers: procedures>+≡
elemental subroutine quantum_numbers_add_color_offset (qn, offset)
type(quantum_numbers_t), intent(inout) :: qn
integer, intent(in) :: offset
call color_add_offset (qn%c, offset)
end subroutine quantum_numbers_add_color_offset

```

Given a quantum number array, return all possible color contractions, leaving the other quantum numbers intact.

```

<Quantum numbers: public>+≡
public :: quantum_number_array_make_color_contractions

<Quantum numbers: procedures>+≡
subroutine quantum_number_array_make_color_contractions (qn_in, qn_out)
type(quantum_numbers_t), dimension(:), intent(in) :: qn_in
type(quantum_numbers_t), dimension(:,:), intent(out), allocatable :: qn_out
type(color_t), dimension(:,:), allocatable :: col
integer :: i
call color_array_make_contractions (qn_in%c, col)
allocate (qn_out (size (col, 1), size (col, 2)))
do i = 1, size (qn_out, 2)
qn_out(:,i)%f = qn_in%f
qn_out(:,i)%c = col(:,i)
qn_out(:,i)%h = qn_in%h
end do
end subroutine quantum_number_array_make_color_contractions

```

Inherited from the color component: invert the color, switching particle/antiparticle.

```

<Quantum numbers: public>+≡
public :: quantum_numbers_invert_color

<Quantum numbers: procedures>+≡
elemental subroutine quantum_numbers_invert_color (qn)
type(quantum_numbers_t), intent(inout) :: qn
call color_invert (qn%c)
end subroutine quantum_numbers_invert_color

```

Merge two quantum number sets: for each entry, if both are defined, combine them to an off-diagonal entry (meaningful only if the input was diagonal). If either entry is undefined, take the defined one.

For flavor, off-diagonal entries are invalid, so both flavors must be equal, otherwise an invalid flavor is inserted.

```

<Quantum numbers: public>+≡
  public :: operator(.merge.)

<Quantum numbers: interfaces>+≡
  interface operator(.merge.)
    module procedure merge_quantum_numbers0
    module procedure merge_quantum_numbers1
  end interface

<Quantum numbers: procedures>+≡
  function merge_quantum_numbers0 (qn1, qn2) result (qn3)
    type(quantum_numbers_t) :: qn3
    type(quantum_numbers_t), intent(in) :: qn1, qn2
    qn3%f = qn1%f .merge. qn2%f
    qn3%c = qn1%c .merge. qn2%c
    qn3%h = qn1%h .merge. qn2%h
  end function merge_quantum_numbers0

  function merge_quantum_numbers1 (qn1, qn2) result (qn3)
    type(quantum_numbers_t), dimension(:), intent(in) :: qn1, qn2
    type(quantum_numbers_t), dimension(size(qn1)) :: qn3
    qn3%f = qn1%f .merge. qn2%f
    qn3%c = qn1%c .merge. qn2%c
    qn3%h = qn1%h .merge. qn2%h
  end function merge_quantum_numbers1

```

7.4.7 The quantum number mask

The quantum numbers mask is true for quantum numbers that should be ignored or summed over. The three mandatory entries correspond to flavor, color, and helicity, respectively.

There is an additional entry `cg`: If false, the color-ghosts property should be kept even if color is ignored. This is relevant only if `c` is set, otherwise it is always false.

The flag `hd` tells that only diagonal entries in helicity should be kept. If `h` is set, `hd` is irrelevant and will be kept `.false.`

```

<Quantum numbers: public>+≡
  public :: quantum_numbers_mask_t

<Quantum numbers: types>+≡
  type :: quantum_numbers_mask_t
    private
    logical :: f = .false.
    logical :: c = .false.
    logical :: cg = .false.
    logical :: h = .false.
    logical :: hd = .false.

```

```
end type quantum_numbers_mask_t
```

Define a quantum number mask: Constructor form

```
<Quantum numbers: public>+≡
  public :: new_quantum_numbers_mask

<Quantum numbers: procedures>+≡
  elemental function new_quantum_numbers_mask &
    (mask_f, mask_c, mask_h, mask_cg, mask_hd) result (mask)
    type(quantum_numbers_mask_t) :: mask
    logical, intent(in) :: mask_f, mask_c, mask_h
    logical, intent(in), optional :: mask_cg
    logical, intent(in), optional :: mask_hd
    call quantum_numbers_mask_init &
      (mask, mask_f, mask_c, mask_h, mask_cg, mask_hd)
  end function new_quantum_numbers_mask
```

Define quantum numbers: Initializer form

```
<Quantum numbers: public>+≡
  public :: quantum_numbers_mask_init

<Quantum numbers: procedures>+≡
  elemental subroutine quantum_numbers_mask_init &
    (mask, mask_f, mask_c, mask_h, mask_cg, mask_hd)
    type(quantum_numbers_mask_t), intent(out) :: mask
    logical, intent(in) :: mask_f, mask_c, mask_h
    logical, intent(in), optional :: mask_cg, mask_hd
    mask%f = mask_f
    mask%c = mask_c
    mask%h = mask_h
    if (present (mask_cg)) then
      if (mask%c) mask%cg = mask_cg
    else
      mask%cg = mask_c
    end if
    if (present (mask_hd)) then
      if (.not. mask%h) mask%hd = mask_hd
    end if
  end subroutine quantum_numbers_mask_init
```

Write a quantum numbers mask

```
<Quantum numbers: public>+≡
  public :: quantum_numbers_mask_write

<Quantum numbers: interfaces>+≡
  interface quantum_numbers_mask_write
    module procedure quantum_numbers_mask_write_single
    module procedure quantum_numbers_mask_write_array
  end interface

<Quantum numbers: procedures>+≡
  subroutine quantum_numbers_mask_write_single (mask, unit)
    type(quantum_numbers_mask_t), intent(in) :: mask
    integer, intent(in), optional :: unit
```

```

integer :: u
u = output_unit (unit); if (u < 0) return
write (u, "(A)", advance="no") "["
write (u, "(L1)", advance="no") mask%f
write (u, "(L1)", advance="no") mask%c
if (.not.mask%cg) write (u, "('g')", advance="no")
write (u, "(L1)", advance="no") mask%h
if (mask%hd) write (u, "('d')", advance="no")
write (u, "(A)", advance="no") "]"
end subroutine quantum_numbers_mask_write_single

subroutine quantum_numbers_mask_write_array (mask, unit)
type(quantum_numbers_mask_t), dimension(:), intent(in) :: mask
integer, intent(in), optional :: unit
integer :: u, i
u = output_unit (unit); if (u < 0) return
write (u, "(A)", advance="no") "["
do i = 1, size (mask)
  if (i > 1) write (u, "(A)", advance="no") "/"
  write (u, "(L1)", advance="no") mask(i)%f
  write (u, "(L1)", advance="no") mask(i)%c
  if (.not.mask(i)%cg) write (u, "('g')", advance="no")
  write (u, "(L1)", advance="no") mask(i)%h
  if (mask(i)%hd) write (u, "('d')", advance="no")
end do
write (u, "(A)", advance="no") "]"
end subroutine quantum_numbers_mask_write_array

```

7.4.8 Setting mask components

<Quantum numbers: public>+≡

```

public :: quantum_numbers_mask_set_flavor
public :: quantum_numbers_mask_set_color
public :: quantum_numbers_mask_set_helicity

```

<Quantum numbers: procedures>+≡

```

elemental subroutine quantum_numbers_mask_set_flavor (mask, mask_f)
  type(quantum_numbers_mask_t), intent(inout) :: mask
  logical, intent(in) :: mask_f
  mask%f = mask_f
end subroutine quantum_numbers_mask_set_flavor

elemental subroutine quantum_numbers_mask_set_color (mask, mask_c, mask_cg)
  type(quantum_numbers_mask_t), intent(inout) :: mask
  logical, intent(in) :: mask_c
  logical, intent(in), optional :: mask_cg
  mask%c = mask_c
  if (present (mask_cg)) then
    if (mask%c) mask%cg = mask_cg
  else
    mask%cg = mask_c
  end if
end subroutine quantum_numbers_mask_set_color

```

```

elemental subroutine quantum_numbers_mask_set_helicity (mask, mask_h, mask_hd)
  type(quantum_numbers_mask_t), intent(inout) :: mask
  logical, intent(in) :: mask_h
  logical, intent(in), optional :: mask_hd
  mask%h = mask_h
  if (present (mask_hd)) then
    if (.not. mask%h) mask%hd = mask_hd
  end if
end subroutine quantum_numbers_mask_set_helicity

```

7.4.9 Mask predicates

Return true if either one of the entries is set:

```

<Quantum numbers: public>+≡
  public :: any

<Quantum numbers: interfaces>+≡
  interface any
    module procedure quantum_numbers_mask_any
  end interface

<Quantum numbers: procedures>+≡
  function quantum_numbers_mask_any (mask) result (match)
    logical :: match
    type(quantum_numbers_mask_t), intent(in) :: mask
    match = mask%f .or. mask%c .or. mask%h .or. mask%hd
  end function quantum_numbers_mask_any

```

7.4.10 Operators

The OR operation is applied to all components.

```

<Quantum numbers: public>+≡
  public :: operator(.or.)

<Quantum numbers: interfaces>+≡
  interface operator(.or.)
    module procedure quantum_numbers_mask_or
  end interface

<Quantum numbers: procedures>+≡
  elemental function quantum_numbers_mask_or (mask1, mask2) result (mask)
    type(quantum_numbers_mask_t) :: mask
    type(quantum_numbers_mask_t), intent(in) :: mask1, mask2
    mask%f = mask1%f .or. mask2%f
    mask%c = mask1%c .or. mask2%c
    if (mask%c) mask%cg = mask1%cg .or. mask2%cg
    mask%h = mask1%h .or. mask2%h
    if (.not. mask%h) mask%hd = mask1%hd .or. mask2%hd
  end function quantum_numbers_mask_or

```

7.4.11 Mask comparisons

Return true if the two masks are equivalent / differ:

```
<Quantum numbers: public>+≡
    public :: operator(.eqv.)
    public :: operator(.neqv.)

<Quantum numbers: interfaces>+≡
    interface operator(.eqv.)
        module procedure quantum_numbers_mask_eqv
    end interface
    interface operator(.neqv.)
        module procedure quantum_numbers_mask_neqv
    end interface

<Quantum numbers: procedures>+≡
    elemental function quantum_numbers_mask_eqv (mask1, mask2) result (eqv)
        logical :: eqv
        type(quantum_numbers_mask_t), intent(in) :: mask1, mask2
        eqv = (mask1%f .eqv. mask2%f) .and. &
            (mask1%c .eqv. mask2%c) .and. &
            (mask1%cg .eqv. mask2%cg) .and. &
            (mask1%h .eqv. mask2%h) .and. &
            (mask1%hd .eqv. mask2%hd)
    end function quantum_numbers_mask_eqv

    elemental function quantum_numbers_mask_neqv (mask1, mask2) result (neqv)
        logical :: neqv
        type(quantum_numbers_mask_t), intent(in) :: mask1, mask2
        neqv = (mask1%f .neqv. mask2%f) .or. &
            (mask1%c .neqv. mask2%c) .or. &
            (mask1%cg .neqv. mask2%cg) .or. &
            (mask1%h .neqv. mask2%h) .or. &
            (mask1%hd .neqv. mask2%hd)
    end function quantum_numbers_mask_neqv
```

7.4.12 Apply a mask

Applying a mask to the quantum number object means undefining those entries where the mask is set. The others remain unaffected.

The `hd` mask has the special property that it “diagonalizes” helicity, i.e., the second helicity entry is dropped and the result is a diagonal helicity quantum number.

```
<Quantum numbers: public>+≡
    public :: quantum_numbers_undefine
    public :: quantum_numbers_undefined

<Quantum numbers: interfaces>+≡
    interface quantum_numbers_undefined
        module procedure quantum_numbers_undefined0
        module procedure quantum_numbers_undefined1
        module procedure quantum_numbers_undefined11
    end interface
```

```

<Quantum numbers: procedures>+≡
  elemental subroutine quantum_numbers_undefine (qn, mask)
    type(quantum_numbers_t), intent(inout) :: qn
    type(quantum_numbers_mask_t), intent(in) :: mask
    if (mask%f) call flavor_undefine (qn%f)
    if (mask%c) call color_undefine (qn%c, undefine_ghost=mask%cg)
    if (mask%h) then
      call helicity_undefine (qn%h)
    else if (mask%hd) then
      if (.not. helicity_is_diagonal (qn%h)) then
        call helicity_diagonalize (qn%h)
      end if
    end if
  end subroutine quantum_numbers_undefine

function quantum_numbers_undefined0 (qn, mask) result (qn_new)
  type(quantum_numbers_t), intent(in) :: qn
  type(quantum_numbers_mask_t), intent(in) :: mask
  type(quantum_numbers_t) :: qn_new
  qn_new = qn
  call quantum_numbers_undefine (qn_new, mask)
end function quantum_numbers_undefined0

function quantum_numbers_undefined1 (qn, mask) result (qn_new)
  type(quantum_numbers_t), dimension(:), intent(in) :: qn
  type(quantum_numbers_mask_t), intent(in) :: mask
  type(quantum_numbers_t), dimension(size(qn)) :: qn_new
  qn_new = qn
  call quantum_numbers_undefine (qn_new, mask)
end function quantum_numbers_undefined1

function quantum_numbers_undefined11 (qn, mask) result (qn_new)
  type(quantum_numbers_t), dimension(:), intent(in) :: qn
  type(quantum_numbers_mask_t), dimension(:), intent(in) :: mask
  type(quantum_numbers_t), dimension(size(qn)) :: qn_new
  qn_new = qn
  call quantum_numbers_undefine (qn_new, mask)
end function quantum_numbers_undefined11

```

Return true if the input quantum number set has entries that would be removed by the applied mask, e.g., if polarization is defined but `mask%h` is set:

```

<Quantum numbers: public>+≡
  public :: quantum_numbers_are_redundant

<Quantum numbers: procedures>+≡
  elemental function quantum_numbers_are_redundant (qn, mask) &
    result (redundant)
    logical :: redundant
    type(quantum_numbers_t), intent(in) :: qn
    type(quantum_numbers_mask_t), intent(in) :: mask
    redundant = .false.
    if (mask%f) then
      redundant = flavor_is_defined (qn%f)
    end if

```

```

if (mask%c) then
    redundant = color_is_defined (qn%c)
end if
if (mask%h) then
    redundant = helicity_is_defined (qn%h)
else if (mask%hd) then
    redundant = .not. helicity_is_diagonal (qn%h)
end if
end function quantum_numbers_are_redundant

```

7.5 State matrices

This module deals with the internal state of a particle system, i.e., with its density matrix in flavor, color, and helicity space.

```
<state_matrices.f90>≡  
  <File header>  
  
  module state_matrices  
  
    <Use kinds>  
    <Use file utils>  
    use diagnostics !NODEP!  
    use models  
    use flavors  
    use colors  
    use helicities  
    use quantum_numbers  
  
    <Standard module head>  
  
    <State matrices: public>  
  
    <State matrices: parameters>  
  
    <State matrices: types>  
  
    <State matrices: interfaces>  
  
    contains  
  
    <State matrices: procedures>  
  
  end module state_matrices
```

7.5.1 Nodes of the quantum state trie

A quantum state object represents an unnormalized density matrix, i.e., an array of possibilities for flavor, color, and helicity indices with associated complex values. Physically, the trace of this matrix is the summed squared matrix element for an interaction, and the matrix elements divided by this value correspond to the flavor-color-helicity density matrix. (Flavor and color are diagonal.)

We store density matrices as tries, that is, as trees where each branching represents the possible quantum numbers of a particle. The first branching is the first particle in the system. A leaf (the node corresponding to the last particle) contains the value of the matrix element.

Each node contains a flavor, color, and helicity entry. Note that each of those entries may be actually undefined, so we can also represent, e.g., unpolarized particles.

The value is meaningful only for leaves, which have no child nodes. There is a pointer to the parent node which allows for following the trie downwards from a leaf, it is null for a root node. The child nodes are implemented as a list,

so there is a pointer to the first and last child, and each node also has a **next** pointer to the next sibling.

The root node does not correspond to a particle, only its children do. The quantum numbers of the root node are irrelevant and will not be set. However, we use a common type for the three classes (root, branch, leaf); they may easily be distinguished by the association status of parent and child.

Node type

The node is linked in all directions: the parent, the first and last in the list of children, and the previous and next sibling. This allows us for adding and removing nodes and whole branches anywhere in the trie. (Circular links are not allowed, however.). The node holds its associated set of quantum numbers. The integer index, which is set only for leaf nodes, is the index of the corresponding matrix element value within the state matrix.

Temporarily, matrix-element values may be stored within a leaf node. This is used during state-matrix factorization. When the state matrix is **frozen**, these values are transferred to the matrix-element array within the host state matrix.

```

(State matrices: types)≡
  type :: node_t
    private
    type(quantum_numbers_t) :: qn
    type(node_t), pointer :: parent => null ()
    type(node_t), pointer :: child_first => null ()
    type(node_t), pointer :: child_last => null ()
    type(node_t), pointer :: next => null ()
    type(node_t), pointer :: previous => null ()
    integer :: me_index = 0
    integer, dimension(:), allocatable :: me_count
    complex(default) :: me
  end type node_t

```

Operations on nodes

Recursively deallocate all children of the current node. This includes any values associated with the children.

```

(State matrices: procedures)≡
  pure recursive subroutine node_delete_offspring (node)
    type(node_t), pointer :: node
    type(node_t), pointer :: child
    child => node%child_first
    do while (associated (child))
      node%child_first => node%child_first%next
      call node_delete_offspring (child)
      deallocate (child)
    end do
    node%child_last => null ()
  end subroutine node_delete_offspring

```

Remove a node including its offspring. Adjust the pointers of parent and siblings, if necessary.

```

<State matrices: procedures>+≡
  pure subroutine node_delete (node)
    type(node_t), pointer :: node
    call node_delete_offspring (node)
    if (associated (node%previous)) then
      node%previous%next => node%next
    else if (associated (node%parent)) then
      node%parent%child_first => node%next
    end if
    if (associated (node%next)) then
      node%next%previous => node%previous
    else if (associated (node%parent)) then
      node%parent%child_last => node%previous
    end if
    deallocate (node)
  end subroutine node_delete

```

Append a child node

```

<State matrices: procedures>+≡
  subroutine node_append_child (node, child)
    type(node_t), target, intent(inout) :: node
    type(node_t), pointer :: child
    allocate (child)
    if (associated (node%child_last)) then
      node%child_last%next => child
      child%previous => node%child_last
    else
      node%child_first => child
    end if
    node%child_last => child
    child%parent => node
  end subroutine node_append_child

```

I/O

Output of a single node, no recursion. We print the quantum numbers in square brackets, then the value (if any).

```

<State matrices: procedures>+≡
  subroutine node_write (node, me_array, verbose, unit)
    type(node_t), intent(in) :: node
    complex(default), dimension(:), intent(in), optional :: me_array
    logical, intent(in), optional :: verbose
    integer, intent(in), optional :: unit
    logical :: verb
    integer :: u
    verb = .false.; if (present (verbose)) verb = verbose
    u = output_unit (unit); if (u < 0) return
    call quantum_numbers_write (node%qn, u)
    if (node%me_index /= 0) then
      write (u, "(A,I0,A)", advance="no") " => ME(", node%me_index, ")"
    end if
  end subroutine node_write

```

```

    if (present (me_array)) then
      write (u, "(A)", advance="no") " = "
      if (aimag (me_array(node%me_index)) == 0) then
        write (u, "(1P,G19.12)", advance="no") real (me_array(node%me_index))
      else
        write (u, "(1P,G19.12,',',G19.12)", advance="no") me_array(node%me_index)
      end if
    end if
  end if
end if
write (u, *)
if (verb) then
  call ptr_write ("parent      ", node%parent)
  call ptr_write ("child_first", node%child_first)
  call ptr_write ("child_last ", node%child_last)
  call ptr_write ("next       ", node%next)
  call ptr_write ("previous   ", node%previous)
end if
contains
subroutine ptr_write (label, node)
  character(*), intent(in) :: label
  type(node_t), pointer :: node
  if (associated (node)) then
    write (u, "(10x,A,1x,'->',1x)", advance="no") label
    call quantum_numbers_write (node%qn, u)
    write (u, *)
  end if
end subroutine ptr_write
end subroutine node_write

```

Recursive output of a node:

(State matrices: procedures)+≡

```

recursive subroutine node_write_rec (node, me_array, verbose, indent, unit)
  type(node_t), intent(in), target :: node
  complex(default), dimension(:), intent(in), optional :: me_array
  logical, intent(in), optional :: verbose
  integer, intent(in), optional :: indent
  integer, intent(in), optional :: unit
  type(node_t), pointer :: current
  logical :: verb
  integer :: i, u
  verb = .false.; if (present (verbose)) verb = verbose
  i = 0; if (present (indent)) i = indent
  u = output_unit (unit); if (u < 0) return
  current => node%child_first
  do while (associated (current))
    write (u, "(A)", advance="no") repeat (" ", i)
    call node_write (current, me_array, verb, u)
    call node_write_rec (current, me_array, verb, i+2, u)
    current => current%next
  end do
end subroutine node_write_rec

```

Binary I/O. Matrix elements are written only for leaf nodes. this was actually

a pointer is lost.

(State matrices: procedures)+≡

```

recursive subroutine node_write_raw_rec (node, u)
  type(node_t), intent(in), target :: node
  integer, intent(in) :: u
  logical :: associated_child_first, associated_next
  call quantum_numbers_write_raw (node%qn, u)
  associated_child_first = associated (node%child_first)
  write (u) associated_child_first
  associated_next = associated (node%next)
  write (u) associated_next
  if (associated_child_first) then
    call node_write_raw_rec (node%child_first, u)
  else
    write (u) node%me_index
  end if
  if (associated_next) then
    call node_write_raw_rec (node%next, u)
  end if
end subroutine node_write_raw_rec

recursive subroutine node_read_raw_rec (node, u, parent, iostat)
  type(node_t), intent(out), target :: node
  integer, intent(in) :: u
  type(node_t), intent(in), optional, target :: parent
  integer, intent(out), optional :: iostat
  logical :: associated_child_first, associated_next
  type(node_t), pointer :: child
  call quantum_numbers_read_raw (node%qn, u, iostat=iostat)
  read (u, iostat=iostat) associated_child_first
  read (u, iostat=iostat) associated_next
  if (present (parent)) node%parent => parent
  if (associated_child_first) then
    allocate (child)
    node%child_first => child
    node%child_last => null ()
    call node_read_raw_rec (child, u, node, iostat=iostat)
    do while (associated (child))
      child%previous => node%child_last
      node%child_last => child
      child => child%next
    end do
  else
    read (u, iostat=iostat) node%me_index
  end if
  if (associated_next) then
    allocate (node%next)
    call node_read_raw_rec (node%next, u, parent, iostat=iostat)
  end if
end subroutine node_read_raw_rec

```

7.5.2 State matrix

Definition

The quantum state object is a container that keeps and hides the root node. For direct accessibility of values, value pointers are stored in a separate array.

```

<State matrices: public>≡
    public :: state_matrix_t

<State matrices: types>+≡
    type :: state_matrix_t
        private
            type(node_t), pointer :: root => null ()
            integer :: depth = 0
            integer :: n_matrix_elements = 0
            logical :: leaf_nodes_store_values = .false.
            integer :: n_counters = 0
            complex(default), dimension(:), allocatable :: me
        end type state_matrix_t

```

This initializer allocates the root node but does not fill anything. We declare whether values are stored within the nodes during state-matrix construction, and how many counters should be maintained (default: none).

```

<State matrices: public>+≡
    public :: state_matrix_init

<State matrices: procedures>+≡
    elemental subroutine state_matrix_init (state, store_values, n_counters)
        type(state_matrix_t), intent(out) :: state
        logical, intent(in), optional :: store_values
        integer, intent(in), optional :: n_counters
        allocate (state%root)
        if (present (store_values)) state%leaf_nodes_store_values = .true.
        if (present (n_counters)) state%n_counters = n_counters
    end subroutine state_matrix_init

```

This recursively deletes all children of the root node, restoring the initial state. The matrix element array is not finalized, since it does not contain physical entries, just pointers.

```

<State matrices: public>+≡
    public :: state_matrix_final

<State matrices: procedures>+≡
    elemental subroutine state_matrix_final (state)
        type(state_matrix_t), intent(inout) :: state
        if (allocated (state%me)) deallocate (state%me)
        if (associated (state%root)) call node_delete (state%root)
        state%depth = 0
        state%n_matrix_elements = 0
    end subroutine state_matrix_final

```

Output: Present the tree as a nested list with appropriate indentation.

```

<State matrices: public>+≡
    public :: state_matrix_write

```

<State matrices: procedures>+≡

```

subroutine state_matrix_write (state, unit, write_value_list, verbose)
  type(state_matrix_t), intent(in) :: state
  logical, intent(in), optional :: write_value_list, verbose
  integer, intent(in), optional :: unit
  integer :: u
  integer :: i
  u = output_unit (unit); if (u < 0) return
  if (associated (state%root)) then
    if (allocated (state%me)) then
      call node_write_rec (state%root, state%me, verbose, 1, u)
    else
      call node_write_rec (state%root, verbose=verbose, indent=1, unit=u)
    end if
  end if
  if (present (write_value_list)) then
    if (write_value_list .and. allocated (state%me)) then
      do i = 1, size (state%me)
        write (u, "(1x,I0,A)", advance="no") i, ":"
        write (u, *) state%me(i)
      end do
    end if
  end if
end subroutine state_matrix_write

```

Binary I/O. The auxiliary matrix-element array is not written, but reconstructed after reading the tree.

<State matrices: public>+≡

```

public :: state_matrix_write_raw
public :: state_matrix_read_raw

```

<State matrices: procedures>+≡

```

subroutine state_matrix_write_raw (state, u)
  type(state_matrix_t), intent(in) :: state
  integer, intent(in) :: u
  logical :: associated_root
  associated_root = associated (state%root)
  write (u) associated_root
  if (associated_root) then
    write (u) state%depth
    call node_write_raw_rec (state%root, u)
  end if
end subroutine state_matrix_write_raw

subroutine state_matrix_read_raw (state, u, iostat)
  type(state_matrix_t), intent(out) :: state
  integer, intent(in) :: u
  integer, intent(out), optional :: iostat
  logical :: associated_root
  read (u, iostat=iostat) associated_root
  if (associated_root) then
    read (u, iostat=iostat) state%depth
    call state_matrix_init (state)
    call node_read_raw_rec (state%root, u, iostat=iostat)
  end if
end subroutine state_matrix_read_raw

```

```

        call state_matrix_freeze (state)
    end if
end subroutine state_matrix_read_raw

```

Properties of the quantum state

A state is defined if its root is allocated:

```

<State matrices: public>+≡
    public :: state_matrix_is_defined

<State matrices: procedures>+≡
    elemental function state_matrix_is_defined (state) result (defined)
        logical :: defined
        type(state_matrix_t), intent(in) :: state
        defined = associated (state%root)
    end function state_matrix_is_defined

```

A state is empty if its depth is zero:

```

<State matrices: public>+≡
    public :: state_matrix_is_empty

<State matrices: procedures>+≡
    elemental function state_matrix_is_empty (state) result (flag)
        logical :: flag
        type(state_matrix_t), intent(in) :: state
        flag = state%depth == 0
    end function state_matrix_is_empty

```

Return the number of matrix-element values.

```

<State matrices: public>+≡
    public :: state_matrix_get_n_matrix_elements

<State matrices: procedures>+≡
    function state_matrix_get_n_matrix_elements (state) result (n)
        integer :: n
        type(state_matrix_t), intent(in) :: state
        n = state%n_matrix_elements
    end function state_matrix_get_n_matrix_elements

```

Return the number of leaves. This can be larger than the number of independent matrix elements.

```

<State matrices: public>+≡
    public :: state_matrix_get_n_leaves

<State matrices: procedures>+≡
    function state_matrix_get_n_leaves (state) result (n)
        integer :: n
        type(state_matrix_t), intent(in) :: state
        type(state_iterator_t) :: it
        n = 0
        call state_iterator_init (it, state)
        do while (state_iterator_is_valid (it))

```

```

        n = n + 1
        call state_iterator_advance (it)
    end do
end function state_matrix_get_n_leaves

```

Return the depth:

```

⟨State matrices: public⟩+≡
    public :: state_matrix_get_depth

⟨State matrices: procedures⟩+≡
    function state_matrix_get_depth (state) result (depth)
        integer :: depth
        type(state_matrix_t), intent(in) :: state
        depth = state%depth
    end function state_matrix_get_depth

```

Retrieving contents

Return the quantum number array, using an index. We have to scan the state matrix since there is no shortcut.

```

⟨State matrices: public⟩+≡
    public :: state_matrix_get_quantum_numbers

⟨State matrices: procedures⟩+≡
    function state_matrix_get_quantum_numbers (state, i) result (qn)
        type(state_matrix_t), intent(in), target :: state
        integer, intent(in) :: i
        type(quantum_numbers_t), dimension(state%depth) :: qn
        type(state_iterator_t) :: it
        integer :: k
        k = 0
        call state_iterator_init (it, state)
        do while (state_iterator_is_valid (it))
            k = k + 1
            if (k == i) then
                qn = state_iterator_get_quantum_numbers (it)
                return
            end if
            call state_iterator_advance (it)
        end do
    end function state_matrix_get_quantum_numbers

```

Return a single matrix element using its index. Works only if the shortcut array is allocated.

```

⟨State matrices: public⟩+≡
    public :: state_matrix_get_matrix_element

⟨State matrices: procedures⟩+≡
    function state_matrix_get_matrix_element (state, i) result (me)
        complex(default) :: me
        type(state_matrix_t), intent(in) :: state
        integer, intent(in) :: i

```

```

        if (allocated (state%me)) then
            me = state%me(i)
        else
            me = 0
        end if
    end function state_matrix_get_matrix_element

```

Return the color index with maximum value that is present within the state matrix.

```

<State matrices: public>+≡
    public :: state_matrix_get_max_color_value

<State matrices: procedures>+≡
    function state_matrix_get_max_color_value (state) result (cmax)
        integer :: cmax
        type(state_matrix_t), intent(in) :: state
        if (associated (state%root)) then
            cmax = node_get_max_color_value (state%root)
        else
            cmax = 0
        end if
    contains
        recursive function node_get_max_color_value (node) result (cmax)
            integer :: cmax
            type(node_t), intent(in), target :: node
            type(node_t), pointer :: current
            cmax = quantum_numbers_get_max_color_value (node%qn)
            current => node%child_first
            do while (associated (current))
                cmax = max (cmax, node_get_max_color_value (node%child_first))
                current => current%next
            end do
        end function node_get_max_color_value
    end function state_matrix_get_max_color_value

```

Building the quantum state

The procedure generates a branch associated to the input array of quantum numbers. If the branch exists already, it is used.

Optionally, we set the matrix-element index, a value (which may be added to the previous one), and increment one of the possible counters. We may also return the matrix element index of the current node.

```

<State matrices: public>+≡
    public :: state_matrix_add_state

<State matrices: procedures>+≡
    subroutine state_matrix_add_state &
        (state, qn, index, value, sum_values, counter_index, me_index)
        type(state_matrix_t), intent(inout) :: state
        type(quantum_numbers_t), dimension(:), intent(in) :: qn
        integer, intent(in), optional :: index
        complex(default), intent(in), optional :: value
    end subroutine state_matrix_add_state

```

```

logical, intent(in), optional :: sum_values
integer, intent(in), optional :: counter_index
integer, intent(out), optional :: me_index
logical :: set_index, get_index, add
set_index = present (index)
get_index = present (me_index)
add = .false.; if (present (sum_values)) add = sum_values
if (state%depth == 0) then
    state%depth = size (qn)
else if (state%depth /= size (qn)) then
    call state_matrix_write (state)
    call msg_bug ("State matrix: depth mismatch")
end if
call node_make_branch (state%root, qn)
contains
recursive subroutine node_make_branch (parent, qn)
    type(node_t), pointer :: parent
    type(quantum_numbers_t), dimension(:), intent(in) :: qn
    type(node_t), pointer :: child
    logical :: match
    match = .false.
    child => parent%child_first
    SCAN_CHILDREN: do while (associated (child))
        match = child%qn == qn(1)
        if (match) exit SCAN_CHILDREN
        child => child%next
    end do SCAN_CHILDREN
    if (.not. match) then
        call node_append_child (parent, child)
        child%qn = qn(1)
    end if
    if (size (qn) == 1) then
        if (.not. match) then
            state%n_matrix_elements = state%n_matrix_elements + 1
            child%me_index = state%n_matrix_elements
        end if
        if (set_index) then
            child%me_index = index
        end if
        if (get_index) then
            me_index = child%me_index
        end if
        if (present (counter_index)) then
            if (.not. allocated (child%me_count)) then
                allocate (child%me_count (state%n_counters))
                child%me_count = 0
            end if
            child%me_count(counter_index) = child%me_count(counter_index) + 1
        end if
        if (present (value)) then
            if (add) then
                child%me = child%me + value
            else
                child%me = value
            end if
        end if
    end if
end subroutine node_make_branch

```

```

        end if
    end if
else
    call node_make_branch (child, qn(2:))
end if
end subroutine node_make_branch
end subroutine state_matrix_add_state

```

Remove irrelevant flavor/color/helicity labels and the corresponding branchings. The masks indicate which particles are affected; the masks length should coincide with the depth of the trie (without the root node). Recursively scan the whole tree, starting from the leaf nodes and working up to the root node. If a mask entry is set for the current tree level, scan the children there. For each child within that level make a new empty branch where the masked quantum number is undefined. Then recursively combine all following children with matching quantum number into this new node and move on.

```

<State matrices: public>+≡
    public :: state_matrix_collapse

<State matrices: procedures>+≡
    subroutine state_matrix_collapse (state, mask)
        type(state_matrix_t), intent(inout) :: state
        type(quantum_numbers_mask_t), dimension(:), intent(in) :: mask
        type(state_matrix_t) :: red_state
        if (state_matrix_is_defined (state)) then
            call state_matrix_reduce (state, mask, red_state)
            call state_matrix_final (state)
            state = red_state
        end if
    end subroutine state_matrix_collapse

```

Transform the given state matrix into a reduced state matrix where some quantum numbers are removed, as indicated by the mask. The procedure creates a new state matrix, so the old one can be deleted after this if it is no longer used.

```

<State matrices: public>+≡
    public :: state_matrix_reduce

<State matrices: procedures>+≡
    subroutine state_matrix_reduce (state, mask, red_state)
        type(state_matrix_t), intent(in), target :: state
        type(quantum_numbers_mask_t), dimension(:), intent(in) :: mask
        type(state_matrix_t), intent(out) :: red_state
        type(state_iterator_t) :: it
        type(quantum_numbers_t), dimension(size(mask)) :: qn
        call state_matrix_init (red_state)
        call state_iterator_init (it, state)
        do while (state_iterator_is_valid (it))
            qn = state_iterator_get_quantum_numbers (it)
            call quantum_numbers_undefine (qn, mask)
            call state_matrix_add_state (red_state, qn)
            call state_iterator_advance (it)
        end do
    end subroutine state_matrix_reduce

```

This subroutine sets up the matrix-element array. The leaf nodes acquire the index values that point to the appropriate matrix-element entry.

We recursively scan the trie. Once we arrive at a leaf node, the index is increased and associated to that node. Finally, we allocate the matrix-element array with the appropriate size.

If matrix element values are temporarily stored within the leaf nodes, we scan the state again and transfer them to the matrix-element array.

```

<State matrices: public>+≡
    public :: state_matrix_freeze

<State matrices: interfaces>≡
    interface state_matrix_freeze
        module procedure state_matrix_freeze1
        module procedure state_matrix_freeze2
    end interface

<State matrices: procedures>+≡
    subroutine state_matrix_freeze1 (state)
        type(state_matrix_t), intent(inout), target :: state
        type(state_iterator_t) :: it
        if (associated (state%root)) then
            if (allocated (state%me)) deallocate (state%me)
            allocate (state%me (state%n_matrix_elements))
        end if
        if (state%leaf_nodes_store_values) then
            call state_iterator_init (it, state)
            do while (state_iterator_is_valid (it))
                state%me(state_iterator_get_me_index (it)) &
                    = state_iterator_get_matrix_element (it)
                call state_iterator_advance (it)
            end do
            state%leaf_nodes_store_values = .false.
        end if
    end subroutine state_matrix_freeze1

    subroutine state_matrix_freeze2 (state)
        type(state_matrix_t), dimension(:), intent(inout), target :: state
        integer :: i
        do i = 1, size (state)
            call state_matrix_freeze1 (state(i))
        end do
    end subroutine state_matrix_freeze2

```

Direct access to the value array

Several methods for setting a value directly are summarized in this generic:

```

<State matrices: public>+≡
    public :: state_matrix_set_matrix_element

<State matrices: interfaces>+≡
    interface state_matrix_set_matrix_element
        module procedure state_matrix_set_matrix_element_qn
        module procedure state_matrix_set_matrix_element_all
    end interface

```

```

        module procedure state_matrix_set_matrix_element_array
        module procedure state_matrix_set_matrix_element_single
    end interface

```

Set a value that corresponds to a quantum number array:

```

<State matrices: procedures>+≡
subroutine state_matrix_set_matrix_element_qn (state, qn, value)
    type(state_matrix_t), intent(inout), target :: state
    type(quantum_numbers_t), dimension(:), intent(in) :: qn
    complex(default), intent(in) :: value
    type(state_iterator_t) :: it
    call state_iterator_init (it, state)
    do while (state_iterator_is_valid (it))
        if (all (qn == state_iterator_get_quantum_numbers (it))) then
            call state_iterator_set_matrix_element (it, value)
            return
        end if
        call state_iterator_advance (it)
    end do
end subroutine state_matrix_set_matrix_element_qn

```

Set all matrix elements to a single value

```

<State matrices: procedures>+≡
subroutine state_matrix_set_matrix_element_all (state, value)
    type(state_matrix_t), intent(inout) :: state
    complex(default), intent(in) :: value
    state%me = value
end subroutine state_matrix_set_matrix_element_all

```

Set the matrix-element array directly.

```

<State matrices: procedures>+≡
subroutine state_matrix_set_matrix_element_array (state, value)
    type(state_matrix_t), intent(inout) :: state
    complex(default), dimension(:), intent(in) :: value
    state%me = value
end subroutine state_matrix_set_matrix_element_array

pure subroutine state_matrix_set_matrix_element_single (state, i, value)
    type(state_matrix_t), intent(inout) :: state
    integer, intent(in) :: i
    complex(default), intent(in) :: value
    state%me(i) = value
end subroutine state_matrix_set_matrix_element_single

```

Add a value to a matrix element

```

<State matrices: public>+≡
public :: state_matrix_add_to_matrix_element

<State matrices: procedures>+≡
subroutine state_matrix_add_to_matrix_element (state, i, value)
    type(state_matrix_t), intent(inout) :: state
    integer, intent(in) :: i
    complex(default), intent(in) :: value

```

```

state%me(i) = state%me(i) + value
end subroutine state_matrix_add_to_matrix_element

```

7.5.3 State iterators

Accessing the quantum state from outside is best done using a specialized iterator, i.e., a pointer to a particular branch of the quantum state trie. Technically, the iterator contains a pointer to a leaf node, but via parent pointers it allows to access the whole branch where the leaf is attached. For quick access, we also keep the branch depth (which is assumed to be universal for a quantum state).

```

<State matrices: public>+≡
public :: state_iterator_t

<State matrices: types>+≡
type :: state_iterator_t
private
integer :: depth = 0
type(state_matrix_t), pointer :: state => null ()
type(node_t), pointer :: node => null ()
end type state_iterator_t

```

The initializer: Point at the first branch. Note that this cannot be pure, thus not be elemental, because the iterator can be used to manipulate data in the state matrix.

```

<State matrices: public>+≡
public :: state_iterator_init

<State matrices: procedures>+≡
subroutine state_iterator_init (it, state)
type(state_iterator_t), intent(out) :: it
type(state_matrix_t), intent(in), target :: state
it%state => state
it%depth = state%depth
if (state_matrix_is_defined (state)) then
it%node => state%root
do while (associated (it%node%child_first))
it%node => it%node%child_first
end do
else
it%node => null ()
end if
end subroutine state_iterator_init

```

Go forward. Recursively programmed: if the next node does not exist, go back to the parent node and look at its successor (if present), etc.

There is a possible pitfall in the implementation: If the dummy pointer argument to the `find_next` routine is used directly, we still get the correct result for the iterator, but calling the recursion on `node%parent` means that we manipulate a parent pointer in the original state in addition to the iterator.

Making a local copy of the pointer avoids this. Using pointer intent would be helpful, but we do not yet rely on this F2003 feature.

```

<State matrices: public>+≡
    public :: state_iterator_advance

<State matrices: procedures>+≡
    subroutine state_iterator_advance (it)
        type(state_iterator_t), intent(inout) :: it
        call find_next (it%node)
    contains
        recursive subroutine find_next (node_in)
            type(node_t), intent(in), target :: node_in
            type(node_t), pointer :: node
            node => node_in
            if (associated (node%next)) then
                node => node%next
                do while (associated (node%child_first))
                    node => node%child_first
                end do
                it%node => node
            else if (associated (node%parent)) then
                call find_next (node%parent)
            else
                it%node => null ()
            end if
        end subroutine find_next
    end subroutine state_iterator_advance

```

If all has been scanned, the iterator is at an undefined state. Check for this:

```

<State matrices: public>+≡
    public :: state_iterator_is_valid

<State matrices: procedures>+≡
    function state_iterator_is_valid (it) result (defined)
        logical :: defined
        type(state_iterator_t), intent(in) :: it
        defined = associated (it%node)
    end function state_iterator_is_valid

```

Return the matrix-element index that corresponds to the current node

```

<State matrices: public>+≡
    public :: state_iterator_get_me_index

<State matrices: procedures>+≡
    function state_iterator_get_me_index (it) result (n)
        integer :: n
        type(state_iterator_t), intent(in) :: it
        n = it%node%me_index
    end function state_iterator_get_me_index

```

Return the number of times this quantum-number state has been added (noting that it is physically inserted only the first time). Note that for each state, there is an array of counters.

```

<State matrices: public>+≡

```

```

public :: state_iterator_get_me_count
<State matrices: procedures>+≡
function state_iterator_get_me_count (it) result (n)
  integer, dimension(:), allocatable :: n
  type(state_iterator_t), intent(in) :: it
  if (allocated (it%node%me_count)) then
    allocate (n (size (it%node%me_count)))
    n = it%node%me_count
  else
    allocate (n (0))
  end if
end function state_iterator_get_me_count

```

Use the iterator to retrieve quantum-number information:

```

<State matrices: public>+≡
public :: state_iterator_get_quantum_numbers
public :: state_iterator_get_flavor
public :: state_iterator_get_color
public :: state_iterator_get_helicity

<State matrices: interfaces>+≡
interface state_iterator_get_quantum_numbers
  module procedure state_iterator_get_qn_multi
  module procedure state_iterator_get_qn_slice
  module procedure state_iterator_get_qn_range
  module procedure state_iterator_get_qn_single
end interface

interface state_iterator_get_flavor
  module procedure state_iterator_get_flv_multi
  module procedure state_iterator_get_flv_slice
  module procedure state_iterator_get_flv_range
  module procedure state_iterator_get_flv_single
end interface

interface state_iterator_get_color
  module procedure state_iterator_get_col_multi
  module procedure state_iterator_get_col_slice
  module procedure state_iterator_get_col_range
  module procedure state_iterator_get_col_single
end interface

interface state_iterator_get_helicity
  module procedure state_iterator_get_hel_multi
  module procedure state_iterator_get_hel_slice
  module procedure state_iterator_get_hel_range
  module procedure state_iterator_get_hel_single
end interface

```

These versions return the whole quantum number array

```

<State matrices: procedures>+≡
function state_iterator_get_qn_multi (it) result (qn)
  type(state_iterator_t), intent(in) :: it

```

```

    type(quantum_numbers_t), dimension(it%depth) :: qn
    type(node_t), pointer :: node
    integer :: i
    node => it%node
    do i = it%depth, 1, -1
        qn(i) = node%qn
        node => node%parent
    end do
end function state_iterator_get_qn_multi

function state_iterator_get_flv_multi (it) result (flv)
    type(state_iterator_t), intent(in) :: it
    type(flavor_t), dimension(it%depth) :: flv
    flv = quantum_numbers_get_flavor &
        (state_iterator_get_quantum_numbers (it))
end function state_iterator_get_flv_multi

function state_iterator_get_col_multi (it) result (col)
    type(state_iterator_t), intent(in) :: it
    type(color_t), dimension(it%depth) :: col
    col = quantum_numbers_get_color &
        (state_iterator_get_quantum_numbers (it))
end function state_iterator_get_col_multi

function state_iterator_get_hel_multi (it) result (hel)
    type(state_iterator_t), intent(in) :: it
    type(helicity_t), dimension(it%depth) :: hel
    hel = quantum_numbers_get_helicity &
        (state_iterator_get_quantum_numbers (it))
end function state_iterator_get_hel_multi

```

An array slice (derived from the above).

(State matrices: procedures)+≡

```

function state_iterator_get_qn_slice (it, index) result (qn)
    type(state_iterator_t), intent(in) :: it
    integer, dimension(:), intent(in) :: index
    type(quantum_numbers_t), dimension(size(index)) :: qn
    type(quantum_numbers_t), dimension(it%depth) :: qn_tmp
    qn_tmp = state_iterator_get_qn_multi (it)
    qn = qn_tmp(index)
end function state_iterator_get_qn_slice

function state_iterator_get_flv_slice (it, index) result (flv)
    type(state_iterator_t), intent(in) :: it
    integer, dimension(:), intent(in) :: index
    type(flavor_t), dimension(size(index)) :: flv
    flv = quantum_numbers_get_flavor &
        (state_iterator_get_quantum_numbers (it, index))
end function state_iterator_get_flv_slice

function state_iterator_get_col_slice (it, index) result (col)
    type(state_iterator_t), intent(in) :: it
    integer, dimension(:), intent(in) :: index
    type(color_t), dimension(size(index)) :: col

```

```

        col = quantum_numbers_get_color &
            (state_iterator_get_quantum_numbers (it, index))
end function state_iterator_get_col_slice

function state_iterator_get_hel_slice (it, index) result (hel)
    type(state_iterator_t), intent(in) :: it
    integer, dimension(:), intent(in) :: index
    type(helicity_t), dimension(size(index)) :: hel
    hel = quantum_numbers_get_helicity &
        (state_iterator_get_quantum_numbers (it, index))
end function state_iterator_get_hel_slice

```

An array range (implemented directly).

(State matrices: procedures)+≡

```

function state_iterator_get_qn_range (it, k1, k2) result (qn)
    type(state_iterator_t), intent(in) :: it
    integer, intent(in) :: k1, k2
    type(quantum_numbers_t), dimension(k2-k1+1) :: qn
    type(node_t), pointer :: node
    integer :: i
    node => it%node
    SCAN: do i = it%depth, 1, -1
        if (k1 <= i .and. i <= k2) then
            qn(i-k1+1) = node%qn
        else
            node => node%parent
        end if
    end do SCAN
end function state_iterator_get_qn_range

function state_iterator_get_flv_range (it, k1, k2) result (flv)
    type(state_iterator_t), intent(in) :: it
    integer, intent(in) :: k1, k2
    type(flavor_t), dimension(k2-k1+1) :: flv
    flv = quantum_numbers_get_flavor &
        (state_iterator_get_quantum_numbers (it, k1, k2))
end function state_iterator_get_flv_range

function state_iterator_get_col_range (it, k1, k2) result (col)
    type(state_iterator_t), intent(in) :: it
    integer, intent(in) :: k1, k2
    type(color_t), dimension(k2-k1+1) :: col
    col = quantum_numbers_get_color &
        (state_iterator_get_quantum_numbers (it, k1, k2))
end function state_iterator_get_col_range

function state_iterator_get_hel_range (it, k1, k2) result (hel)
    type(state_iterator_t), intent(in) :: it
    integer, intent(in) :: k1, k2
    type(helicity_t), dimension(k2-k1+1) :: hel
    hel = quantum_numbers_get_helicity &
        (state_iterator_get_quantum_numbers (it, k1, k2))
end function state_iterator_get_hel_range

```

Just a specific single element

(State matrices: procedures)+≡

```

function state_iterator_get_qn_single (it, k) result (qn)
  type(state_iterator_t), intent(in) :: it
  integer, intent(in) :: k
  type(quantum_numbers_t) :: qn
  type(node_t), pointer :: node
  integer :: i
  node => it%node
  SCAN: do i = it%depth, 1, -1
    if (i == k) then
      qn = node%qn
      exit SCAN
    else
      node => node%parent
    end if
  end do SCAN
end function state_iterator_get_qn_single

function state_iterator_get_flv_single (it, k) result (flv)
  type(state_iterator_t), intent(in) :: it
  integer, intent(in) :: k
  type(flavor_t) :: flv
  flv = quantum_numbers_get_flavor &
    (state_iterator_get_quantum_numbers (it, k))
end function state_iterator_get_flv_single

function state_iterator_get_col_single (it, k) result (col)
  type(state_iterator_t), intent(in) :: it
  integer, intent(in) :: k
  type(color_t) :: col
  col = quantum_numbers_get_color &
    (state_iterator_get_quantum_numbers (it, k))
end function state_iterator_get_col_single

function state_iterator_get_hel_single (it, k) result (hel)
  type(state_iterator_t), intent(in) :: it
  integer, intent(in) :: k
  type(helicity_t) :: hel
  hel = quantum_numbers_get_helicity &
    (state_iterator_get_quantum_numbers (it, k))
end function state_iterator_get_hel_single

```

Retrieve the matrix element value associated with the current node.

(State matrices: public)+≡

public :: state_iterator_get_matrix_element

(State matrices: procedures)+≡

```

function state_iterator_get_matrix_element (it) result (me)
  complex(default) :: me
  type(state_iterator_t), intent(in) :: it
  if (it%state%leaf_nodes_store_values) then
    me = it%node%me
  else if (it%node%me_index /= 0) then

```

```

        me = it%state%me(it%node%me_index)
    else
        me = 0
    end if
end function state_iterator_get_matrix_element

```

Set the matrix element value using the state iterator.

```

<State matrices: public>+≡
    public :: state_iterator_set_matrix_element

<State matrices: procedures>+≡
    subroutine state_iterator_set_matrix_element (it, value)
        type(state_iterator_t), intent(inout) :: it
        complex(default), intent(in) :: value
        if (it%node%me_index /= 0) then
            it%state%me(it%node%me_index) = value
        end if
    end subroutine state_iterator_set_matrix_element

```

7.5.4 Operations on quantum states

Return a deep copy of a state matrix.

```

<State matrices: public>+≡
    public :: assignment(=)

<State matrices: interfaces>+≡
    interface assignment(=)
        module procedure state_matrix_assign
    end interface

<State matrices: procedures>+≡
    subroutine state_matrix_assign (state_out, state_in)
        type(state_matrix_t), intent(out) :: state_out
        type(state_matrix_t), intent(in), target :: state_in
        type(state_iterator_t) :: it
        call state_matrix_init (state_out)
        call state_iterator_init (it, state_in)
        do while (state_iterator_is_valid (it))
            call state_matrix_add_state (state_out, &
                state_iterator_get_quantum_numbers (it), &
                state_iterator_get_me_index (it))
            call state_iterator_advance (it)
        end do
        if (allocated (state_in%me)) then
            allocate (state_out%me (size (state_in%me)))
            state_out%me = state_in%me
        end if
    end subroutine state_matrix_assign

```

Normalize all matrix elements, i.e., multiply by a common factor. Assuming that the factor is nonzero, of course.

```

<State matrices: public>+≡
    public :: state_matrix_renormalize

<State matrices: procedures>+≡
    subroutine state_matrix_renormalize (state, factor)
        type(state_matrix_t), intent(inout) :: state
        complex(default), intent(in) :: factor
        state%me = state%me * factor
    end subroutine state_matrix_renormalize

```

Return the sum of all matrix element values.

```

<State matrices: public>+≡
    public :: state_matrix_sum

<State matrices: procedures>+≡
    function state_matrix_sum (state) result (value)
        complex(default) :: value
        type(state_matrix_t), intent(in) :: state
        value = sum (state%me)
    end function state_matrix_sum

```

Return the trace of a state matrix, i.e., the sum over all diagonal values. If `qn_in` is provided, only branches that match this quantum-numbers array are considered.

```

<State matrices: public>+≡
    public :: state_matrix_trace

<State matrices: procedures>+≡
    function state_matrix_trace (state, qn_in) result (trace)
        complex(default) :: trace
        type(state_matrix_t), intent(in), target :: state
        type(quantum_numbers_t), dimension(:), intent(in), optional :: qn_in
        type(quantum_numbers_t), dimension(:), allocatable :: qn
        type(state_iterator_t) :: it
        allocate (qn (state_matrix_get_depth (state)))
        trace = 0
        call state_iterator_init (it, state)
        do while (state_iterator_is_valid (it))
            qn = state_iterator_get_quantum_numbers (it)
            if (present (qn_in)) then
                if (.not. all (qn .match. qn_in)) then
                    call state_iterator_advance (it); cycle
                end if
            end if
            if (all (quantum_numbers_are_diagonal (qn))) then
                trace = trace + state_iterator_get_matrix_element (it)
            end if
            call state_iterator_advance (it)
        end do
    end function state_matrix_trace

```

Append new states which are color-contracted versions of the existing states. The matrix element index of each color contraction coincides with the index of its origin, so no new matrix elements are generated. After this operation, no `freeze` must be performed anymore.

```

<State matrices: public>+≡
    public :: state_matrix_add_color_contractions

<State matrices: procedures>+≡
    subroutine state_matrix_add_color_contractions (state)
        type(state_matrix_t), intent(inout), target :: state
        type(state_iterator_t) :: it
        type(quantum_numbers_t), dimension(:,:), allocatable :: qn
        type(quantum_numbers_t), dimension(:,:), allocatable :: qn_con
        integer, dimension(:), allocatable :: me_index
        integer :: depth, n_me, i, j
        depth = state_matrix_get_depth (state)
        n_me = state_matrix_get_n_matrix_elements (state)
        allocate (qn (depth, n_me))
        allocate (me_index (n_me))
        i = 0
        call state_iterator_init (it, state)
        do while (state_iterator_is_valid (it))
            i = i + 1
            qn(:,i) = state_iterator_get_quantum_numbers (it)
            me_index(i) = state_iterator_get_me_index (it)
            call state_iterator_advance (it)
        end do
        do i = 1, n_me
            call quantum_number_array_make_color_contractions (qn(:,i), qn_con)
            do j = 1, size (qn_con, 2)
                call state_matrix_add_state (state, qn_con(:,j), index = me_index(i))
            end do
        end do
    end subroutine state_matrix_add_color_contractions

```

This procedure merges two state matrices of equal depth. For each quantum number (flavor, color, helicity), we take the entry from the first argument where defined, otherwise the second one. (If both are defined, we get an off-diagonal matrix.) The resulting trie combines the information of the input tries in all possible ways. Note that values are ignored, all values in the result are zero.

```

<State matrices: public>+≡
    public :: merge_state_matrices

<State matrices: procedures>+≡
    subroutine merge_state_matrices (state1, state2, state3)
        type(state_matrix_t), intent(in), target :: state1, state2
        type(state_matrix_t), intent(out) :: state3
        type(state_iterator_t) :: it1, it2
        type(quantum_numbers_t), dimension(state1%depth) :: qn1, qn2
        if (state1%depth /= state2%depth) then
            call state_matrix_write (state1)
            call state_matrix_write (state2)
            call msg_bug ("State matrices merge impossible: incompatible depths")
        end if
    end subroutine

```

```

call state_matrix_init (state3)
call state_iterator_init (it1, state1)
do while (state_iterator_is_valid (it1))
  qn1 = state_iterator_get_quantum_numbers (it1)
  call state_iterator_init (it2, state2)
  do while (state_iterator_is_valid (it2))
    qn2 = state_iterator_get_quantum_numbers (it2)
    call state_matrix_add_state &
      (state3, qn1 .merge. qn2)
    call state_iterator_advance (it2)
  end do
  call state_iterator_advance (it1)
end do
call state_matrix_freeze (state3)
end subroutine merge_state_matrices

```

Multiply matrix elements from two state matrices. Choose the elements as given by the integer index arrays, multiply them and store the sum of products in the indicated matrix element. The suffixes mean: c=conjugate first factor; f=include weighting factor.

Note that the `dot_product` intrinsic function conjugates its first complex argument. This is intended for the c suffix case, but must be reverted for the plain-product case.

(State matrices: public)+≡

```

public :: state_matrix_evaluate_product
public :: state_matrix_evaluate_product_cf
public :: state_matrix_evaluate_square_c
public :: state_matrix_evaluate_sum

```

(State matrices: procedures)+≡

```

pure subroutine state_matrix_evaluate_product &
  (state, i, state1, state2, index1, index2)
  type(state_matrix_t), intent(inout) :: state
  integer, intent(in) :: i
  type(state_matrix_t), intent(in) :: state1, state2
  integer, dimension(:), intent(in) :: index1, index2
  state%me(i) = &
    dot_product (conjg (state1%me(index1)), state2%me(index2))
end subroutine state_matrix_evaluate_product

```

```

pure subroutine state_matrix_evaluate_product_cf &
  (state, i, state1, state2, index1, index2, factor)
  type(state_matrix_t), intent(inout) :: state
  integer, intent(in) :: i
  type(state_matrix_t), intent(in) :: state1, state2
  integer, dimension(:), intent(in) :: index1, index2
  complex(default), dimension(:), intent(in) :: factor
  state%me(i) = &
    dot_product (state1%me(index1), factor * state2%me(index2))
end subroutine state_matrix_evaluate_product_cf

```

```

pure subroutine state_matrix_evaluate_square_c (state, i, state1, index1)
  type(state_matrix_t), intent(inout) :: state

```

```

integer, intent(in) :: i
type(state_matrix_t), intent(in) :: state1
integer, dimension(:), intent(in) :: index1
state%me(i) = &
    dot_product (state1%me(index1), state1%me(index1))
end subroutine state_matrix_evaluate_square_c

pure subroutine state_matrix_evaluate_sum (state, i, state1, index1)
type(state_matrix_t), intent(inout) :: state
integer, intent(in) :: i
type(state_matrix_t), intent(in) :: state1
integer, dimension(:), intent(in) :: index1
state%me(i) = &
    sum (state1%me(index1))
end subroutine state_matrix_evaluate_sum

```

Outer product (of states and matrix elements):

```

<State matrices: public>+≡
public :: outer_multiply

<State matrices: interfaces>+≡
interface outer_multiply
module procedure outer_multiply_pair
module procedure outer_multiply_array
end interface

```

This procedure constructs the outer product of two state matrices.

```

<State matrices: procedures>+≡
subroutine outer_multiply_pair (state1, state2, state3)
type(state_matrix_t), intent(in), target :: state1, state2
type(state_matrix_t), intent(out) :: state3
type(state_iterator_t) :: it1, it2
type(quantum_numbers_t), dimension(state1%depth) :: qn1
type(quantum_numbers_t), dimension(state2%depth) :: qn2
type(quantum_numbers_t), dimension(state1%depth+state2%depth) :: qn3
complex(default) :: val1, val2
call state_matrix_init (state3, store_values=.true.)
call state_iterator_init (it1, state1)
do while (state_iterator_is_valid (it1))
    qn1 = state_iterator_get_quantum_numbers (it1)
    val1 = state_iterator_get_matrix_element (it1)
    call state_iterator_init (it2, state2)
    do while (state_iterator_is_valid (it2))
        qn2 = state_iterator_get_quantum_numbers (it2)
        val2 = state_iterator_get_matrix_element (it2)
        qn3(:state1%depth) = qn1
        qn3(state1%depth+1:) = qn2
        call state_matrix_add_state (state3, qn3, value=val1 * val2)
        call state_iterator_advance (it2)
    end do
    call state_iterator_advance (it1)
end do
call state_matrix_freeze (state3)

```

```
end subroutine outer_multiply_pair
```

This executes the above routine iteratively for an arbitrary number of state matrices.

(State matrices: procedures)+≡

```
subroutine outer_multiply_array (state_in, state_out)
  type(state_matrix_t), dimension(:), intent(in), target :: state_in
  type(state_matrix_t), intent(out) :: state_out
  type(state_matrix_t), dimension(:), allocatable, target :: state_tmp
  integer :: i, n
  n = size (state_in)
  select case (n)
  case (0)
    call state_matrix_init (state_out)
  case (1)
    state_out = state_in(1)
  case (2)
    call outer_multiply_pair (state_in(1), state_in(2), state_out)
  case default
    allocate (state_tmp (n-2))
    call outer_multiply_pair (state_in(1), state_in(2), state_tmp(1))
    do i = 2, n - 2
      call outer_multiply_pair (state_tmp(i-1), state_in(i+1), state_tmp(i))
    end do
    call outer_multiply_pair (state_tmp(n-2), state_in(n), state_out)
    call state_matrix_final (state_tmp)
  end select
end subroutine outer_multiply_array
```

7.5.5 Factorization

In physical events, the state matrix is factorized into single-particle state matrices. This is essentially a measurement.

In a simulation, we select one particular branch of the state matrix with a probability that is determined by the matrix elements at the leaves. (This makes sense only if the state matrix represents a squared amplitude.) The selection is based on a (random) value x between 0 and one that is provided as the third argument.

For flavor and color, we select a unique value for each particle. For polarization, we have three options (modes). Option 1 is to drop helicity information altogether and sum over all diagonal helicities. Option 2 is to select a unique diagonal helicity in the same way as flavor and color. Option 3 is, for each particle, to trace over all remaining helicities in order to obtain an array of independent single-particle helicity matrices.

Only branches that match the given quantum-number array `qn_in`, if present, are considered. For this array, color is ignored.

If the optional `correlated_state` is provided, it is assigned the correlated density matrix for the selected flavor-color branch, so multi-particle spin correlations remain available even if they are dropped in the single-particle density matrices.

The algorithm is as follows: First, we determine the normalization by summing over all diagonal matrix elements. In a second scan, we select one of the diagonal matrix elements by a cumulative comparison with the normalized random number. In the corresponding quantum number array, we undefine the helicity entries. Then, we scan the third time. For each branch that matches the selected quantum number array (i.e., definite flavor and color, arbitrary helicity), we determine its contribution to any of the single-particle state matrices. The matrix-element value is added if all other quantum numbers are diagonal, while the helicity of the chosen particle may be arbitrary; this helicity determines the branch in the single-particle state.

As a result, flavor and color quantum numbers are selected with the correct probability. Within this subset of states, each single-particle state matrix results from tracing over all other particles. Note that the single-particle state matrices are not normalized.

```

<State matrices: parameters>≡
  integer, parameter, public :: FM_IGNORE_HELICITY = 1
  integer, parameter, public :: FM_SELECT_HELICITY = 2
  integer, parameter, public :: FM_FACTOR_HELICITY = 3

<State matrices: public>+≡
  public :: state_matrix_factorize

<State matrices: procedures>+≡
  subroutine state_matrix_factorize &
    (state, mode, x, single_state, correlated_state, qn_in)
    type(state_matrix_t), intent(in), target :: state
    integer, intent(in) :: mode
    real(default), intent(in) :: x
    type(state_matrix_t), &
      dimension(:), allocatable, intent(out) :: single_state
    type(state_matrix_t), intent(out), optional :: correlated_state
    type(quantum_numbers_t), dimension(:), intent(in), optional :: qn_in
    type(state_iterator_t) :: it
    real(default) :: s, xt
    complex(default) :: value
    integer :: i, depth
    type(quantum_numbers_t), dimension(:), allocatable :: qn, qn1
    type(quantum_numbers_mask_t), dimension(:), allocatable :: qn_mask
    logical, dimension(:), allocatable :: diagonal
    logical, dimension(:,:), allocatable :: mask
    if (x /= 0) then
      xt = x * state_matrix_trace (state, qn_in)
    else
      xt = 0
    end if
    s = 0
    depth = state_matrix_get_depth (state)
    allocate (qn (depth), qn1 (depth), diagonal (depth))
    call state_iterator_init (it, state)
    do while (state_iterator_is_valid (it))
      qn = state_iterator_get_quantum_numbers (it)
      if (present (qn_in)) then
        if (.not. all (qn .fmatch. qn_in)) then

```

```

        call state_iterator_advance (it); cycle
    end if
end if
if (all (quantum_numbers_are_diagonal (qn))) then
    value = state_iterator_get_matrix_element (it)
    if (real (value, default) < 0) then
        print *, value
        call msg_bug ("Event generation: " &
            // "Negative real part of matrix element value")
        value = 0
    end if
    s = s + value
    if (s > xt) exit
end if
call state_iterator_advance (it)
end do
if (.not. state_iterator_is_valid (it)) then
    if (s == 0) then
        call state_matrix_write (state)
        call msg_bug ("Event factorization called for zero matrix element")
    else
        call state_iterator_init (it, state)
    end if
end if
allocate (single_state (depth))
call state_matrix_init (single_state, store_values=.true.)
if (present (correlated_state)) &
    call state_matrix_init (correlated_state, store_values=.true.)
qn = state_iterator_get_quantum_numbers (it)
select case (mode)
case (FM_SELECT_HELICITY) ! single branch selected; shortcut
    do i = 1, depth
        call state_matrix_add_state (single_state(i), &
            (/qn(i)/), value=value)
    end do
    if (.not. present (correlated_state)) then
        call state_matrix_freeze (single_state)
        return
    end if
end select
allocate (qn_mask (depth))
call quantum_numbers_mask_init (qn_mask, .false., .false., .false., .true.)
call quantum_numbers_undefine (qn, qn_mask)
select case (mode)
case (FM_FACTOR_HELICITY)
    allocate (mask (depth, depth))
    mask = .false.
    forall (i = 1:depth) mask(i,i) = .true.
end select
call state_iterator_init (it, state)
do while (state_iterator_is_valid (it))
    qn1 = state_iterator_get_quantum_numbers (it)
    if (all (qn .match. qn1)) then
        diagonal = quantum_numbers_are_diagonal (qn1)
    end if
end do

```

```

value = state_iterator_get_matrix_element (it)
select case (mode)
case (FM_IGNORE_HELICITY) ! trace over diagonal states that match qn
  if (all (diagonal)) then
    do i = 1, depth
      call state_matrix_add_state (single_state(i), &
        (/qn(i)/), value=value, sum_values=.true.)
    end do
  end if
case (FM_FACTOR_HELICITY) ! trace over all other particles
  do i = 1, depth
    if (all (diagonal .or. mask(:,i))) then
      call state_matrix_add_state (single_state(i), &
        (/qn1(i)/), value=value, sum_values=.true.)
    end if
  end do
end select
if (present (correlated_state)) &
  call state_matrix_add_state (correlated_state, qn1, value=value)
end if
call state_iterator_advance (it)
end do
call state_matrix_freeze (single_state)
if (present (correlated_state)) &
  call state_matrix_freeze (correlated_state)
end subroutine state_matrix_factorize

```

7.5.6 Test

```

<State matrices: public>+≡
  public :: state_matrix_test

<State matrices: procedures>+≡
  subroutine state_matrix_test ()
  !   print *, "State matrix test 1"
  !   call state_matrix_test1 ()
  !   print *
  !   print *, "State matrix test 2"
  !   call state_matrix_test2 ()
  print *
  print *, "State matrix test 3"
  call state_matrix_test3 ()
  end subroutine state_matrix_test

```

Create two quantum states of equal depth and merge them.

```

<State matrices: procedures>+≡
  subroutine state_matrix_test1 ()
  type(state_matrix_t) :: state1, state2, state3
  type(flavor_t), dimension(3) :: flv
  type(color_t), dimension(3) :: col
  type(helicity_t), dimension(3) :: hel
  type(quantum_numbers_t), dimension(3) :: qn

```

```

call state_matrix_init (state1)
call flavor_init (flv, (/ 1, 2, 11 /))
call helicity_init (hel, (/ 1, 1, 1 /))
call quantum_numbers_init (qn, flv, hel)
call state_matrix_add_state (state1, qn)
call helicity_init (hel, (/ 1, 1, 1 /), (/ -1, 1, -1/))
call quantum_numbers_init (qn, flv, hel)
call state_matrix_add_state (state1, qn)
call state_matrix_freeze (state1)
call state_matrix_write (state1)
print *
call state_matrix_init (state2)
call color_init (col(1), (/ 501 /))
call color_init (col(2), (/ -501 /))
call color_init (col(3), (/ 0 /))
call helicity_init (hel, (/ -1, -1, 0 /))
call quantum_numbers_init (qn, col, hel)
call state_matrix_add_state (state2, qn)
call color_init (col(3), (/ 99 /))
call helicity_init (hel, (/ -1, -1, 0 /))
call quantum_numbers_init (qn, col, hel)
call state_matrix_add_state (state2, qn)
call state_matrix_freeze (state2)
call state_matrix_write (state2)
print *
call merge_state_matrices (state1, state2, state3)
call state_matrix_write (state3)
print *
call state_matrix_collapse (state3, &
    new_quantum_numbers_mask (.false., .false., &
        (/ .true., .false., .false. /)))
call state_matrix_write (state3)
call state_matrix_final (state1)
call state_matrix_final (state2)
call state_matrix_final (state3)
end subroutine state_matrix_test1

```

Create a correlated three-particle state matrix and factorize it.

<State matrices: procedures>+≡

```

subroutine state_matrix_test2
  type(state_matrix_t) :: state
  type(state_matrix_t), dimension(:), allocatable :: single_state
  type(state_matrix_t) :: correlated_state
  complex(default) :: u, val
  complex(default), dimension(-1:1) :: v
  integer :: f, h11, h12, h21, h22, i, mode
  type(flavor_t), dimension(2) :: flv
  type(color_t), dimension(2) :: col
  type(helicity_t), dimension(2) :: hel
  type(quantum_numbers_t), dimension(2) :: qn
  u = 1 / 2._default
  v(-1) = (0.6_default, 0._default)
  v( 1) = (0._default, 0.8_default)
  call state_matrix_init (state)

```

```

do f = 1, 2
  do h11 = -1, 1, 2
    do h12 = -1, 1, 2
      do h21 = -1, 1, 2
        do h22 = -1, 1, 2
          call flavor_init (flv, (/f, -f/))
          call color_init (col(1), (/ 1/))
          call color_init (col(2), (/ -1/))
          call helicity_init (hel, (/h11,h12/), (/h21, h22/))
          call quantum_numbers_init (qn, flv, col, hel)
          val = u * v(h11) * v(h12) * conjg (v(h21) * v(h22))
          call state_matrix_add_state (state, qn)
        end do
      end do
    end do
  end do
end do
call state_matrix_freeze (state)
call state_matrix_write (state)
print *, "trace = ", state_matrix_trace (state)
do mode = 1, 3
  print *
  print *, "Mode = ", mode
  call state_matrix_factorize &
    (state, mode, 0.15_default, single_state, correlated_state)
  do i = 1, size (single_state)
    print *
    call state_matrix_write (single_state(i))
    print *, "trace = ", state_matrix_trace (single_state(i))
  end do
  print *
  call state_matrix_write (correlated_state)
  print *, "trace = ", state_matrix_trace (correlated_state)
  call state_matrix_final (single_state)
  call state_matrix_final (correlated_state)
end do
call state_matrix_final (state)
end subroutine state_matrix_test2

```

Create a colored state matrix and add color contractions.

(State matrices: procedures)+≡

```

subroutine state_matrix_test3
  type(state_matrix_t) :: state
  type(flavor_t), dimension(4) :: flv
  type(color_t), dimension(4) :: col
  type(quantum_numbers_t), dimension(4) :: qn
  call state_matrix_init (state)
  call flavor_init (flv, &
    (/ 1, -HADRON_REMNANT_TRIPLET, -1, HADRON_REMNANT_TRIPLET /))
  call color_init (col(1), (/17/))
  call color_init (col(2), (/ -17/))
  call color_init (col(3), (/ -19/))
  call color_init (col(4), (/19/))
  call quantum_numbers_init (qn, flv=flv, col=col)

```

```

call state_matrix_add_state (state, qn)
call flavor_init (flv, &
  (/ 1, -HADRON_REMNANT_TRIPLET, 21, HADRON_REMNANT_OCTET /))
call color_init (col(1), (/17/))
call color_init (col(2), (/ -17/))
call color_init (col(3), (/3, -5/))
call color_init (col(4), (/5, -3/))
call quantum_numbers_init (qn, flv=flv, col=col)
call state_matrix_add_state (state, qn)
call state_matrix_freeze (state)
print *, "State:"
call state_matrix_write (state)
call state_matrix_add_color_contractions (state)
print *, "State with contractions:"
call state_matrix_write (state)
call state_matrix_final (state)
end subroutine state_matrix_test3

```

7.6 Interactions

This module defines the `interaction_t` type. It is an extension of the `state_matrix_t` type.

The state matrix is a representation of a multi-particle density matrix. It implements all possible flavor, color, and quantum-number assignments of the entries in a generic density matrix, and it can hold a complex matrix element for each entry. (Note that this matrix can hold non-diagonal entries in color and helicity space.) The `interaction_t` object associates this with a list of momenta, such that the whole object represents a multi-particle state.

The `interaction_t` holds information about which particles are incoming, virtual (i.e., kept for the records), or outgoing. Each particle can be associated to a source within another interaction. This allows us to automatically fill those interaction momenta which have been computed or defined elsewhere. It also contains internal parent-child relations and flags for (virtual) particles which are to be treated as resonances.

A quantum-number mask array summarizes, for each particle within the interaction, the treatment of flavor, color, or helicity (expose or ignore). A list of locks states which particles are bound to have an identical quantum-number mask. This is useful when the mask is changed at one place.

```

<interactions.f90>≡
  <File header>

```

```

module interactions

```

```

  <Use kinds>

```

```

  <Use file utils>

```

```

  use diagnostics !NODEP!

```

```

  use lorentz !NODEP!

```

```

  use prt_lists

```

```

  use expressions

```

```

  use flavors

```

```

    use colors
    use helicities
    use quantum_numbers
    use state_matrices

    <Standard module head>

    <Interactions: public>

    <Interactions: types>

    <Interactions: interfaces>

contains

    <Interactions: procedures>

end module interactions

```

7.6.1 External interaction links

Each particle in an interaction can have a link to a corresponding particle in another interaction. This allows to fetch the momenta of incoming or virtual particles from the interaction where they are defined. The link object consists of a pointer to the interaction and an index.

```

<Interactions: types>≡
    type :: external_link_t
    private
        type(interaction_t), pointer :: int => null ()
        integer :: i
    end type external_link_t

```

Set an external link.

```

<Interactions: procedures>≡
    subroutine external_link_set (link, int, i)
        type(external_link_t), intent(out) :: link
        type(interaction_t), target, intent(in) :: int
        integer, intent(in) :: i
        if (i /= 0) then
            link%int => int
            link%i = i
        end if
    end subroutine external_link_set

```

Reassign an external link to a new interaction (which should be an image of the original target).

```

<Interactions: procedures>+≡
    subroutine external_link_reassign (link, int_src, int_target)
        type(external_link_t), intent(inout) :: link
        type(interaction_t), intent(in) :: int_src
        type(interaction_t), intent(in), target :: int_target
        if (associated (link%int)) then

```

```

        if (link%int%tag == int_src%tag) link%int => int_target
    end if
end subroutine external_link_reassign

```

Return true if the link is set

```

<Interactions: procedures>+≡
function external_link_is_set (link) result (flag)
    logical :: flag
    type(external_link_t), intent(in) :: link
    flag = associated (link%int)
end function external_link_is_set

```

Return the interaction pointer.

```

<Interactions: procedures>+≡
function external_link_get_ptr (link) result (int)
    type(interaction_t), pointer :: int
    type(external_link_t), intent(in) :: link
    int => link%int
end function external_link_get_ptr

```

Return the index within that interaction

```

<Interactions: procedures>+≡
function external_link_get_index (link) result (i)
    integer :: i
    type(external_link_t), intent(in) :: link
    i = link%i
end function external_link_get_index

```

Return a pointer to the momentum of the corresponding particle. If there is no association, return a null pointer.

```

<Interactions: procedures>+≡
function external_link_get_momentum_ptr (link) result (p)
    type(vector4_t), pointer :: p
    type(external_link_t), intent(in) :: link
    if (associated (link%int)) then
        p => link%int%p(link%i)
    else
        p => null ()
    end if
end function external_link_get_momentum_ptr

```

7.6.2 Internal relations

In addition to the external links, particles within the interaction have parent-child relations. Here, more than one link is possible, and we set up a list.

```

<Interactions: types>+≡
type :: internal_link_t
private
integer :: i
type(internal_link_t), pointer :: next => null ()

```

```

end type internal_link_t

type :: internal_link_list_t
  private
  integer :: length = 0
  type(internal_link_t), pointer :: first => null ()
  type(internal_link_t), pointer :: last => null ()
end type internal_link_list_t

```

Add an internal link.

```

<Interactions: procedures>+=
  subroutine internal_link_list_append (link_list, i)
    type(internal_link_list_t), intent(inout) :: link_list
    integer, intent(in) :: i
    type(internal_link_t), pointer :: current
    allocate (current)
    current%i = i
    if (associated (link_list%first)) then
      link_list%last%next => current
    else
      link_list%first => current
    end if
    link_list%last => current
    link_list%length = link_list%length + 1
  end subroutine internal_link_list_append

```

Finalize the list of internal links.

```

<Interactions: procedures>+=
  subroutine internal_link_list_final (link_list)
    type(internal_link_list_t), intent(inout) :: link_list
    type(internal_link_t), pointer :: current
    do while (associated (link_list%first))
      current => link_list%first
      link_list%first => current%next
      deallocate (current)
    end do
    link_list%last => null ()
    link_list%length = 0
  end subroutine internal_link_list_final

```

We need a deep copy of this list when we assign interaction objects.

```

<Interactions: interfaces>=
  interface assignment(=)
    module procedure internal_link_list_assign
  end interface

<Interactions: procedures>+=
  subroutine internal_link_list_assign (link_list_out, link_list_in)
    type(internal_link_list_t), intent(in) :: link_list_in
    type(internal_link_list_t), intent(out) :: link_list_out
    type(internal_link_t), pointer :: current, copy
    current => link_list_in%first

```

```

do while (associated (current))
  allocate (copy)
  copy%i = current%i
  if (associated (link_list_out%first)) then
    link_list_out%last%next => copy
  else
    link_list_out%first => copy
  end if
  link_list_out%last => copy
  current => current%next
end do
end subroutine internal_link_list_assign

```

Return true if the link list is nonempty:

```

<Interactions: procedures>+≡
function internal_link_list_has_entries (link_list) result (flag)
  logical :: flag
  type(internal_link_list_t), intent(in) :: link_list
  flag = associated (link_list%first)
end function internal_link_list_has_entries

```

Return a pointer to the first entry:

```

<Interactions: procedures>+≡
function internal_link_list_get_first_ptr (link_list) result (link)
  type(internal_link_list_t), intent(in) :: link_list
  type(internal_link_t), pointer :: link
  link => link_list%first
end function internal_link_list_get_first_ptr

```

Advance this pointer.

```

<Interactions: procedures>+≡
subroutine internal_link_advance (link)
  type(internal_link_t), pointer :: link
  link => link%next
end subroutine internal_link_advance

```

Return the index.

```

<Interactions: procedures>+≡
function internal_link_get_index (link) result (i)
  integer :: i
  type(internal_link_t), intent(in) :: link
  i = link%i
end function internal_link_get_index

```

Return the list length

```

<Interactions: procedures>+≡
function internal_link_list_get_length (link_list) result (length)
  integer :: length
  type(internal_link_list_t), intent(in) :: link_list
  length = link_list%length
end function internal_link_list_get_length

```

7.6.3 The interaction type

An interaction is an entangled system of particles. Thus, the interaction object consists of two parts: the particle list, and the quantum state which technically is a trie. The subnode levels beyond the trie root node are in correspondence to the particle list, so both should be traversed in parallel.

The particle list is implemented as an allocatable array of four-momenta. The first `n_in` particles are incoming, `n_vir` particles in-between can be kept for bookkeeping, and the last `n_out` particles are outgoing.

Distinct interactions are linked by their particles: for each particle, we have the possibility of links to corresponding particles in other interactions. Furthermore, for bookkeeping purposes we have a self-link array `relations` where the parent-child relations are kept, and a flag array `resonant` which is set for an intermediate resonance.

Each momentum is associated with masks for flavor, color, and helicity. If a mask entry is set, the associated quantum number is to be ignored for that particle. If any mask has changed, the flag `update` is set.

We can have particle pairs locked together. If this is the case, the corresponding mask entries are bound to be equal. This is useful for particles that go through the interaction.

The interaction tag serves bookkeeping purposes. In particular, it identifies links in printout.

```

<Interactions: public>≡
    public :: interaction_t

<Interactions: types>+≡
    type :: interaction_t
        private
            integer :: tag = 0
            type(state_matrix_t) :: state_matrix
            integer :: n_in = 0
            integer :: n_vir = 0
            integer :: n_out = 0
            integer :: n_tot = 0
            type(vector4_t), allocatable :: p
            type(external_link_t), allocatable :: source
            type(internal_link_list_t), allocatable :: parents
            type(internal_link_list_t), allocatable :: children
            logical, allocatable :: resonant
            type(quantum_numbers_mask_t), allocatable :: mask
            integer, allocatable :: lock
            logical :: update_state_matrix = .false.
            logical :: update_values = .false.
        end type interaction_t

```

Initialize the particle array with a fixed size. The first `n_in` particles are incoming, the rest outgoing. Masks are optional. There is also an optional tag. The interaction still needs fixing the values, but that is to be done after all branches have been added.

Interaction tags are assigned consecutively, using a `saved` variable local to this procedure. If desired, we can provide a seed for the interaction tags. Such

a seed should be positive. The default seed is one. `tag=0` indicates an empty interaction.

If `set_relations` is set and true, we establish parent-child relations for all incoming and outgoing particles. Virtual particles are skipped; this option is normally used only for interactions without virtual particles.

```

<Interactions: public>+≡
    public :: interaction_init

<Interactions: procedures>+≡
    subroutine interaction_init &
        (int, n_in, n_vir, n_out, &
         tag, resonant, mask, lock, set_relations, store_values)
        type(interaction_t), intent(out) :: int
        integer, intent(in) :: n_in, n_vir, n_out
        integer, intent(in), optional :: tag
        logical, dimension(:), intent(in), optional :: resonant
        type(quantum_numbers_mask_t), dimension(:), intent(in), optional :: mask
        integer, dimension(:), intent(in), optional :: lock
        logical, intent(in), optional :: set_relations, store_values
        logical :: set_rel
        integer :: i, j
        set_rel = .false.; if (present (set_relations)) set_rel = set_relations
        call interaction_set_tag (int, tag)
        call state_matrix_init (int%state_matrix, store_values)
        int%n_in = n_in
        int%n_vir = n_vir
        int%n_out = n_out
        int%n_tot = n_in + n_vir + n_out
        allocate (int%p (int%n_tot))
        allocate (int%source (int%n_tot))
        allocate (int%parents (int%n_tot))
        allocate (int%children (int%n_tot))
        allocate (int%resonant (int%n_tot))
        if (present (resonant)) then
            int%resonant = resonant
        else
            int%resonant = .false.
        end if
        allocate (int%mask (int%n_tot))
        allocate (int%lock (int%n_tot))
        if (present (mask)) then
            int%mask = mask
        end if
        if (present (lock)) then
            int%lock = lock
        else
            int%lock = 0
        end if
        int%update_state_matrix = .false.
        int%update_values = .true.
        if (set_rel) then
            do i = 1, n_in
                do j = 1, n_out
                    call interaction_relate (int, i, n_in + j)
                end do
            end do
        end if
    end subroutine

```

```

        end do
    end do
end if
end subroutine interaction_init

```

Set or create a unique tag for the interaction.

```

<Interactions: procedures>+≡
subroutine interaction_set_tag (int, tag)
    type(interaction_t), intent(inout) :: int
    integer, intent(in), optional :: tag
    integer, save :: stored_tag = 1
    if (present (tag)) then
        int%tag = tag
    else
        int%tag = stored_tag
        stored_tag = stored_tag + 1
    end if
end subroutine interaction_set_tag

```

Finalizer: The state-matrix object contains pointers.

```

<Interactions: public>+≡
    public :: interaction_final

<Interactions: procedures>+≡
    elemental subroutine interaction_final (int)
        type(interaction_t), intent(inout) :: int
        call state_matrix_final (int%state_matrix)
    end subroutine interaction_final

```

Output. The `verbose` option refers to the state matrix output.

```

<Interactions: public>+≡
    public :: interaction_write

<Interactions: procedures>+≡
subroutine interaction_write &
    (int, unit, verbose, show_momentum_sum, show_mass)
    type(interaction_t), intent(in) :: int
    integer, intent(in), optional :: unit
    logical, intent(in), optional :: verbose, show_momentum_sum, show_mass
    integer :: u
    integer :: i, index_link
    type(internal_link_t), pointer :: link
    type(interaction_t), pointer :: int_link
    u = output_unit (unit); if (u < 0) return
    if (int%tag /= 0) then
        write (u, *) "Interaction:", int%tag
        do i = 1, int%n_tot
            if (i == 1 .and. int%n_in > 0) then
                write (u, *) "Incoming:"
            else if (i == int%n_in + 1 .and. int%n_vir > 0) then
                write (u, *) "Virtual:"
            else if (i == int%n_in + int%n_vir + 1 .and. int%n_out > 0) then
                write (u, *) "Outgoing:"
            end if
        end do
    end if
end subroutine interaction_write

```

```

end if
write (u, "(1x,A,1x,I0)", advance="no") "Particle", i
if (allocated (int%resonant)) then
  if (int%resonant(i)) then
    write (u, *) "[r]"
  else
    write (u, *)
  end if
else
  write (u, *)
end if
if (allocated (int%p)) then
  call vector4_write (int%p(i), u, show_mass)
else
  write (u, *) "[momentum not allocated]"
end if
if (allocated (int%mask)) then
  write (u, "(1x,A)", advance="no") "mask [fch] = "
  call quantum_numbers_mask_write (int%mask(i), u)
  write (u, *)
end if
if (internal_link_list_has_entries (int%parents(i)) &
    .or. internal_link_list_has_entries (int%children(i))) then
  write (u, "(1x,A)", advance="no") "internal links:"
  link => internal_link_list_get_first_ptr (int%parents(i))
  do while (associated (link))
    write (u, "(1x,I0)", advance="no") &
      internal_link_get_index (link)
    call internal_link_advance (link)
  end do
  if (internal_link_list_has_entries (int%parents(i))) &
    write (u, "(1x,A)", advance="no") "=>"
  write (u, "(1x,A)", advance="no") "X"
  if (internal_link_list_has_entries (int%children(i))) &
    write (u, "(1x,A)", advance="no") "=>"
  link => internal_link_list_get_first_ptr (int%children(i))
  do while (associated (link))
    write (u, "(1x,I0)", advance="no") &
      internal_link_get_index (link)
    call internal_link_advance (link)
  end do
  write (u, *)
end if
if (allocated (int%lock)) then
  if (int%lock(i) /= 0) then
    write (u, "(1x,A,1x,I0)") "lock:", int%lock(i)
  end if
end if
if (external_link_is_set (int%source(i))) then
  write (u, "(1x,A)", advance="no") "source:"
  int_link => external_link_get_ptr (int%source(i))
  index_link = external_link_get_index (int%source(i))
  write (u, "(1x,'(,I0,)',I0)", advance="no") &
    int_link%tag, index_link

```

```

        write (u, *)
    end if
end do
if (present (show_momentum_sum)) then
    if (allocated (int%p) .and. show_momentum_sum) then
        write (u, *) "Incoming particles (sum):"
        call vector4_write &
            (sum (int%p(1:int%n_in)), u, show_mass)
        write (u, *) "Outgoing particles (sum):"
        call vector4_write &
            (sum (int%p(int%n_in+int%n_vir+1:)), u, show_mass)
        write (u, *)
    end if
end if
write (u, *) "Density matrix entries:"
call state_matrix_write (int%state_matrix, &
    write_value_list=verbose, verbose=verbose, unit=unit)
else
    write (u, *) "Interaction: [empty]"
end if
end subroutine interaction_write

```

Assignment: We implement this as a deep copy. This applies, in particular, to the state-matrix and internal-link components. Furthermore, the new interaction acquires a new tag.

```

<Interactions: public>+≡
    public :: assignment(=)

<Interactions: interfaces>+≡
    interface assignment(=)
        module procedure interaction_assign
    end interface

<Interactions: procedures>+≡
    subroutine interaction_assign (int_out, int_in)
        type(interaction_t), intent(out) :: int_out
        type(interaction_t), intent(in), target :: int_in
        call interaction_set_tag (int_out)
        int_out%state_matrix = int_in%state_matrix
        int_out%n_in = int_in%n_in
        int_out%n_out = int_in%n_out
        int_out%n_vir = int_in%n_vir
        int_out%n_tot = int_in%n_tot
        if (allocated (int_in%p)) then
            allocate (int_out%p (size (int_in%p)))
            int_out%p = int_in%p
        end if
        if (allocated (int_in%source)) then
            allocate (int_out%source (size (int_in%source)))
            int_out%source = int_in%source
        end if
        if (allocated (int_in%parents)) then
            allocate (int_out%parents (size (int_in%parents)))

```

```

        int_out%parents = int_in%parents
    end if
    if (allocated (int_in%children)) then
        allocate (int_out%children (size (int_in%children)))
        int_out%children = int_in%children
    end if
    if (allocated (int_in%resonant)) then
        allocate (int_out%resonant (size (int_in%resonant)))
        int_out%resonant = int_in%resonant
    end if
    if (allocated (int_in%mask)) then
        allocate (int_out%mask (size (int_in%mask)))
        int_out%mask = int_in%mask
    end if
    if (allocated (int_in%lock)) then
        allocate (int_out%lock (size (int_in%lock)))
        int_out%lock = int_in%lock
    end if
    int_out%update_state_matrix = int_in%update_state_matrix
    int_out%update_values = int_in%update_values
end subroutine interaction_assign

```

7.6.4 Methods inherited from the state matrix member

Until F2003 is standard, we cannot implement inheritance directly. Therefore, we need wrappers for “inherited” methods.

Make a new branch in the state matrix if it does not yet exist. This is not just a wrapper but it introduces the interaction mask: where a quantum number is masked, it is not transferred but set undefined. After this, the value array has to be updated.

```

<Interactions: public>+≡
    public :: interaction_add_state

<Interactions: procedures>+≡
    subroutine interaction_add_state &
        (int, qn, index, value, sum_values, counter_index, me_index)
        type(interaction_t), intent(inout) :: int
        type(quantum_numbers_t), dimension(:), intent(in) :: qn
        integer, intent(in), optional :: index
        complex(default), intent(in), optional :: value
        logical, intent(in), optional :: sum_values
        integer, intent(in), optional :: counter_index
        integer, intent(out), optional :: me_index
        type(quantum_numbers_t), dimension(size(qn)) :: qn_tmp
        qn_tmp = qn
        call quantum_numbers_undefine (qn_tmp, int%mask)
        call state_matrix_add_state &
            (int%state_matrix, qn_tmp, index, value, sum_values, &
             counter_index, me_index)
        int%update_values = .true.
    end subroutine interaction_add_state

```

Freeze the quantum state: First collapse the quantum state, i.e., remove quantum numbers if any mask has changed, then fix the array of value pointers.

```

<Interactions: public>+≡
    public :: interaction_freeze

<Interactions: procedures>+≡
    subroutine interaction_freeze (int)
        type(interaction_t), intent(inout) :: int
        if (int%update_state_matrix) then
            call state_matrix_collapse (int%state_matrix, int%mask)
            int%update_state_matrix = .false.
            int%update_values = .true.
        end if
        if (int%update_values) then
            call state_matrix_freeze (int%state_matrix)
            int%update_values = .false.
        end if
    end subroutine interaction_freeze

```

Return true if the state matrix is empty.

```

<Interactions: public>+≡
    public :: interaction_is_empty

<Interactions: procedures>+≡
    function interaction_is_empty (int) result (flag)
        logical :: flag
        type(interaction_t), intent(in) :: int
        flag = state_matrix_is_empty (int%state_matrix)
    end function interaction_is_empty

```

Get the number of values stored in the state matrix:

```

<Interactions: public>+≡
    public :: interaction_get_n_matrix_elements

<Interactions: procedures>+≡
    function interaction_get_n_matrix_elements (int) result (n)
        integer :: n
        type(interaction_t), intent(in) :: int
        n = state_matrix_get_n_matrix_elements (int%state_matrix)
    end function interaction_get_n_matrix_elements

```

Get the quantum number array that corresponds to a given index.

```

<Interactions: public>+≡
    public :: interaction_get_quantum_numbers

<Interactions: procedures>+≡
    function interaction_get_quantum_numbers (int, i) result (qn)
        type(quantum_numbers_t), dimension(:), allocatable :: qn
        type(interaction_t), intent(in), target :: int
        integer, intent(in) :: i
        allocate (qn (state_matrix_get_depth (int%state_matrix)))
        qn = state_matrix_get_quantum_numbers (int%state_matrix, i)
    end function interaction_get_quantum_numbers

```

Get the matrix element that corresponds to a set of quantum numbers, a given index, or return the whole array.

```

<Interactions: public>+≡
    public :: interaction_get_matrix_element

<Interactions: procedures>+≡
    function interaction_get_matrix_element (int, i) result (me)
        complex(default) :: me
        type(interaction_t), intent(in) :: int
        integer, intent(in) :: i
        me = state_matrix_get_matrix_element (int%state_matrix, i)
    end function interaction_get_matrix_element

```

Set the complex value(s) stored in the quantum state.

```

<Interactions: public>+≡
    public :: interaction_set_matrix_element

<Interactions: interfaces>+≡
    interface interaction_set_matrix_element
        module procedure interaction_set_matrix_element_qn
        module procedure interaction_set_matrix_element_all
        module procedure interaction_set_matrix_element_array
        module procedure interaction_set_matrix_element_single
    end interface

```

Indirect access via the quantum number array:

```

<Interactions: procedures>+≡
    subroutine interaction_set_matrix_element_qn (int, qn, val)
        type(interaction_t), intent(inout) :: int
        type(quantum_numbers_t), dimension(:), intent(in) :: qn
        complex(default), intent(in) :: val
        call state_matrix_set_matrix_element (int%state_matrix, qn, val)
    end subroutine interaction_set_matrix_element_qn

```

Set all entries of the matrix-element array to a given value.

```

<Interactions: procedures>+≡
    subroutine interaction_set_matrix_element_all (int, value)
        type(interaction_t), intent(inout) :: int
        complex(default), intent(in) :: value
        call state_matrix_set_matrix_element (int%state_matrix, value)
    end subroutine interaction_set_matrix_element_all

```

Set the matrix-element array directly.

```

<Interactions: procedures>+≡
    subroutine interaction_set_matrix_element_array (int, value)
        type(interaction_t), intent(inout) :: int
        complex(default), dimension(:), intent(in) :: value
        call state_matrix_set_matrix_element (int%state_matrix, value)
    end subroutine interaction_set_matrix_element_array

    pure subroutine interaction_set_matrix_element_single (int, i, value)
        type(interaction_t), intent(inout) :: int
        integer, intent(in) :: i

```

```

        complex(default), intent(in) :: value
        call state_matrix_set_matrix_element (int%state_matrix, i, value)
    end subroutine interaction_set_matrix_element_single

```

Return the maximum absolute value of color indices.

```

<Interactions: public>+≡
    public :: interaction_get_max_color_value

<Interactions: procedures>+≡
    function interaction_get_max_color_value (int) result (cmax)
        integer :: cmax
        type(interaction_t), intent(in) :: int
        cmax = state_matrix_get_max_color_value (int%state_matrix)
    end function interaction_get_max_color_value

```

Factorize the state matrix into single-particle state matrices, the branch selection depending on a (random) value between 0 and 1; optionally also return a correlated state matrix.

```

<Interactions: public>+≡
    public :: interaction_factorize

<Interactions: procedures>+≡
    subroutine interaction_factorize &
        (int, mode, x, single_state, correlated_state, qn_in)
        type(interaction_t), intent(in), target :: int
        integer, intent(in) :: mode
        real(default), intent(in) :: x
        type(state_matrix_t), &
            dimension(:), allocatable, intent(out) :: single_state
        type(state_matrix_t), intent(out), optional :: correlated_state
        type(quantum_numbers_t), dimension(:), intent(in), optional :: qn_in
        call state_matrix_factorize &
            (int%state_matrix, mode, x, single_state, correlated_state, qn_in)
    end subroutine interaction_factorize

```

Sum all matrix element values

```

<Interactions: public>+≡
    public :: interaction_sum

<Interactions: procedures>+≡
    function interaction_sum (int) result (value)
        complex(default) :: value
        type(interaction_t), intent(in) :: int
        value = state_matrix_sum (int%state_matrix)
    end function interaction_sum

```

Append new states which are color-contracted versions of the existing states. The matrix element index of each color contraction coincides with the index of its origin, so no new matrix elements are generated. After this operation, no `freeze` must be performed anymore.

```

<Interactions: public>+≡
    public :: interaction_add_color_contractions

```

```

<Interactions: procedures>+=
  subroutine interaction_add_color_contractions (int)
    type(interaction_t), intent(inout) :: int
    call state_matrix_add_color_contractions (int%state_matrix)
  end subroutine interaction_add_color_contractions

```

Multiply matrix elements from two interactions. Choose the elements as given by the integer index arrays, multiply them and store the sum of products in the indicated matrix element. The suffixes mean: c=conjugate first factor; f=include weighting factor.

```

<Interactions: public>+=
  public :: interaction_evaluate_product
  public :: interaction_evaluate_product_cf
  public :: interaction_evaluate_square_c
  public :: interaction_evaluate_sum

<Interactions: procedures>+=
  pure subroutine interaction_evaluate_product &
    (int, i, int1, int2, index1, index2)
    type(interaction_t), intent(inout) :: int
    integer, intent(in) :: i
    type(interaction_t), intent(in) :: int1, int2
    integer, dimension(:), intent(in) :: index1, index2
    call state_matrix_evaluate_product &
      (int%state_matrix, i, int1%state_matrix, int2%state_matrix, &
        index1, index2)
  end subroutine interaction_evaluate_product

  pure subroutine interaction_evaluate_product_cf &
    (int, i, int1, int2, index1, index2, factor)
    type(interaction_t), intent(inout) :: int
    integer, intent(in) :: i
    type(interaction_t), intent(in) :: int1, int2
    integer, dimension(:), intent(in) :: index1, index2
    complex(default), dimension(:), intent(in) :: factor
    call state_matrix_evaluate_product_cf &
      (int%state_matrix, i, int1%state_matrix, int2%state_matrix, &
        index1, index2, factor)
  end subroutine interaction_evaluate_product_cf

  pure subroutine interaction_evaluate_square_c (int, i, int1, index1)
    type(interaction_t), intent(inout) :: int
    integer, intent(in) :: i
    type(interaction_t), intent(in) :: int1
    integer, dimension(:), intent(in) :: index1
    call state_matrix_evaluate_square_c &
      (int%state_matrix, i, int1%state_matrix, index1)
  end subroutine interaction_evaluate_square_c

  pure subroutine interaction_evaluate_sum (int, i, int1, index1)
    type(interaction_t), intent(inout) :: int
    integer, intent(in) :: i
    type(interaction_t), intent(in) :: int1
    integer, dimension(:), intent(in) :: index1

```

```

    call state_matrix_evaluate_sum &
      (int%state_matrix, i, int1%state_matrix, index1)
  end subroutine interaction_evaluate_sum

```

7.6.5 Accessing contents

Return the integer tag.

```

<Interactions: public>+≡
  public :: interaction_get_tag

<Interactions: procedures>+≡
  function interaction_get_tag (int) result (tag)
    integer :: tag
    type(interaction_t), intent(in) :: int
    tag = int%tag
  end function interaction_get_tag

```

Return the number of particles.

```

<Interactions: public>+≡
  public :: interaction_get_n_tot
  public :: interaction_get_n_in
  public :: interaction_get_n_vir
  public :: interaction_get_n_out

<Interactions: procedures>+≡
  function interaction_get_n_tot (int) result (n_tot)
    integer :: n_tot
    type(interaction_t), intent(in) :: int
    n_tot = int%n_tot
  end function interaction_get_n_tot

  function interaction_get_n_in (int) result (n_in)
    integer :: n_in
    type(interaction_t), intent(in) :: int
    n_in = int%n_in
  end function interaction_get_n_in

  function interaction_get_n_vir (int) result (n_vir)
    integer :: n_vir
    type(interaction_t), intent(in) :: int
    n_vir = int%n_vir
  end function interaction_get_n_vir

  function interaction_get_n_out (int) result (n_out)
    integer :: n_out
    type(interaction_t), intent(in) :: int
    n_out = int%n_out
  end function interaction_get_n_out

```

Return a momentum index. The flags specify whether to keep/drop incoming, virtual, or outgoing momenta. Check for illegal values.

```

<Interactions: procedures>+≡

```

```

function idx (int, i, outgoing)
  integer :: idx
  type(interaction_t), intent(in) :: int
  integer, intent(in) :: i
  logical, intent(in), optional :: outgoing
  logical :: in, vir, out
  if (present (outgoing)) then
    in = .not. outgoing
    vir = .false.
    out = outgoing
  else
    in = .true.
    vir = .true.
    out = .true.
  end if
  idx = 0
  if (in) then
    if (vir) then
      if (out) then
        if (i <= int%n_tot) idx = i
      else
        if (i <= int%n_in + int%n_vir) idx = i
      end if
    else if (out) then
      if (i <= int%n_in) then
        idx = i
      else if (i <= int%n_in + int%n_out) then
        idx = int%n_vir + i
      end if
    else
      if (i <= int%n_in) idx = i
    end if
  else if (vir) then
    if (out) then
      if (i <= int%n_vir + int%n_out) idx = int%n_in + i
    else
      if (i <= int%n_vir) idx = int%n_in + i
    end if
  else if (out) then
    if (i <= int%n_out) idx = int%n_in + int%n_vir + i
  end if
  if (idx == 0) then
    call interaction_write (int)
    print *, i, in, vir, out
    call msg_bug (" Momentum index is out of range for this interaction")
  end if
end function idx

```

Return all or just a specific four-momentum.

<Interactions: public>+≡

```

  public :: interaction_get_momenta
  public :: interaction_get_momentum

```

<Interactions: procedures>+≡

```

function interaction_get_momenta (int, outgoing) result (p)
  type(vector4_t), dimension(:), allocatable :: p
  type(interaction_t), intent(in) :: int
  logical, intent(in), optional :: outgoing
  integer :: i
  if (present (outgoing)) then
    if (outgoing) then
      allocate (p (int%n_out))
    else
      allocate (p (int%n_in))
    end if
  else
    allocate (p (int%n_tot))
  end if
  do i = 1, size (p)
    p(i) = int%p(idx (int, i, outgoing))
  end do
end function interaction_get_momenta

function interaction_get_momentum (int, i, outgoing) result (p)
  type(vector4_t) :: p
  type(interaction_t), intent(in) :: int
  integer, intent(in) :: i
  logical, intent(in), optional :: outgoing
  p = int%p(idx (int, i, outgoing))
end function interaction_get_momentum

```

Transfer PDG codes, masses (initialization) and momenta to a predefined particle list. We use the flavor assignment of the first branch in the interaction state matrix. Only incoming and outgoing particles are transferred. Switch momentum sign for incoming particles.

```

<Interactions: public>+≡
  public :: interaction_init_prt_list
  public :: interaction_momenta_to_prt_list

<Interactions: procedures>+≡
  subroutine interaction_init_prt_list (int, prt_list)
    type(interaction_t), intent(in), target :: int
    type(prt_list_t), intent(out) :: prt_list
    type(flavor_t), dimension(:), allocatable :: flv
    integer :: i
    allocate (flv (int%n_tot))
    flv = quantum_numbers_get_flavor (interaction_get_quantum_numbers (int, 1))
    call prt_list_init (prt_list, int%n_in + int%n_out)
    do i = 1, int%n_in
      call prt_list_set_incoming (prt_list, i, &
        flavor_get_pdg (flv(i)), &
        vector4_null, &
        flavor_get_mass (flv(i)) ** 2)
    end do
    do i = 1, int%n_out
      call prt_list_set_outgoing (prt_list, int%n_in+i, &
        flavor_get_pdg (flv(int%n_in+int%n_vir+i)), &
        vector4_null, &

```

```

        flavor_get_mass (flv(int%n_in+int%n_vir+i)) ** 2)
    end do
end subroutine interaction_init_prt_list

subroutine interaction_momenta_to_prt_list (int, prt_list)
    type(interaction_t), intent(in) :: int
    type(prt_list_t), intent(inout) :: prt_list
    call prt_list_set_p_incoming &
        (prt_list, - interaction_get_momenta (int, outgoing=.false.))
    call prt_list_set_p_outgoing &
        (prt_list, interaction_get_momenta (int, outgoing=.true.))
end subroutine interaction_momenta_to_prt_list

```

Return a shallow copy of the state matrix:

```

<Interactions: public>+≡
    public :: interaction_get_state_matrix

<Interactions: procedures>+≡
    function interaction_get_state_matrix (int) result (state)
        type(state_matrix_t) :: state
        type(interaction_t), intent(in) :: int
        state = int%state_matrix
    end function interaction_get_state_matrix

```

Return the array of resonance flags

```

<Interactions: public>+≡
    public :: interaction_get_resonance_flags

<Interactions: procedures>+≡
    function interaction_get_resonance_flags (int) result (resonant)
        type(interaction_t), intent(in) :: int
        logical, dimension(size(int%resonant)) :: resonant
        resonant = int%resonant
    end function interaction_get_resonance_flags

```

Return the quantum-numbers mask (or part of it)

```

<Interactions: public>+≡
    public :: interaction_get_mask

<Interactions: interfaces>+≡
    interface interaction_get_mask
        module procedure interaction_get_mask_all
        module procedure interaction_get_mask_slice
    end interface

<Interactions: procedures>+≡
    function interaction_get_mask_all (int) result (mask)
        type(interaction_t), intent(in) :: int
        type(quantum_numbers_mask_t), dimension(size(int%mask)) :: mask
        mask = int%mask
    end function interaction_get_mask_all

    function interaction_get_mask_slice (int, index) result (mask)

```

```

    type(interaction_t), intent(in) :: int
    integer, dimension(:), intent(in) :: index
    type(quantum_numbers_mask_t), dimension(size(index)) :: mask
    mask = int%mask(index)
end function interaction_get_mask_slice

```

Compute the invariant mass squared of the incoming particles (if any, otherwise outgoing).

```

<Interactions: public>+≡
    public :: interaction_get_s

<Interactions: procedures>+≡
    function interaction_get_s (int) result (s)
        real(default) :: s
        type(interaction_t), intent(in) :: int
        if (int%n_in /= 0) then
            s = sum (int%p(:int%n_in)) ** 2
        else
            s = sum (int%p(int%n_vir+1:)) ** 2
        end if
    end function interaction_get_s

```

Compute the Lorentz transformation that transforms the incoming particles from the center-of-mass frame to the lab frame where they are given. If the c.m. mass squared is negative or zero, return the identity.

```

<Interactions: public>+≡
    public :: interaction_get_cm_transformation

<Interactions: procedures>+≡
    function interaction_get_cm_transformation (int) result (lt)
        type(lorentz_transformation_t) :: lt
        type(interaction_t), intent(in) :: int
        type(vector4_t) :: p_cm
        real(default) :: s
        if (int%n_in /= 0) then
            p_cm = sum (int%p(:int%n_in))
        else
            p_cm = sum (int%p(int%n_vir+1:))
        end if
        s = p_cm ** 2
        if (s > 0) then
            lt = boost (p_cm, sqrt (s))
        else
            lt = identity
        end if
    end function interaction_get_cm_transformation

```

Return flavor, momentum, and position of the first outgoing unstable particle present in the interaction. Note that we need not iterate through the state matrix; if there is an unstable particle, it will be present in all state-matrix entries.

```

<Interactions: public>+≡
    public :: interaction_get_unstable_particle

```

```

<Interactions: procedures>+=
subroutine interaction_get_unstable_particle (int, flv, p, i)
  type(interaction_t), intent(in), target :: int
  type(flavor_t), intent(out) :: flv
  type(vector4_t), intent(out) :: p
  integer, intent(out) :: i
  type(state_iterator_t) :: it
  type(flavor_t), dimension(int%n_tot) :: flv_array
  call state_iterator_init (it, int%state_matrix)
  flv_array = state_iterator_get_flavor (it)
  do i = int%n_in + int%n_vir + 1, int%n_tot
    if (.not. flavor_is_stable (flv_array(i))) then
      flv = flv_array(i)
      p = int%p(i)
      return
    end if
  end do
end subroutine interaction_get_unstable_particle

```

7.6.6 Modifying contents

Set the quantum numbers mask.

```

<Interactions: public>+=
public :: interaction_set_mask

<Interactions: procedures>+=
subroutine interaction_set_mask (int, mask)
  type(interaction_t), intent(inout) :: int
  type(quantum_numbers_mask_t), dimension(:), intent(in) :: mask
  int%mask = mask
  int%update_state_matrix = .true.
end subroutine interaction_set_mask

```

Merge a particular mask entry, respecting a possible lock for this entry. We apply an OR relation, which means that quantum numbers are summed over if either of the two masks requires it.

```

<Interactions: procedures>+=
subroutine interaction_merge_mask_entry (int, i, mask)
  type(interaction_t), intent(inout) :: int
  integer, intent(in) :: i
  type(quantum_numbers_mask_t), intent(in) :: mask
  integer :: ii
  ii = idx (int, i)
  if (int%mask(ii) .neqv. mask) then
    int%mask(ii) = int%mask(ii) .or. mask
    if (int%lock(ii) /= 0) int%mask(int%lock(ii)) = mask
  end if
  int%update_state_matrix = .true.
end subroutine interaction_merge_mask_entry

```

Fill the momenta array, do not care about the quantum numbers of particles.

```

<Interactions: public>+=
  public :: interaction_reset_momenta
  public :: interaction_set_momenta
  public :: interaction_set_momentum

<Interactions: procedures>+=
  subroutine interaction_reset_momenta (int)
    type(interaction_t), intent(inout) :: int
    int%p = vector4_null
  end subroutine interaction_reset_momenta

  subroutine interaction_set_momenta (int, p, outgoing)
    type(interaction_t), intent(inout) :: int
    type(vector4_t), dimension(:), intent(in) :: p
    logical, intent(in), optional :: outgoing
    integer :: i
    do i = 1, size (p)
      int%p(idx (int, i, outgoing)) = p(i)
    end do
  end subroutine interaction_set_momenta

  subroutine interaction_set_momentum (int, p, i, outgoing)
    type(interaction_t), intent(inout) :: int
    type(vector4_t), intent(in) :: p
    integer, intent(in) :: i
    logical, intent(in), optional :: outgoing
    int%p(idx (int, i, outgoing)) = p
  end subroutine interaction_set_momentum

```

This more sophisticated version of setting values is used for structure functions, in particular if nontrivial flavor, color, and helicity may be present: set values selectively for the given flavors. If there is more than one flavor, scan the interaction and check for a matching flavor at the specified particle location. If it matches, insert the value that corresponds to this flavor.

```

<Interactions: public>+=
  public :: interaction_set_flavored_values

<Interactions: procedures>+=
  subroutine interaction_set_flavored_values (int, value, flv_in, pos)
    type(interaction_t), intent(inout) :: int
    complex(default), dimension(:), intent(in) :: value
    type(flavor_t), dimension(:), intent(in) :: flv_in
    integer, intent(in) :: pos
    type(state_iterator_t) :: it
    type(flavor_t) :: flv
    integer :: i
    !   stop "Procedure disabled due to ifort11.0 problem"
    if (size (value) == 1) then
      call interaction_set_matrix_element (int, value(1))
    else
      call state_iterator_init (it, int%state_matrix)
      do while (state_iterator_is_valid (it))
        flv = state_iterator_get_flavor (it, pos)

```

```

SCAN_FLV: do i = 1, size (value)
  if (flv == flv_in(i)) then
    call state_iterator_set_matrix_element (it, value(i))
    exit SCAN_FLV
  end if
end do SCAN_FLV
call state_iterator_advance (it)
end do
end if
end subroutine interaction_set_flavored_values

```

7.6.7 Handling Linked interactions

Store relations between corresponding particles within one interaction. The first particle is the parent, the second one the child. Links are established in both directions.

These relations have no effect on the propagation of momenta etc., they are rather used for mother-daughter relations in event output.

```

<Interactions: public>+≡
  public :: interaction_relate

<Interactions: procedures>+≡
  subroutine interaction_relate (int, i1, i2)
    type(interaction_t), intent(inout), target :: int
    integer, intent(in) :: i1, i2
    if (i1 /= 0 .and. i2 /= 0) then
      call internal_link_list_append (int%children(i1), i2)
      call internal_link_list_append (int%parents(i2), i1)
    end if
  end subroutine interaction_relate

```

Transfer relations defined within one interaction to a new interaction where the particle indices are mapped to. Some outgoing particles may have no image. In that case, a child entry maps to zero, and we skip this relation. Note that outgoing particles have no children, so parent entries never map to zero.

Also transfer resonance flags.

```

<Interactions: public>+≡
  public :: interaction_transfer_relations

<Interactions: procedures>+≡
  subroutine interaction_transfer_relations (int1, int2, map)
    type(interaction_t), intent(in) :: int1
    type(interaction_t), intent(inout), target :: int2
    integer, dimension(:), intent(in) :: map
    type(internal_link_t), pointer :: link
    integer :: i, k
    do i = 1, size (map)
      link => internal_link_list_get_first_ptr (int1%parents(i))
      do while (associated (link))
        k = internal_link_get_index (link)
        call interaction_relate (int2, map(k), map(i))
        call internal_link_advance (link)
      end do
    end do
  end subroutine interaction_transfer_relations

```

```

        end do
        if (map(i) /= 0) then
            int2%resonant(map(i)) = int1%resonant(i)
        end if
    end do
end subroutine interaction_transfer_relations

```

Make up parent-child relations for the particle(s) that are connected to a new interaction.

We scan the connections. For each out/in pair k_1, k_2 that we get, we look at the relations of k_1 within int_1 . For each parent i_1 of k_1 , we relate its image to the image of the in-particle k_2 (which is located in int_2 , but this information is not used).

If `resonant` is defined and true, the connections are marked as resonant in the result interaction

```

<Interactions: public>+≡
    public :: interaction_relate_connections

<Interactions: procedures>+≡
    subroutine interaction_relate_connections &
        (int, int_in, connection_index, &
         map, map_connections, resonant)
        type(interaction_t), intent(inout), target :: int
        type(interaction_t), intent(in) :: int_in
        integer, dimension(:), intent(in) :: connection_index
        integer, dimension(:), intent(in) :: map, map_connections
        logical, intent(in), optional :: resonant
        logical :: reson
        integer :: i, i2, k2
        type(internal_link_t), pointer :: link
        reson = .false.; if (present (resonant)) reson = resonant
        do i = 1, size (map_connections)
            k2 = connection_index(i)
            link => internal_link_list_get_first_ptr (int_in%children(k2))
            do while (associated (link))
                i2 = internal_link_get_index (link)
                call interaction_relate (int, map_connections(i), map(i2))
                call internal_link_advance (link)
            end do
            int%resonant(map_connections(i)) = reson
        end do
    end subroutine interaction_relate_connections

```

Return the source/target links of the internal connections of particle i as an array.

```

<Interactions: public>+≡
    public :: interaction_get_children
    public :: interaction_get_parents

<Interactions: procedures>+≡
    function interaction_get_children (int, i) result (idx)
        integer, dimension(:), allocatable :: idx
        type(interaction_t), intent(in) :: int

```

```

integer, intent(in) :: i
integer :: k
type(internal_link_t), pointer :: link
allocate (idx (internal_link_list_get_length (int%children(i))))
k = 0
link => internal_link_list_get_first_ptr (int%children(i))
do while (associated (link))
    k = k + 1
    idx(k) = internal_link_get_index (link)
    call internal_link_advance (link)
end do
end function interaction_get_children

function interaction_get_parents (int, i) result (idx)
integer, dimension(:), allocatable :: idx
type(interaction_t), intent(in) :: int
integer, intent(in) :: i
integer :: k
type(internal_link_t), pointer :: link
allocate (idx (internal_link_list_get_length (int%parents(i))))
k = 0
link => internal_link_list_get_first_ptr (int%parents(i))
do while (associated (link))
    k = k + 1
    idx(k) = internal_link_get_index (link)
    call internal_link_advance (link)
end do
end function interaction_get_parents

```

Add a source link from an interaction to a corresponding particle within another interaction. These links affect the propagation of particles: the two linked particles are considered as the same particle, outgoing and incoming.

```

<Interactions: public>+≡
public :: interaction_set_source_link

<Interactions: interfaces>+≡
interface interaction_set_source_link
    module procedure interaction_set_source_link_int
end interface

<Interactions: procedures>+≡
subroutine interaction_set_source_link_int (int, i, int1, i1)
type(interaction_t), intent(inout) :: int
integer, intent(in) :: i
type(interaction_t), intent(in), target :: int1
integer, intent(in) :: i1
if (i /= 0) call external_link_set (int%source(i), int1, i1)
end subroutine interaction_set_source_link_int

```

Reassign links to a new interaction (which is an image of the current interaction).

```

<Interactions: public>+≡
public :: interaction_reassign_links

```

```

<Interactions: procedures>+=
subroutine interaction_reassign_links (int, int_src, int_target)
  type(interaction_t), intent(inout) :: int
  type(interaction_t), intent(in) :: int_src
  type(interaction_t), intent(in), target :: int_target
  integer :: i
  if (allocated (int%source)) then
    do i = 1, size (int%source)
      call external_link_reassign (int%source(i), int_src, int_target)
    end do
  end if
end subroutine interaction_reassign_links

```

Since links are one-directional, if we want to follow them backwards we have to scan all possibilities. This procedure returns the index of the particle within `int` which points to the particle `i1` within interaction `int1`. If unsuccessful, return zero.

```

<Interactions: public>+=
public :: interaction_find_link

<Interactions: procedures>+=
function interaction_find_link (int, int1, i1) result (i)
  integer :: i
  type(interaction_t), intent(in) :: int, int1
  integer, intent(in) :: i1
  type(interaction_t), pointer :: int_tmp
  do i = 1, int%n_tot
    int_tmp => external_link_get_ptr (int%source(i))
    if (int_tmp%tag == int1%tag) then
      if (external_link_get_index (int%source(i)) == i1) return
    end if
  end do
  i = 0
end function interaction_find_link

```

Update mask entries by merging them with corresponding masks in interactions linked to the current one. The mask determines quantum numbers which are summed over.

Note that both the mask of the current interaction and the mask of the linked interaction are updated (side effect!). This ensures that both agree for the linked particle.

```

<Interactions: public>+=
public :: interaction_exchange_mask

<Interactions: procedures>+=
subroutine interaction_exchange_mask (int)
  type(interaction_t), intent(inout) :: int
  integer :: i, index_link
  type(interaction_t), pointer :: int_link
  do i = 1, int%n_tot
    if (external_link_is_set (int%source(i))) then
      int_link => external_link_get_ptr (int%source(i))
      index_link = external_link_get_index (int%source(i))
    end if
  end do
end subroutine interaction_exchange_mask

```

```

        call interaction_merge_mask_entry &
            (int, i, int_link%mask(index_link))
        call interaction_merge_mask_entry &
            (int_link, index_link, int%mask(i))
    end if
end do
call interaction_freeze (int)
end subroutine interaction_exchange_mask

```

Copy momenta from interactions linked to the current one.

<Interactions: public>+≡

```
public :: interaction_receive_momenta
```

<Interactions: procedures>+≡

```

subroutine interaction_receive_momenta (int)
    type(interaction_t), intent(inout) :: int
    integer :: i, index_link
    type(interaction_t), pointer :: int_link
    do i = 1, int%n_tot
        if (external_link_is_set (int%source(i))) then
            int_link => external_link_get_ptr (int%source(i))
            index_link = external_link_get_index (int%source(i))
            call interaction_set_momentum (int, int_link%p(index_link), i)
        end if
    end do
end subroutine interaction_receive_momenta

```

7.6.8 Recovering connections

When creating an evaluator for two interactions, we have to know by which particles they are connected. The connection indices can be determined if we have two linked interactions. We assume that `int1` is the source and `int2` the target, so the connections of interest are stored within `int2`. A connection is found if `int2` has a source within `int1`. The result is an array of index pairs.

Connections may also be present indirectly. This is the case if the source of `int2` coincides with the source of `int1`.

To make things simple, we scan the interaction twice, once for counting hits, then allocate the array, then scan again and store the connections.

<Interactions: public>+≡

```
public :: find_connections
```

<Interactions: procedures>+≡

```

subroutine find_connections (int1, int2, n, connection_index)
    type(interaction_t), intent(in) :: int1, int2
    integer, intent(out) :: n
    integer, dimension(:,:), intent(out), allocatable :: connection_index
    integer :: i, j, k
    type(interaction_t), pointer :: int_link, int_link1
    n = 0
    do i = 1, size (int2%source)
        if (external_link_is_set (int2%source(i))) then
            int_link => external_link_get_ptr (int2%source(i))

```

```

    if (int_link%tag == int1%tag) then
        n = n + 1
    else
        k = external_link_get_index (int2%source(i))
        do j = 1, size (int1%source)
            if (external_link_is_set (int1%source(j))) then
                int_link1 => external_link_get_ptr (int1%source(j))
                if (int_link1%tag == int_link%tag) then
                    if (external_link_get_index (int1%source(j)) == k) then
                        n = n + 1
                    end if
                end if
            end if
        end do
    end if
end if
end do
allocate (connection_index (n, 2))
n = 0
do i = 1, size (int2%source)
    if (external_link_is_set (int2%source(i))) then
        int_link => external_link_get_ptr (int2%source(i))
        if (int_link%tag == int1%tag) then
            n = n + 1
            connection_index(n,1) = external_link_get_index (int2%source(i))
            connection_index(n,2) = i
        else
            k = external_link_get_index (int2%source(i))
            do j = 1, size (int1%source)
                if (external_link_is_set (int1%source(j))) then
                    int_link1 => external_link_get_ptr (int1%source(j))
                    if (int_link1%tag == int_link%tag) then
                        if (external_link_get_index (int1%source(j)) == k) then
                            n = n + 1
                            connection_index(n,1) = j
                            connection_index(n,2) = i
                        end if
                    end if
                end if
            end do
        end if
    end if
end do
end subroutine find_connections

```

7.6.9 Test

Generate an interaction of a polarized virtual photon and a colored quark which may be either up or down. Remove the quark polarization. Generate another interaction for the quark radiating a photon and link this to the first interaction. The radiation ignores polarization; transfer this information to the first interaction to simplify it. Then, transfer the momentum to the radiating quark and

perform a splitting.

```

<Interactions: public>+≡
    public :: interaction_test
<Interactions: procedures>+≡
    subroutine interaction_test ()
        type(interaction_t), target :: int, rad
        type(vector4_t), dimension(3) :: p
        type(quantum_numbers_mask_t), dimension(3) :: mask
        p(2) = vector4_moving (500._default, 500._default, 1)
        p(3) = vector4_moving (500._default,-500._default, 1)
        p(1) = p(2) + p(3)
        call interaction_init (int, 1, 0, 2, set_relations=.true.)
        call int_set (1, -1, 1, 1, (0.3_default, 0.1_default))
        call int_set (1, -1,-1, 1, (0.5_default,-0.7_default))
        call int_set (1, 1, 1, 1, (0.1_default, 0._default))
        call int_set (-1, 1, -1, 2, (0.4_default, -0.1_default))
        call int_set (1, 1, 1, 2, (0.2_default, 0._default))
        call interaction_freeze (int)
        call interaction_set_momenta (int, p)
        mask = new_quantum_numbers_mask (.false.,.false., (/true.,.true.,.true./))
        call interaction_init (rad, 1, 0, 2, mask=mask, set_relations=.true.)
        call rad_set (1)
        call rad_set (2)
        call interaction_set_source_link (rad, 1, int, 2)
        call interaction_exchange_mask (rad)
        call interaction_receive_momenta (rad)
        p(1) = interaction_get_momentum (rad, 1)
        p(2) = 0.4_default * p(1)
        p(3) = p(1) - p(2)
        call interaction_set_momenta (rad, p(2:3), outgoing=.true.)
        call interaction_freeze (int)
        call interaction_freeze (rad)
        call interaction_set_matrix_element (rad, (0._default, 0._default))
        call interaction_write (int)
        print *
        call interaction_write (rad)
        call interaction_final (int)
        call interaction_final (rad)
contains
    subroutine int_set (h1, h2, hq, q, val)
        integer, intent(in) :: h1, h2, hq, q
        type(flavor_t), dimension(3) :: flv
        type(color_t), dimension(3) :: col
        type(helicity_t), dimension(3) :: hel
        type(quantum_numbers_t), dimension(3) :: qn
        complex(default), intent(in) :: val
        call flavor_init (flv, (/21, q, -q/))
        call color_init_col_acl (col(2), 5, 0)
        call color_init_col_acl (col(3), 0, 5)
        call helicity_init (hel, (/h1, hq, -hq/), (/h2, hq, -hq/))
        call quantum_numbers_init (qn, flv, col, hel)
        call interaction_add_state (int, qn)
        call interaction_set_matrix_element (int, qn, val)
    end subroutine int_set

```

```

subroutine rad_set (q)
  integer, intent(in) :: q
  type(flavor_t), dimension(3) :: flv
  type(quantum_numbers_t), dimension(3) :: qn
  call flavor_init (flv, (/ q, q, 21 /))
  call quantum_numbers_init (qn, flv)
  call interaction_add_state (rad, qn)
end subroutine rad_set
end subroutine interaction_test

```

7.7 Matrix element evaluation

The `evaluator_t` type is an extension of the `interaction_t` type. It represents either a density matrix as the square of a transition matrix element, or the product of two density matrices. Usually, some quantum numbers are summed over in the result.

The `interaction_t` subobject represents a multi-particle interaction with incoming, virtual, and outgoing particles and the associated (not necessarily diagonal) density matrix of quantum state. When the evaluator is initialized, this interaction is constructed from the input interaction(s).

In addition, the initialization process sets up a multiplication table. For each matrix element of the result, it states which matrix elements are to be taken from the input interaction(s), multiplied (optionally, with an additional weight factor) and summed over.

Eventually, to a processes we associate a chain of evaluators which are to be evaluated sequentially. The physical event and its matrix element value(s) can be extracted from the last evaluator in such a chain.

Evaluators are constructed only once (as long as this is possible) during an initialization step. Then, for each event, momenta are computed and transferred among evaluators using the links within the interaction subobject. The multiplication tables enable fast evaluation of the result without looking at quantum numbers anymore.

```

<evaluators.f90>≡
  <File header>

```

```

module evaluators

  <Use kinds>
  <Use strings>
  <Use file utils>
  use diagnostics !NODEP!
  use lorentz !NODEP!
  use models
  use flavors
  use colors
  use helicities
  use quantum_numbers
  use state_matrices
  use interactions

```

```

⟨Standard module head⟩

⟨Evaluators: public⟩

⟨Evaluators: parameters⟩

⟨Evaluators: types⟩

⟨Evaluators: interfaces⟩

contains

⟨Evaluators: procedures⟩

end module evaluators

```

7.7.1 Array of pairings

The evaluator contains an array of `pairing_array` objects. This makes up the multiplication table.

Each pairing array contains two list of matrix element indices and a list of numerical factors. The matrix element indices correspond to the input interactions. The corresponding matrix elements are to be multiplied and optionally multiplied by a factor. The results are summed over to yield one specific matrix element of the result evaluator.

```

⟨Evaluators: types⟩≡
    type :: pairing_array_t
        integer, dimension(:), allocatable :: i1, i2
        complex(default), dimension(:), allocatable :: factor
    end type pairing_array_t

⟨Evaluators: procedures⟩≡
    elemental subroutine pairing_array_init (pa, n, has_i2, has_factor)
        type(pairing_array_t), intent(out) :: pa
        integer, intent(in) :: n
        logical, intent(in) :: has_i2, has_factor
        allocate (pa%i1 (n))
        if (has_i2) allocate (pa%i2 (n))
        if (has_factor) allocate (pa%factor (n))
    end subroutine pairing_array_init

```

7.7.2 The evaluator type

Possible variants of evaluators:

```

⟨Evaluators: parameters⟩≡
    integer, parameter :: &
        EVAL_UNDEFINED = 0, &
        EVAL_PRODUCT = 1, &
        EVAL_SQUARED_FLOWS = 2, &
        EVAL_SQUARE_WITH_COLOR_FACTORS = 3, &
        EVAL_COLOR_CONTRACTION = 4

```

The evaluator type contains the result interaction and an array of pairing lists, one for each matrix element in the result interaction.

```

(Evaluators: public)≡
    public :: evaluator_t

(Evaluators: types)+≡
    type :: evaluator_t
        private
        integer :: type = EVAL_UNDEFINED
        type(interaction_t), pointer :: int_in1 => null ()
        type(interaction_t), pointer :: int_in2 => null ()
        type(interaction_t) :: int
        type(pairing_array_t), dimension(:), allocatable :: pairing_array
    end type evaluator_t

```

Output.

```

(Evaluators: public)+≡
    public :: evaluator_write

(Evaluators: procedures)+≡
    subroutine evaluator_write (eval, unit, verbose, show_momentum_sum, show_mass)
        type(evaluator_t), intent(in) :: eval
        integer, intent(in), optional :: unit
        logical, intent(in), optional :: verbose, show_momentum_sum, show_mass
        logical :: conjugate, square
        integer :: u, i, j
        u = output_unit (unit); if (u < 0) return
        write (u, "(A)") "Evaluator:"
        call interaction_write &
            (eval%int, unit, verbose, show_momentum_sum, show_mass)
        write (u, "(1x,A)") "Matrix-element multiplication"
        write (u, "(2x,A)", advance="no") "Input interaction 1:"
        if (associated (eval%int_in1)) then
            write (u, "(1x,I0)") interaction_get_tag (eval%int_in1)
        else
            write (u, *) " [undefined]"
        end if
        write (u, "(2x,A)", advance="no") "Input interaction 2:"
        if (associated (eval%int_in2)) then
            write (u, *) interaction_get_tag (eval%int_in2)
        else
            write (u, *) " [undefined]"
        end if
        select case (eval%type)
        case (EVAL_SQUARED_FLOWS, EVAL_SQUARE_WITH_COLOR_FACTORS)
            conjugate = .true.
            square = .true.
        case default
            conjugate = .false.
            square = .false.
        end select
        if (allocated (eval%pairing_array)) then
            do i = 1, size (eval%pairing_array)
                write (u, "(2x,A,I0,A)") "ME(", i, ") = "
            end do
        end if
    end subroutine evaluator_write

```

```

do j = 1, size (eval%pairing_array(i)%i1)
  write (u, "(4x,A)", advance="no") "+"
  if (allocated (eval%pairing_array(i)%i2)) then
    write (u, "(1x,A,I0,A)", advance="no") &
      "ME1(", eval%pairing_array(i)%i1(j), ")"
    if (conjugate) then
      write (u, "(A)", advance="no") "* x"
    else
      write (u, "(A)", advance="no") " x"
    end if
    write (u, "(1x,A,I0,A)", advance="no") &
      "ME2(", eval%pairing_array(i)%i2(j), ")"
  else if (square) then
    write (u, "(1x,A)", advance="no") "|"
    write (u, "(A,I0,A)", advance="no") &
      "ME1(", eval%pairing_array(i)%i1(j), ")"
    write (u, "(A)", advance="no") "|^2"
  else
    write (u, "(1x,A,I0,A)", advance="no") &
      "ME1(", eval%pairing_array(i)%i1(j), ")"
  end if
  if (allocated (eval%pairing_array(i)%factor)) then
    write (u, "(1x,A)", advance="no") "x"
    write (u, *) eval%pairing_array(i)%factor(j)
  else
    write (u, *)
  end if
end do
end do
end if
end subroutine evaluator_write

```

Assignment: Deep copy of the interaction component.

```

<Evaluators: public>+≡
  public :: assignment(=)

<Evaluators: interfaces>≡
  interface assignment(=)
    module procedure evaluator_assign
  end interface

<Evaluators: procedures>+≡
  subroutine evaluator_assign (eval_out, eval_in)
    type(evaluator_t), intent(out) :: eval_out
    type(evaluator_t), intent(in) :: eval_in
    eval_out%type = eval_in%type
    eval_out%int_in1 => eval_in%int_in1
    eval_out%int_in2 => eval_in%int_in2
    eval_out%int = eval_in%int
    if (allocated (eval_in%pairing_array)) then
      allocate (eval_out%pairing_array (size (eval_in%pairing_array)))
      eval_out%pairing_array = eval_in%pairing_array
    end if
  end subroutine evaluator_assign

```

7.7.3 Creating an evaluator

Matrix multiplication

The evaluator for matrix multiplication is the most complicated variant.

The initializer takes two input interactions and constructs the result evaluator, which consists of the interaction and the multiplication table for the product (or convolution) of the two. Normally, the input interactions are connected by one or more common particles (e.g., decay, structure function convolution).

In the result interaction, quantum numbers of the connections can be summed over. This is determined by the `qn_mask_conn` argument. The `qn_mask_rest` argument is its analog for the other particles within the result interaction. (E.g., for the trace of the state matrix, all quantum numbers are summed over.) Finally, the `connections_are_resonant` argument tells whether the connecting particles should be marked as resonant in the final event record. This is useful for decays.

The algorithm consists of the following steps:

1. **find_connections:** Find the particles which are connected, i.e., common to both input interactions. Either they are directly linked, or both are linked to a common source.
2. **compute_index_bounds_and_mappings:** Compute the mappings of particle indices from the input interactions to the result interaction. There is a separate mapping for the connected particles.
3. **accumulate_connected_states:** Create an auxiliary state matrix which lists the possible quantum numbers for the connected particles. When building this matrix, count the number of times each assignment is contained in any of the input states and, for each of the input states, record the index of the matrix element within the new state matrix. For the connected particles, reassign color indices such that no color state is present twice in different color-index assignment. Note that helicity assignments of the connected state can be (and will be) off-diagonal, so no spin correlations are lost in decays.
Do this for both input interactions.
4. **allocate_connection_entries:** Allocate a table of connections. Each table row corresponds to one state in the auxiliary matrix, and to multiple states of the input interactions. It collects all states of the unconnected particles in the two input interactions that are associated with the particular state (quantum-number assignment) of the connected particles.
5. **fill_connection_table:** Fill the table of connections by scanning both input interactions. When copying states, reassign color indices for the unconnected particles such that they match between all involved particle sets (interaction 1, interaction 2, and connected particles).

6. **make_product_interaction**: Scan the table of connections we have just built. For each entry, construct all possible pairs of states of the unconnected particles and combine them with the specific connected-particle state. This is a possible quantum-number assignment of the result interaction. Now mask all quantum numbers that should be summed over, and append this to the result state matrix. Record the matrix element index of the result. We now have the result interaction.
7. **make_pairing_array**: First allocate the pairing array with the number of entries of the result interaction. Then scan the table of connections again. For each entry, record the indices of the matrix elements which have to be multiplied and summed over in order to compute this particular matrix element. This makes up the multiplication table.
8. **record_links**: Transfer all source pointers from the input interactions to the result interaction. Do the same for the internal parent-child relations and resonance assignments. For the connected particles, make up appropriate additional parent-child relations. This allows for fetching momenta from other interactions when a new event is filled, and to reconstruct the event history when the event is analyzed.

After all this is done, for each event, we just have to evaluate the pairing arrays (multiplication tables) in order to compute the result matrix elements in their proper positions. The quantum-number assignments remain fixed from now on.

```

(Evaluators: public)+≡
    public :: evaluator_init_product

(Evaluators: interfaces)+≡
    interface evaluator_init_product
        module procedure evaluator_init_product_ii
        module procedure evaluator_init_product_ie
        module procedure evaluator_init_product_ei
        module procedure evaluator_init_product_ee
    end interface

(Evaluators: procedures)+≡
    subroutine evaluator_init_product_ii &
        (eval, int_in1, int_in2, qn_mask_conn, qn_mask_rest, &
         connections_are_resonant)
        type(evaluator_t), intent(out), target :: eval
        type(interaction_t), intent(in), target :: int_in1, int_in2
        type(quantum_numbers_mask_t), intent(in) :: qn_mask_conn
        type(quantum_numbers_mask_t), intent(in), optional :: qn_mask_rest
        logical, intent(in), optional :: connections_are_resonant
        integer, dimension(:,:), allocatable :: connection_index
        integer :: n_in, n_vir, n_out, n_tot
        integer :: n1, n2, n_connections, n_me_connections
        integer :: color_max1, color_max_conn
        integer, dimension(:), allocatable :: map1, map2, map_connections
        integer, dimension(:), allocatable :: me_index1, me_index2
        logical, dimension(:), allocatable :: connection_mask1, connection_mask2
        type(quantum_numbers_mask_t), dimension(:), allocatable :: &

```

```

        qn_mask_conn_initial
type(state_matrix_t) :: state_connections
type :: connection_table_t
    type(quantum_numbers_t), dimension(:), allocatable :: qn_conn
    integer, dimension(2) :: n_index = 0
    integer, dimension(:), allocatable :: index1, index2
    type(quantum_numbers_t), dimension(:, :), allocatable :: qn1, qn2
end type connection_table_t
type(connection_table_t), dimension(:), allocatable :: connection_table
integer, dimension(:), allocatable :: result_index
eval%type = EVAL_PRODUCT
eval%int_in1 => int_in1
eval%int_in2 => int_in2
!     print *, "Evaluator product"
!     print *, "First interaction"
!     call interaction_write (int_in1)
!     print *
!     print *, "Second interaction"
!     call interaction_write (int_in2)
!     print *
color_max1 = interaction_get_max_color_value (int_in1)
! color_max2 = interaction_get_max_color_value (int_in2)
call find_connections (int_in1, int_in2, n_connections, connection_index)
call compute_index_bounds_and_mappings &
    (int_in1, int_in2, n_connections, &
     n_in, n_vir, n_out, n_tot, &
     n1, n2, map1, map2, map_connections)
allocate (me_index1 (interaction_get_n_matrix_elements (int_in1)))
allocate (me_index2 (interaction_get_n_matrix_elements (int_in2)))
me_index1 = 0
me_index2 = 0
allocate (connection_mask1 (interaction_get_n_tot (int_in1)))
allocate (connection_mask2 (interaction_get_n_tot (int_in2)))
connection_mask1 = .true.
connection_mask2 = .true.
connection_mask1(connection_index(:,1)) = .false.
connection_mask2(connection_index(:,2)) = .false.
allocate (qn_mask_conn_initial (n_connections))
qn_mask_conn_initial = &
    interaction_get_mask (int_in1, connection_index(:,1)) .or. &
    interaction_get_mask (int_in2, connection_index(:,2))
call state_matrix_init (state_connections, n_counters=2)
call accumulate_connected_states (state_connections, me_index1, &
    interaction_get_state_matrix (int_in1), &
    connection_index(:,1), qn_mask_conn_initial, n_connections, 1)
call accumulate_connected_states (state_connections, me_index2, &
    interaction_get_state_matrix (int_in2), &
    connection_index(:,2), qn_mask_conn_initial, n_connections, 2)
color_max_conn = state_matrix_get_max_color_value (state_connections)
n_me_connections = state_matrix_get_n_matrix_elements (state_connections)
allocate (connection_table (n_me_connections))
call allocate_connection_entries &
    (connection_table, state_connections, n_connections, n1, n2)
call fill_connection_table (connection_table, &

```

```

        interaction_get_state_matrix (int_in1), &
        me_index1, connection_mask1, connection_index(:,1), 1, &
        color_max_conn)
call fill_connection_table (connection_table, &
    interaction_get_state_matrix (int_in2), &
    me_index2, connection_mask2, connection_index(:,2), 2, &
    color_max_conn + color_max1)
call make_product_interaction (eval%int, &
    result_index, &
    int_in1, int_in2, &
    n_in, n_vir, n_out, &
    connection_table, n1, n2, n_connections, &
    connection_mask1, connection_mask2, &
    qn_mask_conn_initial, qn_mask_conn, qn_mask_rest)
call make_pairing_array (eval%pairing_array, &
    interaction_get_n_matrix_elements (eval%int), &
    result_index, connection_table)
call record_links (eval%int, &
    int_in1, int_in2, connection_index, map1, map2, map_connections, &
    connection_mask1, connection_mask2, connections_are_resonant)
call state_matrix_final (state_connections)
!   print *, "Result evaluator"
!   call evaluator_write (eval)

```

contains

```

subroutine compute_index_bounds_and_mappings &
    (int1, int2, n_connections, &
    n_in, n_vir, n_out, n_tot, &
    n_tot1, n_tot2, map1, map2, map_connections)
type(interaction_t), intent(in) :: int1, int2
integer, intent(in) :: n_connections
integer, intent(out) :: n_in, n_vir, n_out, n_tot
integer, intent(out) :: n_tot1, n_tot2
integer, dimension(:), allocatable, intent(out) :: map1, map2
integer, dimension(:), allocatable, intent(out) :: map_connections
integer, dimension(:), allocatable :: index
integer :: n_in1, n_vir1, n_out1
integer :: n_in2, n_vir2, n_out2
integer :: k, i
n_in1 = interaction_get_n_in (int1)
n_vir1 = interaction_get_n_vir (int1)
n_out1 = interaction_get_n_out (int1) - n_connections
n_tot1 = n_in1 + n_vir1 + n_out1
n_in2 = interaction_get_n_in (int2) - n_connections
n_vir2 = interaction_get_n_vir (int2)
n_out2 = interaction_get_n_out (int2)
n_tot2 = n_in2 + n_vir2 + n_out2
n_in = n_in1 + n_in2
n_vir = n_vir1 + n_vir2 + n_connections
n_out = n_out1 + n_out2
n_tot = n_in + n_vir + n_out
allocate (map1 (n_tot1))
allocate (map2 (n_tot2))

```

```

allocate (map_connections (n_connections))
allocate (index (n_tot))
index = (/ (i, i = 1, n_tot) /)
map1(1 : n_in1) = index( 1 : n_in1); k = n_in1
map2(1 : n_in2) = index(k+1 : k+n_in2); k = k + n_in2
map1(n_in1+1 : n_in1+n_vir1) = index(k+1 : k+n_vir1); k = k + n_vir1
map2(n_in2+1 : n_in2+n_vir2) = index(k+1 : k+n_vir2); k = k + n_vir2
map_connections = index(k+1 : k+n_connections); k = k + n_connections
map1(n_in1+n_vir1+1 : n_tot1) = index(k+1 : k+n_out1); k = k + n_out1
map2(n_in2+n_vir2+1 : n_tot2) = index(k+1 : k+n_out2)
end subroutine compute_index_bounds_and_mappings

subroutine accumulate_connected_states (state_connections, me_index, &
    state, connection_index, qn_mask_conn, n_connections, i)
    type(state_matrix_t), intent(inout) :: state_connections
    integer, dimension(:), intent(out) :: me_index
    type(state_matrix_t), intent(in) :: state
    integer, dimension(:), intent(in) :: connection_index
    type(quantum_numbers_mask_t), dimension(:), intent(in) :: qn_mask_conn
    integer, intent(in) :: n_connections
    integer, intent(in) :: i
    type(state_iterator_t) :: it
    type(quantum_numbers_t), dimension(n_connections) :: qn
    integer :: me_index_state
    call state_iterator_init (it, state)
    do while (state_iterator_is_valid (it))
        qn = state_iterator_get_quantum_numbers (it, connection_index)
        call quantum_numbers_undefine (qn, qn_mask_conn)
        call quantum_numbers_canonicalize_color (qn)
        me_index_state = state_iterator_get_me_index (it)
        call state_matrix_add_state (state_connections, qn, &
            counter_index = i, &
            me_index = me_index(me_index_state))
        call state_iterator_advance (it)
    end do
end subroutine accumulate_connected_states

subroutine allocate_connection_entries &
    (connection_table, state_connections, n_connections, len1, len2)
    type(connection_table_t), dimension(:), intent(inout) :: &
        connection_table
    type(state_matrix_t), intent(in) :: state_connections
    integer, intent(in) :: n_connections, len1, len2
    type(state_iterator_t) :: it
    integer :: i
    integer, dimension(2) :: n
    call state_iterator_init (it, state_connections)
    do while (state_iterator_is_valid (it))
        i = state_iterator_get_me_index (it)
        n = state_iterator_get_me_count (it)
        allocate (connection_table(i)%qn_conn (n_connections))
        connection_table(i)%qn_conn = state_iterator_get_quantum_numbers (it)
        connection_table(i)%n_index = n
        allocate (connection_table(i)%index1 (n(1)))
    end do
end subroutine allocate_connection_entries

```

```

        allocate (connection_table(i)%index2 (n(2)))
        allocate (connection_table(i)%qn1 (len1, n(1)))
        allocate (connection_table(i)%qn2 (len2, n(2)))
        call state_iterator_advance (it)
    end do
end subroutine allocate_connection_entries

subroutine fill_connection_table (connection_table, &
    state, me_index, connection_mask, connection_index, i, offset)
    type(connection_table_t), dimension(:), intent(inout) :: &
        connection_table
    type(state_matrix_t), intent(in) :: state
    integer, dimension(:), intent(in) :: me_index
    logical, dimension(:), intent(in) :: connection_mask
    integer, dimension(:), intent(in) :: connection_index
    integer, dimension(:, :), allocatable :: color_map
    integer, intent(in) :: i, offset
    integer :: k, index_state, index_conn
    integer, dimension(size(connection_table)) :: count_conn
    type(quantum_numbers_t), dimension(:), allocatable :: qn
    type(state_iterator_t) :: it
    allocate (qn (state_matrix_get_depth (state)))
    count_conn = 0
    call state_iterator_init (it, state)
    do while (state_iterator_is_valid (it))
        index_state = state_iterator_get_me_index (it)
        index_conn = me_index(index_state)
        if (index_conn /= 0) then
            count_conn(index_conn) = count_conn(index_conn) + 1
            k = count_conn(index_conn)
            qn = state_iterator_get_quantum_numbers (it)
            call quantum_numbers_set_color_map (color_map, &
                qn(connection_index), connection_table(index_conn)%qn_conn)
            select case (i)
            case (1)
                connection_table(index_conn)%index1(k) = index_state
                connection_table(index_conn)%qn1(:,k) = &
                    pack (qn, connection_mask)
                call quantum_numbers_translate_color &
                    (connection_table(index_conn)%qn1(:,k), color_map, offset)
            case (2)
                connection_table(index_conn)%index2(k) = index_state
                connection_table(index_conn)%qn2(:,k) = &
                    pack (qn, connection_mask)
                call quantum_numbers_translate_color &
                    (connection_table(index_conn)%qn2(:,k), color_map, offset)
            end select
        end if
        call state_iterator_advance (it)
    end do
end subroutine fill_connection_table

subroutine make_product_interaction (int, &
    result_index, &

```

```

    int1, int2, &
    n_in, n_vir, n_out, &
    connection_table, n1, n2, n_connections, &
    connection_mask1, connection_mask2, &
    qn_mask_conn_initial, qn_mask_conn, qn_mask_rest)
type(interaction_t), intent(out), target :: int
integer, dimension(:), intent(out), allocatable :: result_index
type(interaction_t), intent(in) :: int1, int2
integer, intent(in) :: n_in, n_vir, n_out
type(connection_table_t), dimension(:), intent(in) :: connection_table
integer, intent(in) :: n1, n2, n_connections
type(quantum_numbers_mask_t), dimension(:), intent(in) :: &
    qn_mask_conn_initial
type(quantum_numbers_mask_t), intent(in) :: qn_mask_conn
type(quantum_numbers_mask_t), intent(in), optional :: qn_mask_rest
logical, dimension(:), intent(in) :: connection_mask1, connection_mask2
integer, dimension(n1) :: index1
integer, dimension(n2) :: index2
integer, dimension(n_connections) :: index_conn
integer :: i, j, k, m
integer :: n_result_entries
type(quantum_numbers_t), dimension(n1+n2+n_connections) :: qn
type(quantum_numbers_mask_t), dimension(n1+n2+n_connections) :: qn_mask
index1 = map1 ((/ (i, i = 1, n1) /))
index2 = map2 ((/ (i, i = 1, n2) /))
index_conn = map_connections ((/ (i, i = 1, n_connections) /))
if (present (qn_mask_rest)) then
    qn_mask(index1) = &
        pack (interaction_get_mask (int1), connection_mask1) &
        .or. qn_mask_rest
    qn_mask(index2) = &
        pack (interaction_get_mask (int2), connection_mask2) &
        .or. qn_mask_rest
else
    qn_mask(index1) = &
        pack (interaction_get_mask (int1), connection_mask1)
    qn_mask(index2) = &
        pack (interaction_get_mask (int2), connection_mask2)
end if
qn_mask(index_conn) = qn_mask_conn_initial .or. qn_mask_conn
call interaction_init (eval%int, n_in, n_vir, n_out, mask=qn_mask)
n_result_entries = &
    sum (connection_table%n_index(1) * connection_table%n_index(2))
allocate (result_index (n_result_entries))
m = 1
do i = 1, size (connection_table)
    qn(index_conn) = quantum_numbers_undefined &
        (connection_table(i)%qn_conn, qn_mask_conn)
    do j = 1, connection_table(i)%n_index(1)
        qn(index1) = connection_table(i)%qn1(:,j)
        do k = 1, connection_table(i)%n_index(2)
            qn(index2) = connection_table(i)%qn2(:,k)
            call interaction_add_state (int, qn, &
                me_index = result_index(m))

```

```

        m = m + 1
    end do
end do
end do
if (interaction_is_empty (int)) then
    call msg_message ()
    call msg_message ("First interaction")
    call interaction_write (int_in1)
    call msg_message ()
    call msg_message ("Second interaction")
    call interaction_write (int_in2)
    call msg_message ()
    call msg_bug ("Evaluator product: no matching states found")
end if
call interaction_set_mask (int, qn_mask)
call interaction_freeze (int)
end subroutine make_product_interaction

subroutine make_pairing_array (pa, &
    n_matrix_elements, result_index, connection_table)
    type(pairing_array_t), dimension(:), intent(out), allocatable :: pa
    integer, intent(in) :: n_matrix_elements
    integer, dimension(:), intent(in) :: result_index
    type(connection_table_t), dimension(:), intent(in) :: connection_table
    integer, dimension(:), allocatable :: n_entries
    integer :: i, j, k, m, r
    allocate (pa (n_matrix_elements))
    allocate (n_entries (n_matrix_elements))
    n_entries = 0
    do m = 1, size (result_index)
        r = result_index(m)
        n_entries(r) = n_entries(r) + 1
    end do
    call pairing_array_init &
        (pa, n_entries, has_i2=.true., has_factor=.false.)
    m = 1
    n_entries = 0
    do i = 1, size (connection_table)
        do j = 1, connection_table(i)%n_index(1)
            do k = 1, connection_table(i)%n_index(2)
                r = result_index(m)
                n_entries(r) = n_entries(r) + 1
                pa(r)%i1(n_entries(r)) = connection_table(i)%index1(j)
                pa(r)%i2(n_entries(r)) = connection_table(i)%index2(k)
                m = m + 1
            end do
        end do
    end do
end subroutine make_pairing_array

subroutine record_links (int, &
    int_in1, int_in2, connection_index, map1, map2, map_connections, &
    connection_mask1, connection_mask2, resonant)
    type(interaction_t), intent(inout) :: int

```

```

type(interaction_t), intent(in), target :: int_in1, int_in2
integer, dimension(:,:), intent(in) :: connection_index
integer, dimension(:), intent(in) :: map1, map2, map_connections
logical, dimension(:), intent(in) :: connection_mask1, connection_mask2
logical, intent(in), optional :: resonant
integer, dimension(:), allocatable :: map_all1, map_all2
integer :: i, j, k
allocate (map_all1 (size (connection_mask1)))
k = 0
j = 0
do i = 1, size (connection_mask1)
  if (connection_mask1(i)) then
    j = j + 1
    map_all1(i) = map1(j)
  else
    k = k + 1
    map_all1(i) = map_connections(k)
  end if
  call interaction_set_source_link (int, map_all1(i), int_in1, i)
end do
call interaction_transfer_relations (int_in1, int, map_all1)
allocate (map_all2 (size (connection_mask2)))
j = 0
do i = 1, size (connection_mask2)
  if (connection_mask2(i)) then
    j = j + 1
    map_all2(i) = map2(j)
    call interaction_set_source_link (int, map_all2(i), int_in2, i)
  else
    map_all2(i) = 0
  end if
end do
call interaction_transfer_relations (int_in2, int, map_all2)
call interaction_relate_connections (int, &
  int_in2, connection_index(:,2), map_all2, map_connections, resonant)
end subroutine record_links

end subroutine evaluator_init_product_ii

subroutine evaluator_init_product_ie &
  (eval, int_in1, eval_in2, qn_mask_conn, qn_mask_rest, &
  connections_are_resonant)
type(evaluator_t), intent(out), target :: eval
type(interaction_t), intent(in), target :: int_in1
type(evaluator_t), intent(in), target :: eval_in2
type(quantum_numbers_mask_t), intent(in) :: qn_mask_conn
type(quantum_numbers_mask_t), intent(in), optional :: qn_mask_rest
logical, intent(in), optional :: connections_are_resonant
call evaluator_init_product_ii &
  (eval, int_in1, eval_in2%int, qn_mask_conn, qn_mask_rest, &
  connections_are_resonant)
end subroutine evaluator_init_product_ie

subroutine evaluator_init_product_ei &

```

```

        (eval, eval_in1, int_in2, qn_mask_conn, qn_mask_rest, &
         connections_are_resonant)
    type(evaluator_t), intent(out), target :: eval
    type(evaluator_t), intent(in), target :: eval_in1
    type(interaction_t), intent(in), target :: int_in2
    type(quantum_numbers_mask_t), intent(in) :: qn_mask_conn
    type(quantum_numbers_mask_t), intent(in), optional :: qn_mask_rest
    logical, intent(in), optional :: connections_are_resonant
    call evaluator_init_product_ii &
        (eval, eval_in1%int, int_in2, qn_mask_conn, qn_mask_rest, &
         connections_are_resonant)
end subroutine evaluator_init_product_ei

subroutine evaluator_init_product_ee &
    (eval, eval_in1, eval_in2, qn_mask_conn, qn_mask_rest, &
     connections_are_resonant)
    type(evaluator_t), intent(out), target :: eval
    type(evaluator_t), intent(in), target :: eval_in1, eval_in2
    type(quantum_numbers_mask_t), intent(in) :: qn_mask_conn
    type(quantum_numbers_mask_t), intent(in), optional :: qn_mask_rest
    logical, intent(in), optional :: connections_are_resonant
    call evaluator_init_product_ii &
        (eval, eval_in1%int, eval_in2%int, qn_mask_conn, qn_mask_rest, &
         connections_are_resonant)
end subroutine evaluator_init_product_ee

```

Color-summed squared matrix

The initializer for an evaluator that squares a matrix element, including color factors. Unless requested otherwise by the quantum-number mask, the result contains off-diagonal matrix elements. (The input interaction must be diagonal since it represents an amplitude, not a density matrix.)

There is only one input interaction. The quantum-number mask is an array, one entry for each particle, so they can be treated individually. For academic purposes, we allow for the number of colors being different from three (but 3 is the default).

The algorithm is analogous to multiplication, with a few notable differences:

1. The connected particles are known, the correspondence is one-to-one. All particles are connected, and the mapping of indices is trivial, which simplifies the following steps.
2. `accumulate_connected_states`: The matrix of connected states encompasses all particles, but color indices are removed. However, ghost states are still kept separate from physical color states. No color-index reassignment is necessary.
3. The table of connections contains single index and quantum-number arrays instead of pairs of them. They are paired with themselves in all possible ways.

4. `make_squared_interaction`: Now apply the predefined quantum-numbers mask, which usually collects all color states (physical and ghosts), and possibly a helicity sum.
5. `make_pairing_array`: For each pair of input states, compute the color factor (including a potential ghost-parity sign) and store this in the pairing array together with the matrix-element indices for multiplication.
6. `record_links`: This is again trivial due to the one-to-one correspondence.

(Evaluators: public)+≡

`public :: evaluator_init_square_with_color_factors`

(Evaluators: procedures)+≡

```
subroutine evaluator_init_square_with_color_factors &
  (eval, int_in, qn_mask, nc)
  type(evaluator_t), intent(out), target :: eval
  type(interaction_t), intent(in), target :: int_in
  type(quantum_numbers_mask_t), dimension(:), intent(in) :: qn_mask
  integer, intent(in), optional :: nc
  integer :: ncol
  integer :: n_in, n_vir, n_out, n_tot
  integer, dimension(:), allocatable :: me_index
  type(quantum_numbers_mask_t), dimension(:), allocatable :: qn_mask_initial
  type(state_matrix_t) :: state_connections
  integer :: n_me_connections
  type :: connection_table_t
    type(quantum_numbers_t), dimension(:), allocatable :: qn_conn
    integer :: n_index = 0
    integer, dimension(:), allocatable :: index
    type(quantum_numbers_t), dimension(:, :), allocatable :: qn
  end type connection_table_t
  type(connection_table_t), dimension(:), allocatable :: connection_table
  integer, dimension(:), allocatable :: result_index
  eval%type = EVAL_SQUARE_WITH_COLOR_FACTORS
  ncol = 3; if (present(nc)) ncol = nc
  eval%int_in1 => int_in
!   print *, "Interaction square with color factors"
!   print *, "Input interaction"
!   call interaction_write (int_in)
  n_in = interaction_get_n_in (int_in)
  n_vir = interaction_get_n_vir (int_in)
  n_out = interaction_get_n_out (int_in)
  n_tot = interaction_get_n_tot (int_in)
  allocate (me_index (interaction_get_n_matrix_elements (int_in)))
  me_index = 0
  allocate (qn_mask_initial (n_tot))
  qn_mask_initial = interaction_get_mask (int_in)
  call quantum_numbers_mask_set_color (qn_mask_initial, &
    .true., mask_cg=.false.)
  call state_matrix_init (state_connections, n_counters=1)
  call accumulate_connected_states (state_connections, me_index, &
    interaction_get_state_matrix (int_in), qn_mask_initial, n_tot)
  n_me_connections = state_matrix_get_n_matrix_elements (state_connections)
  allocate (connection_table (n_me_connections))
```

```

call allocate_connection_entries (connection_table, &
    state_connections, n_tot)
call fill_connection_table (connection_table, &
    interaction_get_state_matrix (int_in), me_index)
call make_squared_interaction (eval%int, &
    result_index, &
    n_in, n_vir, n_out, n_tot, &
    connection_table, qn_mask_initial .or. qn_mask)
call make_pairing_array (eval%pairing_array, &
    interaction_get_n_matrix_elements (eval%int), &
    result_index, connection_table, n_in, n_tot, ncol)
call record_links (eval%int, int_in, n_tot)
call state_matrix_final (state_connections)
!   print *, "Result evaluator:"
!   call evaluator_write (eval)

contains

subroutine accumulate_connected_states &
    (state_connections, me_index, state, qn_mask, n_tot)
    type(state_matrix_t), intent(inout) :: state_connections
    integer, dimension(:), intent(out) :: me_index
    type(state_matrix_t), intent(in) :: state
    type(quantum_numbers_mask_t), dimension(:), intent(in) :: qn_mask
    integer, intent(in) :: n_tot
    type(quantum_numbers_t), dimension(n_tot) :: qn
    type(state_iterator_t) :: it
    integer :: me_index_state
    call state_iterator_init (it, state)
    do while (state_iterator_is_valid (it))
        qn = state_iterator_get_quantum_numbers (it)
        call quantum_numbers_undefine (qn, qn_mask)
        me_index_state = state_iterator_get_me_index (it)
        call state_matrix_add_state (state_connections, qn, &
            counter_index = 1, &
            me_index = me_index(me_index_state))
        call state_iterator_advance (it)
    end do
end subroutine accumulate_connected_states

subroutine allocate_connection_entries &
    (connection_table, state_connections, n_tot)
    type(connection_table_t), dimension(:), intent(inout) :: &
        connection_table
    type(state_matrix_t), intent(in) :: state_connections
    integer, intent(in) :: n_tot
    type(state_iterator_t) :: it
    integer :: i
    integer, dimension(1) :: n
    call state_iterator_init (it, state_connections)
    do while (state_iterator_is_valid (it))
        i = state_iterator_get_me_index (it)
        n = state_iterator_get_me_count (it)
        allocate (connection_table(i)%qn_conn (n_tot))

```

```

        connection_table(i)%qn_conn = state_iterator_get_quantum_numbers (it)
        connection_table(i)%n_index = n(1)
        allocate (connection_table(i)%index (n(1)))
        allocate (connection_table(i)%qn (n_tot, n(1)))
        call state_iterator_advance (it)
    end do
end subroutine allocate_connection_entries

subroutine fill_connection_table (connection_table, state, me_index)
    type(connection_table_t), dimension(:), intent(inout) :: &
        connection_table
    type(state_matrix_t), intent(in) :: state
    integer, dimension(:), intent(in) :: me_index
    integer :: k, index_state, index_conn
    integer, dimension(size(connection_table)) :: count_conn
    type(state_iterator_t) :: it
    count_conn = 0
    call state_iterator_init (it, state)
    do while (state_iterator_is_valid (it))
        index_state = state_iterator_get_me_index (it)
        index_conn = me_index(index_state)
        if (index_conn /= 0) then
            count_conn(index_conn) = count_conn(index_conn) + 1
            k = count_conn(index_conn)
            connection_table(index_conn)%index(k) = index_state
            connection_table(index_conn)%qn(:,k) = &
                state_iterator_get_quantum_numbers (it)
        end if
        call state_iterator_advance (it)
    end do
end subroutine fill_connection_table

subroutine make_squared_interaction (int, &
    result_index, &
    n_in, n_vir, n_out, n_tot, &
    connection_table, qn_mask)
    type(interaction_t), intent(out), target :: int
    integer, dimension(:), intent(out), allocatable :: result_index
    integer, intent(in) :: n_in, n_vir, n_out, n_tot
    type(connection_table_t), dimension(:), intent(in) :: connection_table
    type(quantum_numbers_mask_t), dimension(:), intent(in) :: qn_mask
    integer :: i, k, m
    integer :: n_result_entries
    type(quantum_numbers_t), dimension(n_tot) :: qn
    call interaction_init (eval%int, n_in, n_vir, n_out, mask=qn_mask)
    n_result_entries = sum (connection_table%n_index ** 2)
    allocate (result_index (n_result_entries))
    m = 1
    do i = 1, size (connection_table)
        qn = quantum_numbers_undefined (connection_table(i)%qn_conn, qn_mask)
        call interaction_add_state (int, qn, me_index = result_index(m))
        k = connection_table(i)%n_index ** 2
        result_index(m+1:m+k-1) = result_index(m)
        m = m + k
    end do
end subroutine make_squared_interaction

```

```

end do
call interaction_set_mask (int, qn_mask)
call interaction_freeze (int)
end subroutine make_squared_interaction

subroutine make_pairing_array (pa, &
    n_matrix_elements, result_index, connection_table, n_in, n_tot, ncol)
    type(pairing_array_t), dimension(:), intent(out), allocatable :: pa
    integer, intent(in) :: n_matrix_elements
    integer, dimension(:), intent(in) :: result_index
    type(connection_table_t), dimension(:), intent(in) :: connection_table
    integer, intent(in) :: n_in, n_tot, ncol
    integer, dimension(:), allocatable :: n_entries
    integer :: i, j, k, m, r
    integer :: nloops, nghost
    real(default) :: factor
    type(quantum_numbers_t), dimension(n_tot) :: qn
    allocate (pa (n_matrix_elements))
    allocate (n_entries (n_matrix_elements))
    n_entries = 0
    do m = 1, size (result_index)
        r = result_index(m)
        n_entries(r) = n_entries(r) + 1
    end do
    call pairing_array_init &
        (pa, n_entries, has_i2=.true., has_factor=.true.)
    m = 1
    n_entries = 0
    do i = 1, size (connection_table)
        do j = 1, connection_table(i)%n_index
            do k = 1, connection_table(i)%n_index
                r = result_index(m)
                n_entries(r) = n_entries(r) + 1
                pa(r)%i1(n_entries(r)) = connection_table(i)%index(j)
                pa(r)%i2(n_entries(r)) = connection_table(i)%index(k)
                qn = connection_table(i)%qn(:,j) .merge. &
                    connection_table(i)%qn(:,k)
                nloops = count_color_loops (quantum_numbers_get_color (qn))
                nghost = count (quantum_numbers_is_color_ghost (qn))
                factor = real (ncol, default) ** (nloops - nghost) &
                    / product (abs (quantum_numbers_get_color_type (qn(:n_in))))
                if (quantum_numbers_ghost_parity (qn)) factor = - factor
                pa(r)%factor(n_entries(r)) = factor
                m = m + 1
            end do
        end do
    end do
end subroutine make_pairing_array

subroutine record_links (int, int_in, n_tot)
    type(interaction_t), intent(inout) :: int
    type(interaction_t), intent(in), target :: int_in
    integer, intent(in) :: n_tot
    integer, dimension(n_tot) :: map

```

```

integer :: i
do i = 1, n_tot
  call interaction_set_source_link (int, i, int_in, i)
end do
map = (/ (i, i = 1, n_tot) /)
call interaction_transfer_relations (int_in, int, map)
end subroutine record_links

end subroutine evaluator_init_square_with_color_factors

```

Squared matrix distributed among color flows

The evaluator for computing the individual color-flow assignments of the result interaction and their coefficients. This is very similar to the previous initializer. There are further simplifications:

1. **accumulate_connected_states**: Only physical (non-ghost) states are recorded. Color indices are kept. No cross-terms will be generated, therefore each connected state is created only once, no counting is necessary.
2. The table of connections does not hold the original quantum-number assignments, since no color-factor computation is to be done.
3. **make_pairing_array**: Almost trivial since there are no cross terms and no color factors. Instead of a pairing, there is only a single matrix element array in each entry which has to be squared and summed over.

At this point, we have to invert the incoming color assignments, undoing the inversion that has been done when loading the color matrix for the hard process. This is not necessary for the color-summed squared matrix above, since its color indices are removed.

```

(Evaluators: public)+≡
public :: evaluator_init_squared_flows

(Evaluators: procedures)+≡
subroutine evaluator_init_squared_flows (eval, int_in, qn_mask)
  type(evaluator_t), intent(out), target :: eval
  type(interaction_t), intent(in), target :: int_in
  type(quantum_numbers_mask_t), dimension(:), intent(in) :: qn_mask
  integer :: n_in, n_vir, n_out, n_tot
  integer, dimension(:), allocatable :: me_index
  type(quantum_numbers_mask_t), dimension(:), allocatable :: qn_mask_initial
  type(state_matrix_t) :: state_connections
  integer :: n_me_connections
  type :: connection_table_t
    type(quantum_numbers_t), dimension(:), allocatable :: qn_conn
    integer :: index
  end type connection_table_t
  type(connection_table_t), dimension(:), allocatable :: connection_table
  integer, dimension(:), allocatable :: result_index
  eval%type = EVAL_SQUARED_FLOWS
  eval%int_in1 => int_in
!   print *, "Interaction squared as flow coefficients"

```

```

!      print *, "Input interaction"
!      call interaction_write (int_in)
n_in = interaction_get_n_in (int_in)
n_vir = interaction_get_n_vir (int_in)
n_out = interaction_get_n_out (int_in)
n_tot = interaction_get_n_tot (int_in)
allocate (me_index (interaction_get_n_matrix_elements (int_in)))
me_index = 0
allocate (qn_mask_initial (n_tot))
qn_mask_initial = interaction_get_mask (int_in)
call quantum_numbers_mask_set_color (qn_mask_initial, .false.)
call state_matrix_init (state_connections, n_counters=1)
call accumulate_connected_states (state_connections, me_index, &
    interaction_get_state_matrix (int_in), qn_mask_initial, n_tot)
n_me_connections = state_matrix_get_n_matrix_elements (state_connections)
allocate (connection_table (n_me_connections))
call allocate_connection_entries (connection_table, &
    state_connections, n_tot)
call fill_connection_table (connection_table, &
    interaction_get_state_matrix (int_in), me_index)
call make_squared_interaction (eval%int, &
    result_index, &
    n_in, n_vir, n_out, n_tot, &
    connection_table, qn_mask_initial .or. qn_mask)
call make_pairing_array (eval%pairing_array, &
    interaction_get_n_matrix_elements (eval%int), &
    result_index, connection_table, n_in, n_tot)
call record_links (eval%int, int_in, n_tot)
call state_matrix_final (state_connections)
!      print *, "Result evaluator:"
!      call evaluator_write (eval)

```

contains

```

subroutine accumulate_connected_states &
    (state_connections, me_index, state, qn_mask, n_tot)
type(state_matrix_t), intent(inout) :: state_connections
integer, dimension(:), intent(out) :: me_index
type(state_matrix_t), intent(in) :: state
type(quantum_numbers_mask_t), dimension(:), intent(in) :: qn_mask
integer, intent(in) :: n_tot
type(quantum_numbers_t), dimension(n_tot) :: qn
type(state_iterator_t) :: it
integer :: me_index_state
call state_iterator_init (it, state)
do while (state_iterator_is_valid (it))
    qn = state_iterator_get_quantum_numbers (it)
    if (all (quantum_numbers_are_physical (qn))) then
        call quantum_numbers_undefine (qn, qn_mask)
        me_index_state = state_iterator_get_me_index (it)
        call state_matrix_add_state (state_connections, qn, &
            me_index = me_index(me_index_state))
    end if
    call state_iterator_advance (it)
end do

```

```

        end do
    end subroutine accumulate_connected_states

    subroutine allocate_connection_entries &
        (connection_table, state_connections, n_tot)
        type(connection_table_t), dimension(:), intent(inout) :: &
            connection_table
        type(state_matrix_t), intent(in) :: state_connections
        integer, intent(in) :: n_tot
        type(state_iterator_t) :: it
        integer :: i
        call state_iterator_init (it, state_connections)
        do while (state_iterator_is_valid (it))
            i = state_iterator_get_me_index (it)
            allocate (connection_table(i)%qn_conn (n_tot))
            connection_table(i)%qn_conn = state_iterator_get_quantum_numbers (it)
            call state_iterator_advance (it)
        end do
    end subroutine allocate_connection_entries

    subroutine fill_connection_table (connection_table, state, me_index)
        type(connection_table_t), dimension(:), intent(inout) :: &
            connection_table
        type(state_matrix_t), intent(in) :: state
        integer, dimension(:), intent(in) :: me_index
        integer :: index_state, index_conn
        type(state_iterator_t) :: it
        call state_iterator_init (it, state)
        do while (state_iterator_is_valid (it))
            index_state = state_iterator_get_me_index (it)
            index_conn = me_index(index_state)
            if (index_conn /= 0) then
                connection_table(index_conn)%index = index_state
            end if
            call state_iterator_advance (it)
        end do
    end subroutine fill_connection_table

    subroutine make_squared_interaction (int, &
        result_index, &
        n_in, n_vir, n_out, n_tot, &
        connection_table, qn_mask)
        type(interaction_t), intent(out), target :: int
        integer, dimension(:), intent(out), allocatable :: result_index
        integer, intent(in) :: n_in, n_vir, n_out, n_tot
        type(connection_table_t), dimension(:), intent(in) :: connection_table
        type(quantum_numbers_mask_t), dimension(:), intent(in) :: qn_mask
        integer :: i
        integer :: n_result_entries
        type(quantum_numbers_t), dimension(n_tot) :: qn
        call interaction_init (eval%int, n_in, n_vir, n_out, mask=qn_mask)
        n_result_entries = size (connection_table)
        allocate (result_index (n_result_entries))
        do i = 1, size (connection_table)

```

```

        qn = quantum_numbers_undefined (connection_table(i)%qn_conn, qn_mask)
        call quantum_numbers_invert_color (qn(1:n_in))
        call interaction_add_state (int, qn, me_index = result_index(i))
    end do
    call interaction_set_mask (int, qn_mask)
    call interaction_freeze (int)
end subroutine make_squared_interaction

subroutine make_pairing_array (pa, &
    n_matrix_elements, result_index, connection_table, n_in, n_tot)
    type(pairing_array_t), dimension(:), intent(out), allocatable :: pa
    integer, intent(in) :: n_matrix_elements
    integer, dimension(:), intent(in) :: result_index
    type(connection_table_t), dimension(:), intent(in) :: connection_table
    integer, intent(in) :: n_in, n_tot
    integer, dimension(:), allocatable :: n_entries
    integer :: i, r
    allocate (pa (n_matrix_elements))
    allocate (n_entries (n_matrix_elements))
    n_entries = 0
    do i = 1, size (result_index)
        r = result_index(i)
        n_entries(r) = n_entries(r) + 1
    end do
    call pairing_array_init &
        (pa, n_entries, has_i2=.false., has_factor=.false.)
    n_entries = 0
    do i = 1, size (connection_table)
        r = result_index(i)
        n_entries(r) = n_entries(r) + 1
        pa(r)%i1(n_entries(r)) = connection_table(i)%index
    end do
end subroutine make_pairing_array

subroutine record_links (int, int_in, n_tot)
    type(interaction_t), intent(inout) :: int
    type(interaction_t), intent(in), target :: int_in
    integer, intent(in) :: n_tot
    integer, dimension(n_tot) :: map
    integer :: i
    do i = 1, n_tot
        call interaction_set_source_link (int, i, int_in, i)
    end do
    map = (/ (i, i = 1, n_tot) /)
    call interaction_transfer_relations (int_in, int, map)
end subroutine record_links

end subroutine evaluator_init_squared_flows

```

Copy with additional contracted color states

This evaluator involves no square or multiplication, its matrix elements are just copies of the (single) input interaction. However, the state matrix of the

interaction contains additional states that have color indices contracted. This is used for copies of the beam or structure-function interactions that need to match the hard interaction also in the case where its color indices coincide.

(Evaluators: public)+≡

public :: evaluator_init_color_contractions

(Evaluators: procedures)+≡

```

subroutine evaluator_init_color_contractions (eval, int_in)
  type(evaluator_t), intent(out), target :: eval
  type(interaction_t), intent(in), target :: int_in
  integer :: n_in, n_vir, n_out, n_tot
  type(state_matrix_t) :: state_with_contractions
  integer, dimension(:), allocatable :: me_index
  integer, dimension(:), allocatable :: result_index
  eval%type = EVAL_COLOR_CONTRACTION
  eval%int_in1 => int_in
!   print *, "Interaction with additional color contractions"
!   print *, "Input interaction"
!   call interaction_write (int_in)
  n_in = interaction_get_n_in (int_in)
  n_vir = interaction_get_n_vir (int_in)
  n_out = interaction_get_n_out (int_in)
  n_tot = interaction_get_n_tot (int_in)
  state_with_contractions = interaction_get_state_matrix (int_in)
  call state_matrix_add_color_contractions (state_with_contractions)
  call make_contracted_interaction (eval%int, &
    me_index, result_index, &
    n_in, n_vir, n_out, n_tot, &
    state_with_contractions, interaction_get_mask (int_in))
  call make_pairing_array (eval%pairing_array, me_index, result_index)
  call record_links (eval%int, int_in, n_tot)
  call state_matrix_final (state_with_contractions)
!   print *, "Result evaluator:"
!   call evaluator_write (eval)

```

contains

```

subroutine make_contracted_interaction (int, &
  me_index, result_index, &
  n_in, n_vir, n_out, n_tot, state, qn_mask)
  type(interaction_t), intent(out), target :: int
  integer, dimension(:), intent(out), allocatable :: me_index
  integer, dimension(:), intent(out), allocatable :: result_index
  integer, intent(in) :: n_in, n_vir, n_out, n_tot
  type(state_matrix_t), intent(in) :: state
  type(quantum_numbers_mask_t), dimension(:), intent(in) :: qn_mask
  type(state_iterator_t) :: it
  integer :: n_me, i
  type(quantum_numbers_t), dimension(n_tot) :: qn
  call interaction_init (int, n_in, n_vir, n_out, mask=qn_mask)
  n_me = state_matrix_get_n_leaves (state)
  allocate (me_index (n_me))
  allocate (result_index (n_me))
  call state_iterator_init (it, state)

```

```

i = 0
do while (state_iterator_is_valid (it))
  i = i + 1
  me_index(i) = state_iterator_get_me_index (it)
  qn = state_iterator_get_quantum_numbers (it)
  call interaction_add_state (int, qn, me_index = result_index(i))
  call state_iterator_advance (it)
end do
call interaction_freeze (int)
end subroutine make_contracted_interaction

subroutine make_pairing_array (pa, me_index, result_index)
  type(pairing_array_t), dimension(:), intent(out), allocatable :: pa
  integer, dimension(:), intent(in) :: me_index, result_index
  integer, dimension(:), allocatable :: n_entries
  integer :: n_matrix_elements, r, i
  n_matrix_elements = size (me_index)
  allocate (pa (n_matrix_elements))
  allocate (n_entries (n_matrix_elements))
  n_entries = 1
  call pairing_array_init &
    (pa, n_entries, has_i2=.false., has_factor=.false.)
  do i = 1, n_matrix_elements
    r = result_index(i)
    pa(r)%i1(1) = me_index(i)
  end do
end subroutine make_pairing_array

subroutine record_links (int, int_in, n_tot)
  type(interaction_t), intent(inout) :: int
  type(interaction_t), intent(in), target :: int_in
  integer, intent(in) :: n_tot
  integer, dimension(n_tot) :: map
  integer :: i
  do i = 1, n_tot
    call interaction_set_source_link (int, i, int_in, i)
  end do
  map = (/ (i, i = 1, n_tot) /)
  call interaction_transfer_relations (int_in, int, map)
end subroutine record_links

end subroutine evaluator_init_color_contractions

```

Auxiliary procedure for initialization

This will become a standard procedure in F2008. The result is true if the number of true values in the mask is odd. We use the function for determining the ghost parity of a quantum-number array.

```

(Evaluators: procedures)+≡
function parity (mask)
  logical :: parity
  logical, dimension(:) :: mask

```

```

integer :: i
parity = .false.
do i = 1, size (mask)
    if (mask(i)) parity = .not. parity
end do
end function parity

```

7.7.4 Accessing contents

Return the interaction component, as a pointer to avoid any copying.

```

(Evaluators: public)+≡
    public :: evaluator_get_int_ptr

(Evaluators: procedures)+≡
    function evaluator_get_int_ptr (eval) result (int)
        type(interaction_t), pointer :: int
        type(evaluator_t), intent(in), target :: eval
        int => eval%int
    end function evaluator_get_int_ptr

```

7.7.5 Inherited procedures

Return true if the state matrix within the interaction is empty.

```

(Evaluators: public)+≡
    public :: evaluator_is_empty

(Evaluators: procedures)+≡
    function evaluator_is_empty (eval) result (flag)
        logical :: flag
        type(evaluator_t), intent(in) :: eval
        flag = interaction_is_empty (eval%int)
    end function evaluator_is_empty

```

Return the number of particles.

```

(Evaluators: public)+≡
    public :: evaluator_get_n_tot
    public :: evaluator_get_n_in
    public :: evaluator_get_n_vir
    public :: evaluator_get_n_out

(Evaluators: procedures)+≡
    function evaluator_get_n_tot (eval) result (n_tot)
        integer :: n_tot
        type(evaluator_t), intent(in) :: eval
        n_tot = interaction_get_n_tot (eval%int)
    end function evaluator_get_n_tot

    function evaluator_get_n_in (eval) result (n_in)
        integer :: n_in
        type(evaluator_t), intent(in) :: eval
        n_in = interaction_get_n_in (eval%int)
    end function evaluator_get_n_in

```

```

end function evaluator_get_n_in

function evaluator_get_n_vir (eval) result (n_vir)
  integer :: n_vir
  type(evaluator_t), intent(in) :: eval
  n_vir = interaction_get_n_vir (eval%int)
end function evaluator_get_n_vir

function evaluator_get_n_out (eval) result (n_out)
  integer :: n_out
  type(evaluator_t), intent(in) :: eval
  n_out = interaction_get_n_out (eval%int)
end function evaluator_get_n_out

```

Sum all matrix element values.

```

<Evaluators: public>+≡
  public :: evaluator_sum

<Evaluators: procedures>+≡
  function evaluator_sum (eval) result (value)
    complex(default) :: value
    type(evaluator_t), intent(in) :: eval
    value = interaction_sum (eval%int)
  end function evaluator_sum

```

Append color-contracted states. Matrix element array and multiplication table are unaffected by this.

```

<Evaluators: public>+≡
  public :: evaluator_add_color_contractions

<Evaluators: procedures>+≡
  subroutine evaluator_add_color_contractions (eval)
    type(evaluator_t), intent(inout) :: eval
    call interaction_add_color_contractions (eval%int)
  end subroutine evaluator_add_color_contractions

```

Return the quantum-numbers mask of the enclosed interaction.

```

<Evaluators: public>+≡
  public :: evaluator_get_mask

<Evaluators: procedures>+≡
  function evaluator_get_mask (eval) result (mask)
    type(quantum_numbers_mask_t), dimension(:), allocatable :: mask
    type(evaluator_t), intent(in), target :: eval
    allocate (mask (interaction_get_n_tot (eval%int)))
    mask = interaction_get_mask (eval%int)
  end function evaluator_get_mask

```

Extend the linking of interactions to evaluators.

```

<Evaluators: public>+≡
  public :: interaction_set_source_link
  public :: evaluator_set_source_link

```

```

(Evaluators: interfaces)+≡
interface interaction_set_source_link
  module procedure interaction_set_source_link_eval
end interface
interface evaluator_set_source_link
  module procedure evaluator_set_source_link_int
  module procedure evaluator_set_source_link_eval
end interface

(Evaluators: procedures)+≡
subroutine interaction_set_source_link_eval (int, i, eval1, i1)
  type(interaction_t), intent(inout) :: int
  type(evaluator_t), intent(in), target :: eval1
  integer, intent(in) :: i, i1
  call interaction_set_source_link (int, i, eval1%int, i1)
end subroutine interaction_set_source_link_eval

subroutine evaluator_set_source_link_int (eval, i, int1, i1)
  type(evaluator_t), intent(inout) :: eval
  type(interaction_t), intent(in), target :: int1
  integer, intent(in) :: i, i1
  call interaction_set_source_link (eval%int, i, int1, i1)
end subroutine evaluator_set_source_link_int

subroutine evaluator_set_source_link_eval (eval, i, eval1, i1)
  type(evaluator_t), intent(inout) :: eval
  type(evaluator_t), intent(in), target :: eval1
  integer, intent(in) :: i, i1
  call interaction_set_source_link (eval%int, i, eval1%int, i1)
end subroutine evaluator_set_source_link_eval

```

Send momenta to the linked interactions.

```

(Evaluators: public)+≡
public :: evaluator_receive_momenta

(Evaluators: procedures)+≡
subroutine evaluator_receive_momenta (eval)
  type(evaluator_t), intent(inout) :: eval
  call interaction_receive_momenta (eval%int)
end subroutine evaluator_receive_momenta

```

Reassign external source links from one to another.

```

(Evaluators: public)+≡
public :: evaluator_reassign_links

(Evaluators: interfaces)+≡
interface evaluator_reassign_links
  module procedure evaluator_reassign_links_eval
  module procedure evaluator_reassign_links_int
end interface

(Evaluators: procedures)+≡
subroutine evaluator_reassign_links_eval (eval, eval_src, eval_target)
  type(evaluator_t), intent(inout) :: eval

```

```

type(evaluator_t), intent(in) :: eval_src
type(evaluator_t), intent(in), target :: eval_target
if (associated (eval%int_in1)) then
  if (interaction_get_tag (eval%int_in1) &
      == interaction_get_tag (eval_src%int)) then
    eval%int_in1 => eval_target%int
  end if
end if
if (associated (eval%int_in2)) then
  if (interaction_get_tag (eval%int_in2) &
      == interaction_get_tag (eval_src%int)) then
    eval%int_in2 => eval_target%int
  end if
end if
call interaction_reassign_links (eval%int, eval_src%int, eval_target%int)
end subroutine evaluator_reassign_links_eval

subroutine evaluator_reassign_links_int (eval, int_src, int_target)
  type(evaluator_t), intent(inout) :: eval
  type(interaction_t), intent(in) :: int_src
  type(interaction_t), intent(in), target :: int_target
  if (associated (eval%int_in1)) then
    if (interaction_get_tag (eval%int_in1) &
        == interaction_get_tag (int_src)) then
      eval%int_in1 => int_target
    end if
  end if
  if (associated (eval%int_in2)) then
    if (interaction_get_tag (eval%int_in2) &
        == interaction_get_tag (int_src)) then
      eval%int_in2 => int_target
    end if
  end if
  call interaction_reassign_links (eval%int, int_src, int_target)
end subroutine evaluator_reassign_links_int

```

Return flavor, momentum, and position of the first unstable particle present in the interaction.

(Evaluators: public)+≡

```
public :: evaluator_get_unstable_particle
```

(Evaluators: procedures)+≡

```

subroutine evaluator_get_unstable_particle (eval, flv, p, i)
  type(evaluator_t), intent(in) :: eval
  type(flavor_t), intent(out) :: flv
  type(vector4_t), intent(out) :: p
  integer, intent(out) :: i
  call interaction_get_unstable_particle (eval%int, flv, p, i)
end subroutine evaluator_get_unstable_particle

```

7.7.6 Deleting the evaluator

Only the interaction component needs finalization.

```

(Evaluators: public)+≡
  public :: evaluator_final

(Evaluators: procedures)+≡
  elemental subroutine evaluator_final (eval)
    type(evaluator_t), intent(inout) :: eval
    call interaction_final (eval%int)
  end subroutine evaluator_final

```

7.7.7 Evaluation

When the input interactions (which are pointed to in the pairings stored within the evaluator) are filled with values, we can activate the evaluator, i.e., calculate the result values which are stored in the interaction.

The evaluation of matrix elements can be done in parallel. A `forall` construct is not appropriate, however. We would need `do concurrent` here. Nevertheless, the evaluation functions are marked as `pure`.

```

(Evaluators: public)+≡
  public :: evaluator_evaluate

(Evaluators: procedures)+≡
  subroutine evaluator_evaluate (eval)
    type(evaluator_t), intent(inout), target :: eval
    integer :: i
    select case (eval%type)
    case (EVAL_PRODUCT)
      do i = 1, size(eval%pairing_array)
        call interaction_evaluate_product (eval%int, i, &
          eval%int_in1, eval%int_in2, &
          eval%pairing_array(i)%i1, eval%pairing_array(i)%i2)
      end do
    case (EVAL_SQUARE_WITH_COLOR_FACTORS)
      do i = 1, size(eval%pairing_array)
        call interaction_evaluate_product_cf (eval%int, i, &
          eval%int_in1, eval%int_in1, &
          eval%pairing_array(i)%i1, eval%pairing_array(i)%i2, &
          eval%pairing_array(i)%factor)
      end do
    case (EVAL_SQUARED_FLOWS)
      do i = 1, size(eval%pairing_array)
        call interaction_evaluate_square_c (eval%int, i, &
          eval%int_in1, &
          eval%pairing_array(i)%i1)
      end do
    case (EVAL_COLOR_CONTRACTION)
      do i = 1, size(eval%pairing_array)
        call interaction_evaluate_sum (eval%int, i, &
          eval%int_in1, &
          eval%pairing_array(i)%i1)
      end do
    end select
  end subroutine evaluator_evaluate

```

7.7.8 Test

Test: Create two interactions. The interactions are twofold connected. The first connection has a helicity index that is kept, the second connection has a helicity index that is summed over. Concatenate the interactions in an evaluator, which thus contains a result interaction. Fill the input interactions with values, activate the evaluator and print the result.

```

(Evaluators: public)+≡
    public :: evaluator_test

(Evaluators: procedures)+≡
    subroutine evaluator_test (mdl)
        type(model_t), intent(in), target :: mdl
        call evaluator_test1 (mdl)
    end subroutine evaluator_test

    subroutine evaluator_test1 (mdl)
        type(model_t), intent(in), target :: mdl
        type(interaction_t), target :: int_qqtt, int_tbw
        type(flavor_t), dimension(:), allocatable :: flv
        type(color_t), dimension(:), allocatable :: col
        type(helicity_t), dimension(:), allocatable :: hel
        type(quantum_numbers_t), dimension(:), allocatable :: qn
        integer :: f, c, h1, h2, h3
!       type(vector4_t), dimension(4) :: p
!       type(vector4_t), dimension(2) :: q
        type(quantum_numbers_mask_t) :: qn_mask_conn
        type(evaluator_t), target :: eval
        print *, "*** Evaluator for matrix product"
        print *, "*** Construct interaction for qq -> tt"
        call interaction_init (int_qqtt, 2, 0, 2, set_relations=.true.)
        allocate (flv (4), col (4), hel (4), qn (4))
        do c = 1, 2
            select case (c)
            case (1)
                call color_init_col_acl (col, (/ 1, 0, 1, 0 /), (/ 0, 2, 0, 2 /))
            case (2)
                call color_init_col_acl (col, (/ 1, 0, 2, 0 /), (/ 0, 1, 0, 2 /))
            end select
            do f = 1, 2
                call flavor_init (flv, (/f, -f, 6, -6/), mdl)
                do h1 = -1, 1, 2
                    call helicity_init (hel(3), h1)
                    do h2 = -1, 1, 2
                        call helicity_init (hel(4), h2)
                        call quantum_numbers_init (qn, flv, col, hel)
                        call interaction_add_state (int_qqtt, qn)
                    end do
                end do
            end do
        end do
        call interaction_freeze (int_qqtt)
        deallocate (flv, col, hel, qn)
        print *, "*** Construct interaction for t -> bW"
    end subroutine evaluator_test1

```

```

call interaction_init (int_tbw, 1, 0, 2, set_relations=.true.)
allocate (flv (3), col (3), hel (3), qn (3))
call flavor_init (flv, (/ 6, 5, 24 /), mdl)
call color_init_col_acl (col, (/ 1, 1, 0 /), (/ 0, 0, 0 /))
do h1 = -1, 1, 2
  call helicity_init (hel(1), h1)
  do h2 = -1, 1, 2
    call helicity_init (hel(2), h2)
    do h3 = -1, 1
      call helicity_init (hel(3), h3)
      call quantum_numbers_init (qn, flv, col, hel)
      call interaction_add_state (int_tbw, qn)
    end do
  end do
end do
call interaction_freeze (int_tbw)
deallocate (flv, col, hel, qn)
print *, "*** Link interactions"
call interaction_set_source_link (int_tbw, 1, int_qqtt, 3)
qn_mask_conn = new_quantum_numbers_mask (.false.,.false.,.true.)
print *, "*** Show input"
call interaction_write (int_qqtt)
print *
call interaction_write (int_tbw)
print *
print *, "*** Evaluate product"
call evaluator_init_product &
  (eval, int_qqtt, int_tbw, qn_mask_conn)
call evaluator_write (eval)

!   p(1) = vector4_moving (1000._default, 1000._default, 3)
!   p(2) = vector4_moving (200._default, 200._default, 2)
!   p(3) = vector4_moving (100._default, 200._default, 1)
!   p(4) = p(1) - p(2) - p(3)
!   call interaction_set_momenta (int1, p)
!   q(1) = vector4_moving (50._default,-50._default, 3)
!   q(2) = p(2) + p(4) - q(1)
!   call interaction_set_momenta (int2, q, outgoing=.true.)
!   call interaction_set_matrix_element &
!     (int1, ((2._default,0._default), (4._default,1._default), (-3._default,0._default)))
!   call interaction_set_matrix_element &
!     (int2, ((-3._default,0._default), (0._default,1._default), (1._default,2._default)))
!   call evaluator_receive_momenta (eval)
!   call evaluator_evaluate (eval)
!   call interaction_write (int1)
!   print *
!   call interaction_write (int2)
!   print *
!   call evaluator_write (eval)
!   print *
!   call interaction_final (int1)
!   call interaction_final (int2)
!   call evaluator_final (eval)

```

```

!      print *
!      print *, "*** Evaluator for matrix square"
!      call interaction_init (int1, 2, 0, 2, set_relations=.true.)
!      call flavor_init (flv, (/1, -1, 21, 21/), mdl)
!      call color_init (col(1), (/1/))
!      call color_init (col(2), (/2/))
!      call color_init (col(3), (/2, -3/))
!      call color_init (col(4), (/3, -1/))
!      call quantum_numbers_init (qn, flv, col)
!      call interaction_add_state (int1, qn)
!      call color_init (col(3), (/3, -1/))
!      call color_init (col(4), (/2, -3/))
!      call quantum_numbers_init (qn, flv, col)
!      call interaction_add_state (int1, qn)
!      call color_init (col(3), (/2, -1/))
!      call color_init (col(4), .true.)
!      call quantum_numbers_init (qn, flv, col)
!      call interaction_add_state (int1, qn)
!      call interaction_freeze (int1)
!      ! qn_mask2 = all false (default)
!      call evaluator_init_square_with_color_factors (eval, int1, qn_mask2, nc=3)
!      call evaluator_init_squared_flows (eval2, int1, qn_mask2)
!      qn_mask2 = new_quantum_numbers_mask (.false., .true., .true.)
!      call evaluator_init_trace (eval3, eval%int, qn_mask2)
!      call interaction_set_matrix_element &
!          (int1, (/2._default,0._default), (4._default,1._default), (-3._default,0._default)/))
!      call interaction_set_momenta (int1, p)
!      call interaction_write (int1)
!      print *
!      call evaluator_receive_momenta (eval)
!      call evaluator_evaluate (eval)
!      call evaluator_write (eval)
!      print *
!      call evaluator_receive_momenta (eval2)
!      call evaluator_evaluate (eval2)
!      call evaluator_write (eval2)
!      print *
!      call evaluator_receive_momenta (eval3)
!      call evaluator_evaluate (eval3)
!      call evaluator_write (eval3)
!      call interaction_final (int1)
!      call evaluator_final (eval)
!      call evaluator_final (eval2)
!      call evaluator_final (eval3)
end subroutine evaluator_test1

```

Chapter 8

Particles

In this chapter, we deal with particles which have well-defined quantum numbers. While within interactions, all correlations are manifest, a particle array is derived by selecting a particular quantum number set. This involves tracing over all other particles, as far as polarization is concerned. Thus, a particle has definite flavor, color, and a single-particle density matrix for polarization.

8.1 Polarization

Particle polarization is determined by a particular quantum state which has just helicity information. For defining polarizations, we adopt the phase convention for a spin-1/2 particle that

$$\rho = \frac{1}{2}(1 + \vec{\alpha} \cdot \vec{\sigma}) \quad (8.1)$$

with the polarization axis $\vec{\alpha}$. Using this, we define

1. Trivial polarization: $\vec{\alpha} = 0$. [This is unpolarized, but distinct from the particular undefined polarization matrix which has the same meaning.]
2. Circular polarization: $\vec{\alpha}$ points in $\pm z$ direction.
3. Transversal polarization: $\vec{\alpha}$ points orthogonal to the z direction, with a phase ϕ that is 0 for the x axis, and $\pi/2 = 90^\circ$ for the y axis. For antiparticles, the phase switches sign, corresponding to complex conjugation.
4. Axis polarization, where we explicitly give $\vec{\alpha}$.

For higher spin, we retain this definition, but apply it to the two components with maximum and minimum weight. For massless particles, this is sufficient. For massive particles, we add the possibilities:

5. Longitudinal polarization: Only the 0-component is set. This is possible only for bosons.
6. Diagonal polarization: Explicitly specify all components in the helicity basis.

Obviously, this does not exhaust the possible density matrices for higher spin, but it should cover all practical applications.

```

<polarizations.f90>≡
  <File header>

  module polarizations

    <Use kinds>
    <Use strings>
    use constants, only: ii !NODEP!
    <Use file utils>
    use lorentz !NODEP!
    use models
    use flavors
    use colors
    use helicities
    use quantum_numbers
    use state_matrices

    <Standard module head>

    <Polarizations: public>

    <Polarizations: types>

    <Polarizations: interfaces>

    contains

    <Polarizations: procedures>

  end module polarizations

```

8.1.1 The polarization type

This is not an extension, but rather a restriction of the quantum state. Flavor and color are ignored, there is just a one-particle helicity density matrix.

```

<Polarizations: public>≡
  public :: polarization_t

<Polarizations: types>≡
  type :: polarization_t
    logical :: polarized = .false.
    integer :: spin_type = 0
    integer :: multiplicity = 0
    type(state_matrix_t) :: state
  end type polarization_t

```

8.1.2 Basic initializer and finalizer

We need the particle flavor for determining the allowed helicity values. The density matrix is not set. This is private.

```

<Polarizations: procedures>≡
  elemental subroutine polarization_init (pol, flv)
    type(polarization_t), intent(out) :: pol
    type(flavor_t), intent(in) :: flv
    pol%spin_type = flavor_get_spin_type (flv)
    pol%multiplicity = flavor_get_multiplicity (flv)
    call state_matrix_init (pol%state)
  end subroutine polarization_init

```

The finalizer has to be public. The quantum state contains memory allocated to pointers.

```

<Polarizations: public>+≡
  public :: polarization_final

<Polarizations: procedures>+≡
  elemental subroutine polarization_final (pol)
    type(polarization_t), intent(inout) :: pol
    call state_matrix_final (pol%state)
  end subroutine polarization_final

```

8.1.3 I/O

```

<Polarizations: public>+≡
  public :: polarization_write

<Polarizations: procedures>+≡
  subroutine polarization_write (pol, unit)
    type(polarization_t), intent(in) :: pol
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write (u, "(1x,A,I1,A,I1,A)") &
      "Polarization: [spin_type = ", pol%spin_type, &
      ", mult = ", pol%multiplicity, "]"
    call state_matrix_write (pol%state, unit=unit)
  end subroutine polarization_write

```

Defined assignment: deep copy

```

<Polarizations: public>+≡
  public :: assignment(=)

<Polarizations: interfaces>≡
  interface assignment(=)
    module procedure polarization_assign
  end interface

```

```

<Polarizations: procedures>+≡
  subroutine polarization_assign (pol_out, pol_in)
    type(polarization_t), intent(out) :: pol_out
    type(polarization_t), intent(in) :: pol_in
    pol_out%polarized = pol_in%polarized
    pol_out%spin_type = pol_in%spin_type

```

```

    pol_out%multiplicity = pol_in%multiplicity
    pol_out%state = pol_in%state
end subroutine polarization_assign

```

Binary I/O.

```

<Polarizations: public>+≡
    public :: polarization_write_raw
    public :: polarization_read_raw

<Polarizations: procedures>+≡
    subroutine polarization_write_raw (pol, u)
        type(polarization_t), intent(in) :: pol
        integer, intent(in) :: u
        write (u) pol%polarized
        write (u) pol%spin_type
        write (u) pol%multiplicity
        call state_matrix_write_raw (pol%state, u)
    end subroutine polarization_write_raw

    subroutine polarization_read_raw (pol, u, iostat)
        type(polarization_t), intent(out) :: pol
        integer, intent(in) :: u
        integer, intent(out), optional :: iostat
        read (u, iostat=iostat) pol%polarized
        read (u, iostat=iostat) pol%spin_type
        read (u, iostat=iostat) pol%multiplicity
        call state_matrix_read_raw (pol%state, u, iostat=iostat)
    end subroutine polarization_read_raw

```

8.1.4 Accessing contents

Return true if the particle is polarized. This is the case if the first (and only) entry in the quantum state has undefined helicity.

```

<Polarizations: public>+≡
    public :: polarization_is_polarized

<Polarizations: procedures>+≡
    elemental function polarization_is_polarized (pol) result (polarized)
        logical :: polarized
        type(polarization_t), intent(in) :: pol
        polarized = pol%polarized
    end function polarization_is_polarized

```

Return true if the polarization is diagonal, i.e., all entries in the density matrix are diagonal.

```

<Polarizations: public>+≡
    public :: polarization_is_diagonal

<Polarizations: interfaces>+≡
    interface polarization_is_diagonal
        module procedure polarization_is_diagonal0
        module procedure polarization_is_diagonal1
    end interface

```

```
end interface
```

(Polarizations: procedures)+≡

```
function polarization_is_diagonal0 (pol) result (diagonal)
  logical :: diagonal
  type(polarization_t), intent(in) :: pol
  type(state_iterator_t) :: it
  diagonal = .true.
  call state_iterator_init (it, pol%state)
  do while (state_iterator_is_valid (it))
    diagonal = all (quantum_numbers_are_diagonal &
      (state_iterator_get_quantum_numbers (it)))
    if (.not. diagonal) exit
    call state_iterator_advance (it)
  end do
end function polarization_is_diagonal0

function polarization_is_diagonal1 (pol) result (diagonal)
  type(polarization_t), dimension(:), intent(in) :: pol
  logical, dimension(size(pol)) :: diagonal
  integer :: i
  do i = 1, size (pol)
    diagonal(i) = polarization_is_diagonal0 (pol(i))
  end do
end function polarization_is_diagonal1
```

8.1.5 Initialization from state matrix

Here, the state matrix is already known (but not necessarily normalized). The result will be either unpolarized, or a normalized spin density matrix.

(Polarizations: public)+≡

```
public :: polarization_init_state_matrix
```

(Polarizations: procedures)+≡

```
subroutine polarization_init_state_matrix (pol, state)
  type(polarization_t), intent(out) :: pol
  type(state_matrix_t), intent(in), target :: state
  type(state_iterator_t) :: it
  type(flavor_t) :: flv
  type(helicity_t) :: hel
  type(quantum_numbers_t), dimension(1) :: qn
  complex(default) :: value, t
  call state_iterator_init (it, state)
  flv = state_iterator_get_flavor (it, 1)
  hel = state_iterator_get_helicity (it, 1)
  if (helicity_is_defined (hel)) then
    call polarization_init (pol, flv)
    pol%polarized = .true.
    t = 0
  do while (state_iterator_is_valid (it))
    hel = state_iterator_get_helicity (it, 1)
    call quantum_numbers_init (qn(1), hel)
```

```

        value = state_iterator_get_matrix_element (it)
        call state_matrix_add_state (pol%state, qn, value=value)
        if (helicity_is_diagonal (hel)) t = t + value
        call state_iterator_advance (it)
    end do
    call state_matrix_freeze (pol%state)
    if (t /= 0) call state_matrix_renormalize (pol%state, 1._default / t)
else
    call polarization_init_unpolarized (pol, flv)
end if
end subroutine polarization_init_state_matrix

```

8.1.6 Specific initializers

Unpolarized particle, no helicity labels in the density matrix. The value is specified as $1/N$, where N is the multiplicity.

Exception: for left-handed or right-handed particles (neutrinos), polarization is always circular with fraction unity.

```

(Polarizations: public)+≡
    public :: polarization_init_unpolarized

(Polarizations: procedures)+≡
    subroutine polarization_init_unpolarized (pol, flv)
        type(polarization_t), intent(inout) :: pol
        type(flavor_t), intent(in) :: flv
        type(quantum_numbers_t), dimension(1) :: qn
        complex(default) :: value
        if (flavor_is_left_handed (flv)) then
            call polarization_init_circular (pol, flv, -1._default)
        else if (flavor_is_right_handed (flv)) then
            call polarization_init_circular (pol, flv, 1._default)
        else
            call polarization_init (pol, flv)
            value = 1._default / flavor_get_multiplicity (flv)
            call quantum_numbers_init (qn(1), flv = flv)
            call state_matrix_add_state (pol%state, qn)
            call state_matrix_freeze (pol%state)
            call state_matrix_set_matrix_element (pol%state, value)
        end if
    end subroutine polarization_init_unpolarized

```

Unpolarized particle, but explicit density matrix with helicity states allocated according to given flavor. Note that fermions have even spin type, bosons odd. The spin density matrix entries are scaled by **fraction**. This is used for initializing other polarizations:

$$\rho(f) = \frac{|f|}{N} \mathbf{1}.$$

```

(Polarizations: public)+≡
    public :: polarization_init_trivial

```

```

(Polarizations: procedures)+≡
subroutine polarization_init_trivial (pol, flv, fraction)
  type(polarization_t), intent(out) :: pol
  type(flavor_t), intent(in) :: flv
  real(default), intent(in), optional :: fraction
  type(helicity_t) :: hel
  type(quantum_numbers_t), dimension(1) :: qn
  integer :: h, hmax
  logical :: fermion
  complex(default) :: value
  call polarization_init (pol, flv)
  pol%polarized = .true.
  if (present (fraction)) then
    value = fraction / pol%multiplicity
  else
    value = 1._default / pol%multiplicity
  end if
  fermion = mod (pol%spin_type, 2) == 0
  hmax = pol%spin_type / 2
  select case (pol%multiplicity)
  case (2)
    do h = -hmax, hmax, 2*hmax
      call helicity_init (hel, h)
      call quantum_numbers_init (qn(1), hel)
      call state_matrix_add_state (pol%state, qn)
    end do
  case default
    do h = -hmax, hmax
      if (fermion .and. h == 0) cycle
      call helicity_init (hel, h)
      call quantum_numbers_init (qn(1), hel)
      call state_matrix_add_state (pol%state, qn)
    end do
  end select
  call state_matrix_freeze (pol%state)
  call state_matrix_set_matrix_element (pol%state, value)
end subroutine polarization_init_trivial

```

The following three modes are useful mainly for spin-1/2 particle and massless particles of any nonzero spin. Only the highest-weight components are filled.

Circular polarization: The density matrix of the two highest-weight states is

$$\rho(f) = \frac{1 - |f|}{2} \mathbf{1} + |f| \times \begin{cases} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, & f > 0; \\ \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, & f < 0, \end{cases}$$

If the polarization fraction $|f|$ is unity, we need only one entry in the density matrix.

```

(Polarizations: public)+≡
public :: polarization_init_circular

```

```

<Polarizations: procedures>+≡
subroutine polarization_init_circular (pol, flv, fraction)
  type(polarization_t), intent(out) :: pol
  type(flavor_t), intent(in) :: flv
  real(default), intent(in) :: fraction
  type(helicity_t), dimension(2) :: hel
  type(quantum_numbers_t), dimension(1) :: qn
  complex(default) :: value
  integer :: hmax
  call polarization_init (pol, flv)
  pol%polarized = .true.
  hmax = pol%spin_type / 2
  call helicity_init (hel(1), hmax)
  call helicity_init (hel(2), -hmax)
  if (abs (fraction) /= 1) then
    value = (1 + fraction) / 2
    call quantum_numbers_init (qn(1), hel(1))
    call state_matrix_add_state (pol%state, qn, value=value)
    value = (1 - fraction) / 2
    call quantum_numbers_init (qn(1), hel(2))
    call state_matrix_add_state (pol%state, qn, value=value)
  else
    value = abs (fraction)
    if (fraction > 0) then
      call quantum_numbers_init (qn(1), hel(1))
    else
      call quantum_numbers_init (qn(1), hel(2))
    end if
    call state_matrix_add_state (pol%state, qn, value=value)
  end if
  call state_matrix_freeze (pol%state)
end subroutine polarization_init_circular

```

Transversal polarization is analogous to circular, but we get a density matrix

$$\rho(f, \phi) = \frac{1 - |f|}{2} \mathbf{1} + \frac{|f|}{2} \begin{pmatrix} 1 & e^{-i\phi} \\ e^{i\phi} & 1 \end{pmatrix}.$$

The phase is $\phi = 0$ for the x -axis, $\phi = 90^\circ$ for the y axis as polarization vector. For an antiparticle, the phase switches sign, and for $f < 0$, the off-diagonal elements switch sign.

```

<Polarizations: public>+≡
public :: polarization_init_transversal

<Polarizations: procedures>+≡
subroutine polarization_init_transversal (pol, flv, phi, fraction)
  type(polarization_t), intent(inout) :: pol
  type(flavor_t), intent(in) :: flv
  real(default), intent(in) :: phi, fraction
  call polarization_init_axis &
    (pol, flv, fraction * (/ cos (phi), sin (phi), 0._default/))
end subroutine polarization_init_transversal

```

For axis polarization, we again set only the entries with maximum weight.

$$\rho(f, \phi) = \frac{1}{2} \begin{pmatrix} 1 + \alpha_3 & \alpha_1 - i\alpha_2 \\ \alpha_1 + i\alpha_2 & 1 - \alpha_3 \end{pmatrix}.$$

For an antiparticle, α_2 switches sign (complex conjugate).

```

(Polarizations: public)+≡
    public :: polarization_init_axis

(Polarizations: procedures)+≡
    subroutine polarization_init_axis (pol, flv, alpha)
        type(polarization_t), intent(out) :: pol
        type(flavor_t), intent(in) :: flv
        real(default), dimension(3), intent(in) :: alpha
        type(quantum_numbers_t), dimension(1) :: qn
        type(helicity_t), dimension(2,2) :: hel
        complex(default), dimension(2,2) :: value
        integer :: hmax
        call polarization_init (pol, flv)
        pol%polarized = .true.
        hmax = pol%spin_type / 2
        call helicity_init (hel(1,1), hmax, hmax)
        call helicity_init (hel(1,2), hmax, -hmax)
        call helicity_init (hel(2,1), -hmax, hmax)
        call helicity_init (hel(2,2), -hmax, -hmax)
        value(1,1) = (1 + alpha(3)) / 2
        value(2,2) = (1 - alpha(3)) / 2
        if (flavor_is_antiparticle (flv)) then
            value(1,2) = (alpha(1) + ii * alpha(2)) / 2
        else
            value(1,2) = (alpha(1) - ii * alpha(2)) / 2
        end if
        value(2,1) = conjg (value(1,2))
        if (value(1,1) /= 0) then
            call quantum_numbers_init (qn(1), hel(1,1))
            call state_matrix_add_state (pol%state, qn, value=value(1,1))
        end if
        if (value(2,2) /= 0) then
            call quantum_numbers_init (qn(1), hel(2,2))
            call state_matrix_add_state (pol%state, qn, value=value(2,2))
        end if
        if (value(1,2) /= 0) then
            call quantum_numbers_init (qn(1), hel(1,2))
            call state_matrix_add_state (pol%state, qn, value=value(1,2))
            call quantum_numbers_init (qn(1), hel(2,1))
            call state_matrix_add_state (pol%state, qn, value=value(2,1))
        end if
        call state_matrix_freeze (pol%state)
    end subroutine polarization_init_axis

```

This version specifies the polarization axis in terms of r (polarization degree) and θ, ϕ (polar and azimuthal angles).

If one of the angles is a nonzero multiple of π , roundoff errors typically will result in tiny contributions to unwanted components. Therefore, include a catch

for small numbers.

```

(Polarizations: public)+≡
    public :: polarization_init_angles

(Polarizations: procedures)+≡
    subroutine polarization_init_angles (pol, flv, r, theta, phi)
        type(polarization_t), intent(out) :: pol
        type(flavor_t), intent(in) :: flv
        real(default), intent(in) :: r, theta, phi
        real(default), dimension(3) :: alpha
        real(default), parameter :: eps = 10 * epsilon (1._default)
        alpha(1) = r * sin (theta) * cos (phi)
        alpha(2) = r * sin (theta) * sin (phi)
        alpha(3) = r * cos (theta)
        where (abs (alpha) < eps) alpha = 0
        call polarization_init_axis (pol, flv, alpha)
    end subroutine polarization_init_angles

```

Longitudinal polarization is defined only for massive bosons. Only the zero component is filled. Otherwise, unpolarized.

```

(Polarizations: public)+≡
    public :: polarization_init_longitudinal

(Polarizations: procedures)+≡
    subroutine polarization_init_longitudinal (pol, flv, fraction)
        type(polarization_t), intent(out) :: pol
        type(flavor_t), intent(in) :: flv
        real(default), intent(in) :: fraction
        integer :: spin_type, multiplicity
        type(helicity_t) :: hel
        type(quantum_numbers_t), dimension(1) :: qn
        complex(default) :: value
        integer :: n_values
        value = abs (fraction)
        spin_type = flavor_get_spin_type (flv)
        multiplicity = flavor_get_multiplicity (flv)
        if (mod (spin_type, 2) == 1 .and. multiplicity /= 2) then
            if (fraction /= 1) then
                call polarization_init_trivial (pol, flv, 1 - fraction)
                n_values = state_matrix_get_n_matrix_elements (pol%state)
                call state_matrix_add_to_matrix_element &
                    (pol%state, n_values/2 + 1, value)
            else
                call polarization_init (pol, flv)
                pol%polarized = .true.
                call helicity_init (hel, 0)
                call quantum_numbers_init (qn(1), hel)
                call state_matrix_add_state (pol%state, qn)
                call state_matrix_freeze (pol%state)
                call state_matrix_set_matrix_element (pol%state, value)
            end if
        else
            call polarization_init_unpolarized (pol, flv)
        end if
    end subroutine polarization_init_longitudinal

```

```
end subroutine polarization_init_longitudinal
```

This is diagonal polarization: we specify all components explicitly. We use only the positive components. The sum is normalized to unity. We assume that the length of `alpha` is equal to the particle multiplicity.

```
<Polarizations: public>+≡
  public :: polarization_init_diagonal

<Polarizations: procedures>+≡
  subroutine polarization_init_diagonal (pol, flv, alpha)
    type(polarization_t), intent(inout) :: pol
    type(flavor_t), intent(in) :: flv
    real(default), dimension(:), intent(in) :: alpha
    type(helicity_t) :: hel
    type(quantum_numbers_t), dimension(1) :: qn
    logical, dimension(size(alpha)) :: mask
    real(default) :: norm
    complex(default), dimension(:), allocatable :: value
    logical :: fermion
    integer :: h, hmax, i
    mask = alpha > 0
    norm = sum (alpha, mask); if (norm == 0) norm = 1
    allocate (value (count (mask)))
    value = pack (alpha / norm, mask)
    call polarization_init (pol, flv)
    pol%polarized = .true.
    fermion = mod (pol%spin_type, 2) == 0
    hmax = pol%spin_type / 2
    i = 0
    select case (pol%multiplicity)
    case (2)
      do h = -hmax, hmax, 2*hmax
        i = i + 1
        if (mask(i)) then
          call helicity_init (hel, h)
          call quantum_numbers_init (qn(1), hel)
          call state_matrix_add_state (pol%state, qn)
        end if
      end do
    case default
      do h = -hmax, hmax
        if (fermion .and. h == 0) cycle
        i = i + 1
        if (mask(i)) then
          call helicity_init (hel, h)
          call quantum_numbers_init (qn(1), hel)
          call state_matrix_add_state (pol%state, qn)
        end if
      end do
    end select
    call state_matrix_freeze (pol%state)
    call state_matrix_set_matrix_element (pol%state, value)
  end subroutine polarization_init_diagonal
```

Generic polarization: we generate all possible density matrix entries, but the values are left zero.

```

(Polarizations: public)+≡
    public :: polarization_init_generic

(Polarizations: procedures)+≡
    subroutine polarization_init_generic (pol, flv)
        type(polarization_t), intent(out) :: pol
        type(flavor_t), intent(in) :: flv
        type(helicity_t) :: hel
        type(quantum_numbers_t), dimension(1) :: qn
        logical :: fermion
        integer :: hmax, h1, h2
        call polarization_init (pol, flv)
        pol%polarized = .true.
        fermion = mod (pol%spin_type, 2) == 0
        hmax = pol%spin_type / 2
        select case (pol%multiplicity)
        case (2)
            do h1 = -hmax, hmax, 2*hmax
                do h2 = -hmax, hmax, 2*hmax
                    call helicity_init (hel, h1, h2)
                    call quantum_numbers_init (qn(1), hel)
                    call state_matrix_add_state (pol%state, qn)
                end do
            end do
        case default
            do h1 = -hmax, hmax
                if (fermion .and. h1 == 0) cycle
                do h2 = -hmax, hmax
                    if (fermion .and. h2 == 0) cycle
                    call helicity_init (hel, h1, h2)
                    call quantum_numbers_init (qn(1), hel)
                    call state_matrix_add_state (pol%state, qn)
                end do
            end do
        end select
        call state_matrix_freeze (pol%state)
    end subroutine polarization_init_generic

```

8.1.7 Operations

Combine polarization states by computing the outer product of the state matrices.

```

(Polarizations: public)+≡
    public :: combine_polarization_states

(Polarizations: procedures)+≡
    subroutine combine_polarization_states (pol, state)
        type(polarization_t), dimension(:), intent(in), target :: pol
        type(state_matrix_t), intent(out) :: state
        call outer_multiply (pol%state, state)
    end subroutine combine_polarization_states

```

Transform a polarization density matrix into a polarization vector. This is possible without information loss only for spin-1/2 and for massless particles. To get a unique answer in all cases, we consider only the components with highest weight. Obviously, this loses the longitudinal component of a massive vector, for instance.

This is the inverse operation of `polarization_init_axis` above, where the polarization fraction is set to unity.

```

(Polarizations: public)+≡
    public :: polarization_get_axis

(Polarizations: procedures)+≡
    function polarization_get_axis (pol) result (alpha)
        real(default), dimension(3) :: alpha
        type(polarization_t), intent(in) :: pol
        type(state_iterator_t) :: it
        complex(default), dimension(2,2) :: value
        type(helicity_t), dimension(2,2) :: hel
        type(helicity_t), dimension(1) :: hel1
        integer :: hmax, i, j
        if (pol%polarized) then
            hmax = pol%spin_type / 2
            call helicity_init (hel(1,1), hmax, hmax)
            call helicity_init (hel(1,2), hmax,-hmax)
            call helicity_init (hel(2,1),-hmax, hmax)
            call helicity_init (hel(2,2),-hmax,-hmax)
            value = 0
            call state_iterator_init (it, pol%state)
            do while (state_iterator_is_valid (it))
                hel1 = state_iterator_get_helicity (it)
                SCAN_HEL: do i = 1, 2
                    do j = 1, 2
                        if (hel1(1) == hel(i,j)) then
                            value(i,j) = state_iterator_get_matrix_element (it)
                            exit SCAN_HEL
                        end if
                    end do
                end do SCAN_HEL
                call state_iterator_advance (it)
            end do
            alpha(1) = value(1,2) + value(2,1)
            alpha(2) = ii * (value(1,2) - value(2,1))
            alpha(3) = value(1,1) - value(2,2)
        else
            alpha = 0
        end if
    end function polarization_get_axis

```

This function returns polarization degree and polar and azimuthal angles (θ, ϕ) of the polarization axis.

```

(Polarizations: public)+≡
    public :: polarization_to_angles

```

```

<Polarizations: procedures>+≡
subroutine polarization_to_angles (pol, r, theta, phi)
  type(polarization_t), intent(in) :: pol
  real(default), intent(out) :: r, theta, phi
  real(default), dimension(3) :: alpha
  real(default) :: r12
  if (pol%polarized) then
    alpha = polarization_get_axis (pol)
    r = sqrt (sum (alpha**2))
    if (any (alpha /= 0)) then
      r12 = sqrt (alpha(1)**2 + alpha(2)**2)
      theta = atan2 (r12, alpha(3))
      if (any (alpha(1:2) /= 0)) then
        phi = atan2 (alpha(2), alpha(1))
      else
        phi = 0
      end if
    else
      theta = 0
    end if
  else
    r = 0
    theta = 0
    phi = 0
  end if
end subroutine polarization_to_angles

```

8.1.8 Test

```

<Polarizations: public>+≡
public :: polarization_test

<Polarizations: procedures>+≡
subroutine polarization_test
  use os_interface, only: os_data_t
  type(os_data_t) :: os_data
  type(model_t), pointer :: model
  type(polarization_t) :: pol
  type(flavor_t) :: flv
  real(default), dimension(3) :: alpha
  real(default) :: r, theta, phi
  print *, "* Read model file"
  call syntax_model_file_init ()
  call model_list_read_model &
    (var_str("QCD"), var_str("test.mdl"), os_data, model)
  print *, "Unpolarized fermion"
  call flavor_init (flv, 1, model)
  call polarization_init_unpolarized (pol, flv)
  call polarization_write (pol)
  print *, "diagonal =", polarization_is_diagonal (pol)
  call polarization_final (pol)
  print *, "Unpolarized fermion"
  call polarization_init_circular (pol, flv, 0._default)

```

```

call polarization_write (pol)
call polarization_final (pol)
print *, "Transversally polarized fermion, phi=0"
call polarization_init_transversal (pol, flv, 0._default, 1._default)
call polarization_write (pol)
print *, "diagonal =", polarization_is_diagonal (pol)
call polarization_final (pol)
print *, "Transversally polarized fermion, phi=0.9, frac=0.8"
call polarization_init_transversal (pol, flv, 0.9_default, 0.8_default)
call polarization_write (pol)
print *, "diagonal =", polarization_is_diagonal (pol)
call polarization_final (pol)
print *, "All polarization directions of a fermion"
call polarization_init_generic (pol, flv)
call polarization_write (pol)
call polarization_final (pol)
call flavor_init (flv, 21, model)
print *, "Circularly polarized gluon, frac=0.3"
call polarization_init_circular (pol, flv, 0.3_default)
call polarization_write (pol)
call polarization_final (pol)
call flavor_init (flv, 23, model)
print *, "Circularly polarized massive vector, frac=-0.7"
call polarization_init_circular (pol, flv, -0.7_default)
call polarization_write (pol)
call polarization_final (pol)
print *, "Circularly polarized massive vector"
call polarization_init_circular (pol, flv, 1._default)
call polarization_write (pol)
call polarization_final (pol)
print *, "Longitudinally polarized massive vector, frac=0.4"
call polarization_init_longitudinal (pol, flv, 0.4_default)
call polarization_write (pol)
call polarization_final (pol)
print *, "Longitudinally polarized massive vector"
call polarization_init_longitudinal (pol, flv, 1._default)
call polarization_write (pol)
call polarization_final (pol)
print *, "Diagonally polarized massive vector"
call polarization_init_diagonal &
    (pol, flv, (/0._default, 1._default, 2._default/))
call polarization_write (pol)
call polarization_final (pol)
print *, "All polarization directions of a massive vector"
call polarization_init_generic (pol, flv)
call polarization_write (pol)
call polarization_final (pol)
call flavor_init (flv, 21, model)
print *, "Axis polarization (0.2, 0.4, 0.6)"
alpha = (/0.2_default, 0.4_default, 0.6_default/)
call polarization_init_axis (pol, flv, alpha)
call polarization_write (pol)
print *, "Recovered axis:"
alpha = polarization_get_axis (pol)

```

```

print *, "Angle polarization (0.5, 0.6, -1)"
r = 0.5_default
theta = 0.6_default
phi = -1._default
call polarization_init_angles (pol, flv, r, theta, phi)
call polarization_write (pol)
print *, "Recovered parameters (r, theta, phi):"
call polarization_to_angles (pol, r, theta, phi)
print *, r, theta, phi
call polarization_final (pol)
end subroutine polarization_test

```

8.2 Les Houches events

This section provides the interface to the Les Houches Accord for user-defined processes.

```

<les_houches_events.f90>≡
  <File header>

  module les_houches_events

    <Use kinds>
    use constants, only: pb_per_fb !NODEP!
    <Use file utils>
    use lorentz !NODEP!
    use prt_lists
    use flavors
    use colors
    use helicities
    use quantum_numbers
    use polarizations

    <Standard module head>

    <Les Houches events: public>

    <Les Houches events: parameters>

    <Les Houches events: variables>

    <Les Houches events: common blocks>

    <Les Houches events: interfaces>

    contains

    <Les Houches events: procedures>

  end module les_houches_events

```

8.2.1 Les Houches Event File: header/footer

These two routines write the header and footer for the Les Houches Event File format (LHEF).

The current version writes no information except for the generator name and version.

```
<Les Houches events: public>≡
  public :: les_houches_events_write_header
  public :: les_houches_events_write_footer

<Les Houches events: procedures>≡
  subroutine les_houches_events_write_header (unit)
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write (u, *) '<LesHouchesEvents version="1.0">'
    write (u, *) '<header>'
    write (u, *) '  <generator_name>WHIZARD</generator_name>'
    write (u, *) '  <generator_version><Version></generator_version>'
    write (u, *) '</header>'
  end subroutine les_houches_events_write_header

  subroutine les_houches_events_write_footer (unit)
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write (u, *) '</LesHouchesEvents>'
  end subroutine les_houches_events_write_footer
```

8.2.2 The HEPRUP common block

This common block is filled once per run.

Run characteristics

The maximal number of different processes.

```
<Les Houches events: parameters>≡
  integer, parameter :: MAXPUP = 100
```

The beam PDG codes.

```
<Les Houches events: variables>≡
  integer, dimension(2) :: IDBMUP
```

The beam energies in GeV.

```
<Les Houches events: variables>+≡
  double precision, dimension(2) :: EBMUP
```

The PDF group and set for the two beams. (Undefined: use -1; LHAPDF: use group = 0).

```
<Les Houches events: variables>+≡
  integer, dimension(2) :: PDFGUP
  integer, dimension(2) :: PDFSUP
```

The (re)weighting model. 1: events are weighted, the shower generator (SHG) selects processes according to the maximum weight (in pb) and unweights events. 2: events are weighted, the SHG selects processes according to their cross section (in pb) and unweights events. 3: events are unweighted and simply run through the SHG. 4: events are weighted, and the SHG keeps the weight. Negative numbers: negative weights are allowed (and are reweighted to ± 1 by the SHG, if allowed).

WHIZARD only supports modes 3 and 4, as the SHG is not given control over process selection. This is consistent with writing events to file, for offline showering.

```
<Les Houches events: variables>+=
  integer :: IDWTUP
```

The number of different processes.

```
<Les Houches events: variables>+=
  integer :: NPRUP
```

Process characteristics

Cross section and error in pb. (Cross section is needed only for IDWTUP = 2, so here both values are given for informational purposes only.)

```
<Les Houches events: variables>+=
  double precision, dimension(MAXPUP) :: XSECUP
  double precision, dimension(MAXPUP) :: XERRUP
```

Maximum weight, i.e., the maximum value that XWGTUP can take. Also unused for the supported weighting models.

```
<Les Houches events: variables>+=
  double precision, dimension(MAXPUP) :: XMAXUP
```

Internal ID of the selected process, matches IDPRUP below.

```
<Les Houches events: variables>+=
  integer, dimension(MAXPUP) :: LPRUP
```

The common block

```
<Les Houches events: common blocks>=
  common /HEPRUP/ &
    IDBMUP, EBMUP, PDFGUP, PDFSUP, IDWTUP, NPRUP, &
    XSECUP, XERRUP, XMAXUP, LPRUP
  save /HEPRUP/
```

Fill the run characteristics of the common block. The initialization sets the beam properties, number of processes, and weighting model.

```
<Les Houches events: public>+=
  public :: heprup_init
```

```
<Les Houches events: procedures>+=
  subroutine heprup_init &
    (beam_pdg, beam_energy, n_processes, unweighted, negative_weights)
    integer, dimension(2), intent(in) :: beam_pdg
    real(default), dimension(2), intent(in) :: beam_energy
    integer, intent(in) :: n_processes
```

```

logical, intent(in) :: unweighted
logical, intent(in) :: negative_weights
IDBMUP = beam_pdg
EBMUP = beam_energy
PDFGUP = -1
PDFSUP = -1
if (unweighted) then
    IDWTUP = 3
else
    IDWTUP = 4
end if
if (negative_weights) IDWTUP = - IDWTUP
NPRUP = n_processes
end subroutine heprup_init

```

Specify PDF set info. Since we support only LHAPDF, the group entry is zero.

```

<Les Houches events: public>+≡
public :: heprup_set_lhapdf_id

<Les Houches events: procedures>+≡
subroutine heprup_set_lhapdf_id (i_beam, pdf_id)
    integer, intent(in) :: i_beam, pdf_id
    PDFGUP(i_beam) = 0
    PDFSUP(i_beam) = pdf_id
end subroutine heprup_set_lhapdf_id

```

Fill the characteristics for a particular process. Only the process ID is mandatory. Note that WHIZARD computes cross sections in fb, so we have to rescale to pb. The maximum weight is meaningless for unweighted events.

```

<Les Houches events: public>+≡
public :: heprup_set_process_parameters

<Les Houches events: procedures>+≡
subroutine heprup_set_process_parameters &
    (i, process_id, cross_section, error, max_weight)
    integer, intent(in) :: i, process_id
    real(default), intent(in), optional :: cross_section, error, max_weight
    LPRUP(i) = process_id
    if (present (cross_section)) then
        XSECUP(i) = cross_section * pb_per_fb
    else
        XSECUP(i) = 0
    end if
    if (present (error)) then
        XERRUP(i) = error * pb_per_fb
    else
        XERRUP(i) = 0
    end if
    select case (IDWTUP)
    case (3); XMAXUP(i) = 1
    case (4)
        if (present (max_weight)) then
            XMAXUP(i) = max_weight * pb_per_fb
        else

```

```

        XMAXUP(i) = 0
    end if
end select
end subroutine heprup_set_process_parameters

```

8.2.3 Run parameter output

This routine writes the initialization block according to the LHEF standard. It uses the current contents of the HEPRUP block.

```

<Les Houches events: public>+≡
public :: heprup_write_lhef

<Les Houches events: procedures>+≡
subroutine heprup_write_lhef (unit)
    integer, intent(in), optional :: unit
    integer :: u, i
    u = output_unit (unit); if (u < 0) return
    write (u, *) "<init>"
    write (u, *) IDBMUP, EBMUP, PDFGUP, PDFSUP, IDWTUP, NPRUP
    do i = 1, NPRUP
        write (u, *) XSECUP(i), XERRUP(i), XMAXUP(i), LPRUP(i)
    end do
    write (u, *) "</init>"
end subroutine heprup_write_lhef

```

8.2.4 The HEPEUP common block

This common block is filled once per event.

Event characteristics

The maximal number of particles in an event record.

```

<Les Houches events: parameters>+≡
integer, parameter :: MAXNUP = 500

```

The number of particles in this event.

```

<Les Houches events: variables>+≡
integer :: NUP

```

The process ID for this event.

```

<Les Houches events: variables>+≡
integer :: IDPRUP

```

The weight of this event (± 1 for unweighted events).

```

<Les Houches events: variables>+≡
double precision :: XWGTUP

```

The factorization scale that is used for PDF calculation (-1 if undefined).

```

<Les Houches events: variables>+≡
double precision :: SCALUP

```

The QED and QCD couplings α used for this event (-1 if undefined).

```
<Les Houches events: variables>+≡  
  double precision :: AQEDUP  
  double precision :: AQCDUP
```

Particle characteristics

The PDG code:

```
<Les Houches events: variables>+≡  
  integer, dimension(MAXNUP) :: IDUP
```

The status code. Incoming: -1 , outgoing: $+1$. Intermediate t-channel propagator: -2 (currently not used by WHIZARD). Intermediate resonance whose mass should be preserved: 2 . Intermediate resonance for documentation: 3 (currently not used). Beam particles: -9 .

```
<Les Houches events: variables>+≡  
  integer, dimension(MAXNUP) :: ISTUP
```

Index of first and last mother.

```
<Les Houches events: variables>+≡  
  integer, dimension(2,MAXNUP) :: MOTHUP
```

Color line index of the color and anticolor entry for the particle.

```
<Les Houches events: variables>+≡  
  integer, dimension(2,MAXNUP) :: ICOLUP
```

Momentum, energy, and invariant mass: (p_x, p_y, p_z, E, M) . For space-like particles, M is the negative square root of the absolute value of the invariant mass.

```
<Les Houches events: variables>+≡  
  double precision, dimension(5,MAXNUP) :: PUP
```

Invariant lifetime (distance) from production to decay in mm.

```
<Les Houches events: variables>+≡  
  double precision, dimension(MAXNUP) :: VTIMUP
```

Cosine of the angle between the spin-vector and a particle and the 3-momentum of its mother, given in the lab frame. If undefined/unpolarized: 9 .

```
<Les Houches events: variables>+≡  
  double precision, dimension(MAXNUP) :: SPINUP
```

The common block

```
<Les Houches events: common blocks>+≡  
  common /HEPEUP/ &  
    NUP, IDPRUP, XWGTUP, SCALUP, AQEDUP, AQCDUP, &  
    IDUP, ISTUP, MOTHUP, ICOLUP, PUP, VTIMUP, SPINUP  
  save /HEPEUP/
```

Fill the event characteristics of the common block. The initialization sets only the number of particles and initializes the rest with default values. The other routine sets the optional parameters.

```
<Les Houches events: public>+≡  
  public :: hepeup_init  
  public :: hepeup_set_event_parameters
```

```

<Les Houches events: procedures>+=
subroutine hepeup_init (n_tot)
  integer, intent(in) :: n_tot
  NUP = n_tot
  IDPRUP = 0
  XWGTUP = 1
  SCALUP = -1
  AQEDUP = -1
  AQCDUP = -1
end subroutine hepeup_init

subroutine hepeup_set_event_parameters &
  (proc_id, weight, scale, alpha_qed, alpha_qcd)
  integer, intent(in), optional :: proc_id
  real(default), intent(in), optional :: weight, scale, alpha_qed, alpha_qcd
  if (present (proc_id)) IDPRUP = proc_id
  if (present (weight)) XWGTUP = weight
  if (present (scale)) SCALUP = scale
  if (present (alpha_qed)) AQEDUP = alpha_qed
  if (present (alpha_qcd)) AQCDUP = alpha_qcd
end subroutine hepeup_set_event_parameters

```

Below we need the particle status codes which are actually defined in the `prt_lists` module.

Set the entry for a specific particle. All parameters are set with the exception of lifetime and spin, where default values are stored.

```

<Les Houches events: public>+=
public :: hepeup_set_particle

<Les Houches events: procedures>+=
subroutine hepeup_set_particle (i, pdg, status, parent, p, m2)
  integer, intent(in) :: i
  integer, intent(in) :: pdg, status
  integer, dimension(:), intent(in) :: parent
  type(vector4_t), intent(in) :: p
  real(default), intent(in) :: m2
  IDUP(i) = pdg
  select case (status)
    case (PRT_INCOMING); ISTUP(i) = -1
    case (PRT_OUTGOING); ISTUP(i) = 1
    case (PRT_RESONANT); ISTUP(i) = 2
    case default; ISTUP(i) = 0
  end select
  select case (size (parent))
    case (1); MOTHUP(:,i) = parent(1)
    case (2); MOTHUP(:,i) = parent
    case default; MOTHUP(:,i) = 0
  end select
  PUP(1:3,i) = vector3_get_components (space_part (p))
  PUP(4,i) = energy (p)
  PUP(5,i) = sign (sqrt (abs (m2)), m2)
  VTIMUP(i) = 0
  SPINUP(i) = 9
end subroutine hepeup_set_particle

```

Set the lifetime, actually $c\tau$ measured in mm, where τ is the invariant lifetime.

```

<Les Houches events: public>+≡
  public :: hepeup_set_particle_lifetime

<Les Houches events: procedures>+≡
  subroutine hepeup_set_particle_lifetime (i, lifetime)
    integer, intent(in) :: i
    real(default), intent(in) :: lifetime
    VTIMUP(i) = lifetime
  end subroutine hepeup_set_particle_lifetime

```

Set the particle spin entry. We need the cosine of the angle of the spin axis with respect to the three-momentum of the parent particle.

If the particle has a full polarization density matrix given, we need the particle momentum and polarization as well as the mother-particle momentum. The polarization is transformed into a spin vector (which is sensible only for spin-1/2 or massless particles), which then is transformed into the lab frame (by a rotation of the 3-axis to the particle momentum axis). Finally, we compute the scalar product of this vector with the mother-particle three-momentum.

This puts severe restrictions on the applicability of this definition, and Lorentz invariance is lost. Unfortunately, the Les Houches Accord requires this computation.

```

<Les Houches events: public>+≡
  public :: hepeup_set_particle_spin

<Les Houches events: interfaces>≡
  interface hepeup_set_particle_spin
    module procedure hepeup_set_particle_spin_pol
  end interface

<Les Houches events: procedures>+≡
  subroutine hepeup_set_particle_spin_pol (i, p, pol, p_mother)
    integer, intent(in) :: i
    type(vector4_t), intent(in) :: p
    type(polarization_t), intent(in) :: pol
    type(vector4_t), intent(in) :: p_mother
    type(vector3_t) :: s3, p3
    type(vector4_t) :: s4
    s3 = vector3_moving (polarization_get_axis (pol))
    p3 = space_part (p)
    s4 = rotation_to_2nd (3, p3) * vector4_moving (0._default, s3)
    SPINUP(i) = enclosed_angle_ct (s4, p_mother)
  end subroutine hepeup_set_particle_spin_pol

```

8.2.5 Event output

This routine writes event output according to the LHEF standard. It uses the current contents of the HEPEUP block.

```

<Les Houches events: public>+≡
  public :: hepeup_write_lhef

```

```

<Les Houches events: procedures>+=
subroutine hepeup_write_lhef (unit)
  integer, intent(in), optional :: unit
  integer :: u, i
  u = output_unit (unit); if (u < 0) return
  write (u, *) "<event>"
  write (u, *) NUP, IDPRUP, XWGTUP, SCALUP, AQEDUP, AQCDUP
  do i = 1, NUP
    write (u, *) IDUP(i), ISTUP(i), MOTHUP(:,i), ICOLUP(:,i), &
      PUP(:,i), VTIMUP(i), SPINUP(i)
  end do
  write (u, *) "</event>"
end subroutine hepeup_write_lhef

```

8.3 HepMC events

This section provides the interface to the HepMC C++ library for handling Monte-Carlo events.

Each C++ class of HepMC that we use is mirrored by a Fortran type, which contains as its only component the C pointer to the C++ object.

Each C++ method of HepMC that we use has a C wrapper function. This function takes a pointer to the host object as its first argument. Further arguments are either C pointers, or in the case of simple types (integer, real), interoperable C/Fortran objects.

The C wrapper functions have explicit interfaces in the Fortran module. They are called by Fortran wrapper procedures. These are treated as methods of the corresponding Fortran type.

```

(hepmc_interface.f90)≡
<File header>

module hepmc_interface

  use iso_c_binding !NODEP!
  <Use kinds>
  <Use strings>
  use constants !NODEP!
  use lorentz !NODEP!
  use models
  use flavors
  use colors
  use helicities
  use quantum_numbers
  use polarizations

  <Standard module head>

  <HepMC interface: public>

  <HepMC interface: types>

  <HepMC interface: interfaces>

```

```
contains

<HepMC interface: procedures>

end module hepmc_interface
```

8.3.1 Interface check

This function can be called in order to verify that we are using the actual HepMC library, and not the dummy version.

```
<HepMC interface: interfaces>≡
  interface
    logical(c_bool) function hepmc_available () bind(C)
      import
    end function hepmc_available
  end interface

<HepMC interface: public>≡
  public :: hepmc_is_available

<HepMC interface: procedures>≡
  function hepmc_is_available () result (flag)
    logical :: flag
    flag = hepmc_available ()
  end function hepmc_is_available
```

8.3.2 FourVector

The C version of four-vectors is often transferred by value, and the associated procedures are all inlined. The wrapper needs to transfer by reference, so we create FourVector objects on the heap which have to be deleted explicitly. The input is a `vector4_t` or `vector3_t` object from the `lorentz` module.

```
<HepMC interface: public>+≡
  public :: hepmc_four_vector_t

<HepMC interface: types>≡
  type :: hepmc_four_vector_t
    private
    type(c_ptr) :: obj
  end type hepmc_four_vector_t
```

In the C constructor, the zero-component (fourth argument) is optional; if missing, it is set to zero. The Fortran version has initializer form and takes either a three-vector or a four-vector. A further version extracts the four-vector from a HepMC particle object.

```
<HepMC interface: interfaces>+≡
  interface
    type(c_ptr) function new_four_vector_xyz (x, y, z) bind(C)
      import
      real(c_double), value :: x, y, z
    end function new_four_vector_xyz
```

```

end interface
interface
  type(c_ptr) function new_four_vector_xyz (x, y, z, t) bind(C)
  import
    real(c_double), value :: x, y, z, t
  end function new_four_vector_xyz
end interface
<HepMC interface: public>+≡
  public :: hepmc_four_vector_init
<HepMC interface: interfaces>+≡
  interface hepmc_four_vector_init
    module procedure hepmc_four_vector_init_v4
    module procedure hepmc_four_vector_init_v3
    module procedure hepmc_four_vector_init_hepmc_prt
  end interface
<HepMC interface: procedures>+≡
  subroutine hepmc_four_vector_init_v4 (pp, p)
    type(hepmc_four_vector_t), intent(out) :: pp
    type(vector4_t), intent(in) :: p
    real(default), dimension(0:3) :: pa
    pa = vector4_get_components (p)
    pp%obj = new_four_vector_xyz &
      (real (pa(1), c_double), &
       real (pa(2), c_double), &
       real (pa(3), c_double), &
       real (pa(0), c_double))
  end subroutine hepmc_four_vector_init_v4

  subroutine hepmc_four_vector_init_v3 (pp, p)
    type(hepmc_four_vector_t), intent(out) :: pp
    type(vector3_t), intent(in) :: p
    real(default), dimension(3) :: pa
    pa = vector3_get_components (p)
    pp%obj = new_four_vector_xyz &
      (real (pa(1), c_double), &
       real (pa(2), c_double), &
       real (pa(3), c_double))
  end subroutine hepmc_four_vector_init_v3

  subroutine hepmc_four_vector_init_hepmc_prt (pp, prt)
    type(hepmc_four_vector_t), intent(out) :: pp
    type(hepmc_particle_t), intent(in) :: prt
    pp%obj = gen_particle_momentum (prt%obj)
  end subroutine hepmc_four_vector_init_hepmc_prt

```

Here, the destructor is explicitly needed.

```

<HepMC interface: interfaces>+≡
  interface
    subroutine four_vector_delete (p_obj) bind(C)
    import
      type(c_ptr), value :: p_obj
    end subroutine four_vector_delete
  end interface

```

```

<HepMC interface: public>+≡
  public :: hepmc_four_vector_final
<HepMC interface: procedures>+≡
  subroutine hepmc_four_vector_final (p)
    type(hepmc_four_vector_t), intent(inout) :: p
    call four_vector_delete (p%obj)
  end subroutine hepmc_four_vector_final

```

Convert to a Lorentz vector.

```

<HepMC interface: interfaces>+≡
  interface
    function four_vector_px (p_obj) result (px) bind(C)
      import
      real(c_double) :: px
      type(c_ptr), value :: p_obj
    end function four_vector_px
  end interface
  interface
    function four_vector_py (p_obj) result (py) bind(C)
      import
      real(c_double) :: py
      type(c_ptr), value :: p_obj
    end function four_vector_py
  end interface
  interface
    function four_vector_pz (p_obj) result (pz) bind(C)
      import
      real(c_double) :: pz
      type(c_ptr), value :: p_obj
    end function four_vector_pz
  end interface
  interface
    function four_vector_e (p_obj) result (e) bind(C)
      import
      real(c_double) :: e
      type(c_ptr), value :: p_obj
    end function four_vector_e
  end interface
<HepMC interface: public>+≡
  public :: hepmc_four_vector_to_vector4
<HepMC interface: procedures>+≡
  subroutine hepmc_four_vector_to_vector4 (pp, p)
    type(hepmc_four_vector_t), intent(in) :: pp
    type(vector4_t), intent(out) :: p
    real(default) :: E
    real(default), dimension(3) :: p3
    E = four_vector_e (pp%obj)
    p3(1) = four_vector_px (pp%obj)
    p3(2) = four_vector_py (pp%obj)
    p3(3) = four_vector_pz (pp%obj)
    p = vector4_moving (E, vector3_moving (p3))
  end subroutine hepmc_four_vector_to_vector4

```

8.3.3 Polarization

Polarization objects are temporarily used for assigning particle polarization. We add a flag `polarized`. If this is false, the polarization is not set and should not be transferred to `hepmc_particle` objects.

```

<HepMC interface: public>+≡
    public :: hepmc_polarization_t

<HepMC interface: types>+≡
    type :: hepmc_polarization_t
    private
        logical :: polarized = .false.
        type(c_ptr) :: obj
    end type hepmc_polarization_t

```

Constructor. The C wrapper takes polar and azimuthal angle as arguments. The Fortran version allows for either a complete polarization density matrix, or for a definite (diagonal) helicity.

HepMC does not allow to specify the degree of polarization, therefore we have to map it to either 0 or 1. We choose 0 for polarization less than 0.5 and 1 for polarization greater than 0.5. Even this simplification works only for spin-1/2 and for massless particles; massive vector bosons cannot be treated this way. In particular, zero helicity is always translated as unpolarized.

```

<HepMC interface: interfaces>+≡
    interface
        type(c_ptr) function new_polarization (theta, phi) bind(C)
        import
            real(c_double), value :: theta, phi
        end function new_polarization
    end interface

<HepMC interface: public>+≡
    public :: hepmc_polarization_init

<HepMC interface: interfaces>+≡
    interface hepmc_polarization_init
        module procedure hepmc_polarization_init_pol
        module procedure hepmc_polarization_init_hel
    end interface

<HepMC interface: procedures>+≡
    subroutine hepmc_polarization_init_pol (hpol, pol)
        type(hepmc_polarization_t), intent(out) :: hpol
        type(polarization_t), intent(in) :: pol
        real(default) :: r, theta, phi
        if (polarization_is_polarized (pol)) then
            call polarization_to_angles (pol, r, theta, phi)
            if (r >= 0.5) then
                hpol%polarized = .true.
                hpol%obj = new_polarization &
                    (real (theta, c_double), real (phi, c_double))
            end if
        end if
    end subroutine hepmc_polarization_init_pol

```

```

subroutine hepmc_polarization_init_hel (hpol, hel)
  type(hepmc_polarization_t), intent(out) :: hpol
  type(helicity_t), intent(in) :: hel
  integer, dimension(2) :: h
  if (helicity_is_defined (hel)) then
    h = helicity_get (hel)
    select case (h(1))
    case (1:)
      hpol%polarized = .true.
      hpol%obj = new_polarization (0._c_double, 0._c_double)
    case (:-1)
      hpol%polarized = .true.
      hpol%obj = new_polarization (real (pi, c_double), 0._c_double)
    end select
  end if
end subroutine hepmc_polarization_init_hel

```

Destructor. The C object is deallocated only if the polarized flag is set.

```

<HepMC interface: interfaces>+≡
  interface
    subroutine polarization_delete (pol_obj) bind(C)
      import
      type(c_ptr), value :: pol_obj
    end subroutine polarization_delete
  end interface

<HepMC interface: public>+≡
  public :: hepmc_polarization_final

<HepMC interface: procedures>+≡
  subroutine hepmc_polarization_final (hpol)
    type(hepmc_polarization_t), intent(inout) :: hpol
    if (hpol%polarized) call polarization_delete (hpol%obj)
  end subroutine hepmc_polarization_final

```

Recover polarization from HepMC polarization object (with the abovementioned deficiencies).

```

<HepMC interface: interfaces>+≡
  interface
    function polarization_theta (pol_obj) result (theta) bind(C)
      import
      real(c_double) :: theta
      type(c_ptr), value :: pol_obj
    end function polarization_theta
  end interface

  interface
    function polarization_phi (pol_obj) result (phi) bind(C)
      import
      real(c_double) :: phi
      type(c_ptr), value :: pol_obj
    end function polarization_phi
  end interface

<HepMC interface: public>+≡
  public :: hepmc_polarization_to_pol

```

```

<HepMC interface: procedures>+≡
  subroutine hepmc_polarization_to_pol (hpol, flv, pol)
    type(hepmc_polarization_t), intent(in) :: hpol
    type(flavor_t), intent(in) :: flv
    type(polarization_t), intent(out) :: pol
    real(default) :: theta, phi
    theta = polarization_theta (hpol%obj)
    phi = polarization_phi (hpol%obj)
    call polarization_init_angles (pol, flv, 1._default, theta, phi)
  end subroutine hepmc_polarization_to_pol

```

Recover helicity. Here, ϕ is ignored and only the sign of $\cos \theta$ is relevant, mapped to positive/negative helicity.

```

<HepMC interface: public>+≡
  public :: hepmc_polarization_to_hel

<HepMC interface: procedures>+≡
  subroutine hepmc_polarization_to_hel (hpol, flv, hel)
    type(hepmc_polarization_t), intent(in) :: hpol
    type(flavor_t), intent(in) :: flv
    type(helicity_t), intent(out) :: hel
    real(default) :: theta
    integer :: hmax
    theta = polarization_theta (hpol%obj)
    hmax = flavor_get_spin_type (flv) / 2
    call helicity_init (hel, sign (hmax, nint (cos (theta))))
  end subroutine hepmc_polarization_to_hel

```

8.3.4 GenParticle

Particle objects have the obvious meaning.

```

<HepMC interface: public>+≡
  public :: hepmc_particle_t

<HepMC interface: types>+≡
  type :: hepmc_particle_t
  private
  type(c_ptr) :: obj
  end type hepmc_particle_t

```

Constructor. The C version takes a FourVector object, which in the Fortran wrapper is created on the fly from a `vector4` Lorentz vector.

No destructor is needed as long as all particles are entered into vertex containers.

```

<HepMC interface: interfaces>+≡
  interface
    type(c_ptr) function new_gen_particle (prt_obj, pdg_id, status) bind(C)
    import
    type(c_ptr), value :: prt_obj
    integer(c_int), value :: pdg_id, status
  end function new_gen_particle
  end interface

```

```

<HepMC interface: public>+≡
    public :: hepmc_particle_init

<HepMC interface: procedures>+≡
    subroutine hepmc_particle_init (prt, p, pdg, status)
        type(hepmc_particle_t), intent(out) :: prt
        type(vector4_t), intent(in) :: p
        integer, intent(in) :: pdg, status
        type(hepmc_four_vector_t) :: pp
        call hepmc_four_vector_init (pp, p)
        prt%obj = new_gen_particle (pp%obj, int (pdg, c_int), int (status, c_int))
        call hepmc_four_vector_final (pp)
    end subroutine hepmc_particle_init

```

Set the particle color flow.

```

<HepMC interface: interfaces>+≡
    interface
        subroutine gen_particle_set_flow (prt_obj, code_index, code) bind(C)
            import
            type(c_ptr), value :: prt_obj
            integer(c_int), value :: code_index, code
        end subroutine gen_particle_set_flow
    end interface

<HepMC interface: public>+≡
    public :: hepmc_particle_set_color

<HepMC interface: procedures>+≡
    subroutine hepmc_particle_set_color (prt, col)
        type(hepmc_particle_t), intent(inout) :: prt
        type(color_t), intent(in) :: col
        integer(c_int) :: c
        c = color_get_col (col)
        if (c /= 0) call gen_particle_set_flow (prt%obj, 1_c_int, c)
        c = color_get_acl (col)
        if (c /= 0) call gen_particle_set_flow (prt%obj, 2_c_int, c)
    end subroutine hepmc_particle_set_color

```

Set the particle polarization. For the restrictions on particle polarization in HepMC, see above `hepmc_polarization_init`.

```

<HepMC interface: interfaces>+≡
    interface
        subroutine gen_particle_set_polarization (prt_obj, pol_obj) bind(C)
            import
            type(c_ptr), value :: prt_obj, pol_obj
        end subroutine gen_particle_set_polarization
    end interface

<HepMC interface: public>+≡
    public :: hepmc_particle_set_polarization

<HepMC interface: interfaces>+≡
    interface hepmc_particle_set_polarization
        module procedure hepmc_particle_set_polarization_pol
        module procedure hepmc_particle_set_polarization_hel
    end interface

```

```

<HepMC interface: procedures>+≡
  subroutine hepmc_particle_set_polarization_pol (prt, pol)
    type(hepmc_particle_t), intent(inout) :: prt
    type(polarization_t), intent(in) :: pol
    type(hepmc_polarization_t) :: hpol
    call hepmc_polarization_init (hpol, pol)
    if (hpol%polarized) call gen_particle_set_polarization (prt%obj, hpol%obj)
    call hepmc_polarization_final (hpol)
  end subroutine hepmc_particle_set_polarization_pol

  subroutine hepmc_particle_set_polarization_hel (prt, hel)
    type(hepmc_particle_t), intent(inout) :: prt
    type(helicity_t), intent(in) :: hel
    type(hepmc_polarization_t) :: hpol
    call hepmc_polarization_init (hpol, hel)
    if (hpol%polarized) call gen_particle_set_polarization (prt%obj, hpol%obj)
    call hepmc_polarization_final (hpol)
  end subroutine hepmc_particle_set_polarization_hel

```

Return the HepMC barcode (unique integer ID) of the particle.

```

<HepMC interface: interfaces>+≡
  interface
    function gen_particle_barcode (prt_obj) result (barcode) bind(C)
      import
      integer(c_int) :: barcode
      type(c_ptr), value :: prt_obj
    end function gen_particle_barcode
  end interface

<HepMC interface: public>+≡
  public :: hepmc_particle_get_barcode

<HepMC interface: procedures>+≡
  function hepmc_particle_get_barcode (prt) result (barcode)
    integer :: barcode
    type(hepmc_particle_t), intent(in) :: prt
    barcode = gen_particle_barcode (prt%obj)
  end function hepmc_particle_get_barcode

```

Return the four-vector component of the particle object as a `vector4_t` Lorentz vector.

```

<HepMC interface: interfaces>+≡
  interface
    type(c_ptr) function gen_particle_momentum (prt_obj) bind(C)
      import
      type(c_ptr), value :: prt_obj
    end function gen_particle_momentum
  end interface

<HepMC interface: public>+≡
  public :: hepmc_particle_get_momentum

<HepMC interface: procedures>+≡
  function hepmc_particle_get_momentum (prt) result (p)
    type(vector4_t) :: p

```

```

    type(hepmc_particle_t), intent(in) :: prt
    type(hepmc_four_vector_t) :: pp
    call hepmc_four_vector_init (pp, prt)
    call hepmc_four_vector_to_vector4 (pp, p)
    call hepmc_four_vector_final (pp)
end function hepmc_particle_get_momentum

```

Return the invariant mass squared of the particle object. HepMC stores the signed invariant mass (no squaring).

```

<HepMC interface: interfaces>+≡
  interface
    function gen_particle_generated_mass (prt_obj) result (mass) bind(C)
    import
      real(c_double) :: mass
      type(c_ptr), value :: prt_obj
    end function gen_particle_generated_mass
  end interface

<HepMC interface: public>+≡
  public :: hepmc_particle_get_mass_squared

<HepMC interface: procedures>+≡
  function hepmc_particle_get_mass_squared (prt) result (m2)
  real(default) :: m2
  type(hepmc_particle_t), intent(in) :: prt
  real(default) :: m
  m = gen_particle_generated_mass (prt%obj)
  m2 = sign (m**2, m)
end function hepmc_particle_get_mass_squared

```

Return the PDG ID:

```

<HepMC interface: interfaces>+≡
  interface
    function gen_particle_pdg_id (prt_obj) result (pdg_id) bind(C)
    import
      integer(c_int) :: pdg_id
      type(c_ptr), value :: prt_obj
    end function gen_particle_pdg_id
  end interface

<HepMC interface: public>+≡
  public :: hepmc_particle_get_pdg

<HepMC interface: procedures>+≡
  function hepmc_particle_get_pdg (prt) result (pdg)
  integer :: pdg
  type(hepmc_particle_t), intent(in) :: prt
  pdg = gen_particle_pdg_id (prt%obj)
end function hepmc_particle_get_pdg

```

Return the status code:

```

<HepMC interface: interfaces>+≡
  interface
    function gen_particle_status (prt_obj) result (status) bind(C)

```

```

        import
        integer(c_int) :: status
        type(c_ptr), value :: prt_obj
        end function gen_particle_status
    end interface

    <HepMC interface: public>+≡
        public :: hepmc_particle_get_status

    <HepMC interface: procedures>+≡
        function hepmc_particle_get_status (prt) result (status)
            integer :: status
            type(hepmc_particle_t), intent(in) :: prt
            status = gen_particle_status (prt%obj)
        end function hepmc_particle_get_status

```

Return the production/decay vertex (as a pointer, no finalization necessary).

```

    <HepMC interface: interfaces>+≡
        interface
            type(c_ptr) function gen_particle_production_vertex (prt_obj) bind(C)
                import
                type(c_ptr), value :: prt_obj
            end function gen_particle_production_vertex
        end interface

        interface
            type(c_ptr) function gen_particle_end_vertex (prt_obj) bind(C)
                import
                type(c_ptr), value :: prt_obj
            end function gen_particle_end_vertex
        end interface

    <HepMC interface: public>+≡
        public :: hepmc_particle_get_production_vertex
        public :: hepmc_particle_get_decay_vertex

    <HepMC interface: procedures>+≡
        function hepmc_particle_get_production_vertex (prt) result (v)
            type(hepmc_vertex_t) :: v
            type(hepmc_particle_t), intent(in) :: prt
            v%obj = gen_particle_production_vertex (prt%obj)
        end function hepmc_particle_get_production_vertex

        function hepmc_particle_get_decay_vertex (prt) result (v)
            type(hepmc_vertex_t) :: v
            type(hepmc_particle_t), intent(in) :: prt
            v%obj = gen_particle_end_vertex (prt%obj)
        end function hepmc_particle_get_decay_vertex

```

Return the number of parents/children.

```

    <HepMC interface: public>+≡
        public :: hepmc_particle_get_n_parents
        public :: hepmc_particle_get_n_children

    <HepMC interface: procedures>+≡
        function hepmc_particle_get_n_parents (prt) result (n_parents)

```

```

integer :: n_parents
type(hepmc_particle_t), intent(in) :: prt
type(hepmc_vertex_t) :: v
v = hepmc_particle_get_production_vertex (prt)
if (hepmc_vertex_is_valid (v)) then
    n_parents = hepmc_vertex_get_n_in (v)
else
    n_parents = 0
end if
end function hepmc_particle_get_n_parents

function hepmc_particle_get_n_children (prt) result (n_children)
integer :: n_children
type(hepmc_particle_t), intent(in) :: prt
type(hepmc_vertex_t) :: v
v = hepmc_particle_get_decay_vertex (prt)
if (hepmc_vertex_is_valid (v)) then
    n_children = hepmc_vertex_get_n_out (v)
else
    n_children = 0
end if
end function hepmc_particle_get_n_children

```

Convenience function: Return the array of parent particles for a given HepMC particle. The contents are HepMC barcodes that still have to be mapped to the particle indices.

(HepMC interface: public)+≡

```

public :: hepmc_particle_get_parent_barcodes
public :: hepmc_particle_get_child_barcodes

```

(HepMC interface: procedures)+≡

```

function hepmc_particle_get_parent_barcodes (prt) result (parent_barcode)
type(hepmc_particle_t), intent(in) :: prt
integer, dimension(:), allocatable :: parent_barcode
type(hepmc_vertex_t) :: v
type(hepmc_vertex_particle_in_iterator_t) :: it
integer :: i
v = hepmc_particle_get_production_vertex (prt)
if (hepmc_vertex_is_valid (v)) then
    allocate (parent_barcode (hepmc_vertex_get_n_in (v)))
    if (size (parent_barcode) /= 0) then
        call hepmc_vertex_particle_in_iterator_init (it, v)
        do i = 1, size (parent_barcode)
            parent_barcode(i) = hepmc_particle_get_barcode &
                (hepmc_vertex_particle_in_iterator_get (it))
            call hepmc_vertex_particle_in_iterator_advance (it)
        end do
        call hepmc_vertex_particle_in_iterator_final (it)
    end if
else
    allocate (parent_barcode (0))
end if
end function hepmc_particle_get_parent_barcodes

```

```

function hepmc_particle_get_child_barcode (prt) result (child_barcode)
  type(hepmc_particle_t), intent(in) :: prt
  integer, dimension(:), allocatable :: child_barcode
  type(hepmc_vertex_t) :: v
  type(hepmc_vertex_particle_out_iterator_t) :: it
  integer :: i
  v = hepmc_particle_get_decay_vertex (prt)
  if (hepmc_vertex_is_valid (v)) then
    allocate (child_barcode (hepmc_vertex_get_n_out (v)))
    call hepmc_vertex_particle_out_iterator_init (it, v)
    if (size (child_barcode) /= 0) then
      do i = 1, size (child_barcode)
        child_barcode(i) = hepmc_particle_get_barcode &
          (hepmc_vertex_particle_out_iterator_get (it))
        call hepmc_vertex_particle_out_iterator_advance (it)
      end do
      call hepmc_vertex_particle_out_iterator_final (it)
    end if
  else
    allocate (child_barcode (0))
  end if
end function hepmc_particle_get_child_barcode

```

Return the polarization (assuming that the particle is completely polarized).
 Note that the generated polarization object needs finalization.

```

<HepMC interface: interfaces>+≡
  interface
    type(c_ptr) function gen_particle_polarization (prt_obj) bind(C)
    import
    type(c_ptr), value :: prt_obj
  end function gen_particle_polarization
end interface

<HepMC interface: public>+≡
  public :: hepmc_particle_get_polarization

<HepMC interface: procedures>+≡
  function hepmc_particle_get_polarization (prt) result (pol)
    type(hepmc_polarization_t) :: pol
    type(hepmc_particle_t), intent(in) :: prt
    pol%obj = gen_particle_polarization (prt%obj)
  end function hepmc_particle_get_polarization

```

Return the particle color as a two-dimensional array (color, anticolor).

```

<HepMC interface: interfaces>+≡
  interface
    function gen_particle_flow (prt_obj, code_index) result (code) bind(C)
    import
    integer(c_int) :: code
    type(c_ptr), value :: prt_obj
    integer(c_int), value :: code_index
  end function gen_particle_flow
end interface

```

```

<HepMC interface: public>+≡
    public :: hepmc_particle_get_color

<HepMC interface: procedures>+≡
    function hepmc_particle_get_color (prt) result (col)
        integer, dimension(2) :: col
        type(hepmc_particle_t), intent(in) :: prt
        col(1) = gen_particle_flow (prt%obj, 1)
        col(2) = - gen_particle_flow (prt%obj, 2)
    end function hepmc_particle_get_color

```

8.3.5 GenVertex

Vertices are made of particles (incoming and outgoing).

```

<HepMC interface: public>+≡
    public :: hepmc_vertex_t

<HepMC interface: types>+≡
    type :: hepmc_vertex_t
    private
    type(c_ptr) :: obj
    end type hepmc_vertex_t

```

Constructor. Two versions, one plain, one with the position in space and time (measured in mm) as argument. The Fortran version has initializer form, and the vertex position is an optional argument.

A destructor is unnecessary as long as all vertices are entered into an event container.

```

<HepMC interface: interfaces>+≡
    interface
        type(c_ptr) function new_gen_vertex () bind(C)
            import
        end function new_gen_vertex
    end interface
    interface
        type(c_ptr) function new_gen_vertex_pos (prt_obj) bind(C)
            import
            type(c_ptr), value :: prt_obj
        end function new_gen_vertex_pos
    end interface

<HepMC interface: public>+≡
    public :: hepmc_vertex_init

<HepMC interface: procedures>+≡
    subroutine hepmc_vertex_init (v, x)
        type(hepmc_vertex_t), intent(out) :: v
        type(vector4_t), intent(in), optional :: x
        type(hepmc_four_vector_t) :: pos
        if (present (x)) then
            call hepmc_four_vector_init (pos, x)
            v%obj = new_gen_vertex_pos (pos%obj)
            call hepmc_four_vector_final (pos)
        end if
    end subroutine

```

```

    else
        v%obj = new_gen_vertex ()
    end if
end subroutine hepmc_vertex_init

```

Return true if the vertex pointer is non-null:

```

<HepMC interface: interfaces>+≡
interface
    function gen_vertex_is_valid (v_obj) result (flag) bind(C)
        import
        logical(c_bool) :: flag
        type(c_ptr), value :: v_obj
    end function gen_vertex_is_valid
end interface

<HepMC interface: public>+≡
public :: hepmc_vertex_is_valid

<HepMC interface: procedures>+≡
function hepmc_vertex_is_valid (v) result (flag)
    logical :: flag
    type(hepmc_vertex_t), intent(in) :: v
    flag = gen_vertex_is_valid (v%obj)
end function hepmc_vertex_is_valid

```

Add a particle to a vertex, incoming or outgoing.

```

<HepMC interface: interfaces>+≡
interface
    subroutine gen_vertex_add_particle_in (v_obj, prt_obj) bind(C)
        import
        type(c_ptr), value :: v_obj, prt_obj
    end subroutine gen_vertex_add_particle_in
end interface
interface
    subroutine gen_vertex_add_particle_out (v_obj, prt_obj) bind(C)
        import
        type(c_ptr), value :: v_obj, prt_obj
    end subroutine gen_vertex_add_particle_out
end interface

<HepMC interface: public>+≡
public :: hepmc_vertex_add_particle_in
public :: hepmc_vertex_add_particle_out

<HepMC interface: procedures>+≡
subroutine hepmc_vertex_add_particle_in (v, prt)
    type(hepmc_vertex_t), intent(inout) :: v
    type(hepmc_particle_t), intent(in) :: prt
    call gen_vertex_add_particle_in (v%obj, prt%obj)
end subroutine hepmc_vertex_add_particle_in

subroutine hepmc_vertex_add_particle_out (v, prt)
    type(hepmc_vertex_t), intent(inout) :: v
    type(hepmc_particle_t), intent(in) :: prt
    call gen_vertex_add_particle_out (v%obj, prt%obj)
end subroutine hepmc_vertex_add_particle_out

```

```
end subroutine hepmc_vertex_add_particle_out
```

Return the number of incoming/outgoing particles.

(HepMC interface: interfaces)+≡

```
interface
  function gen_vertex_particles_in_size (v_obj) result (size) bind(C)
    import
    integer(c_int) :: size
    type(c_ptr), value :: v_obj
  end function gen_vertex_particles_in_size
end interface
interface
  function gen_vertex_particles_out_size (v_obj) result (size) bind(C)
    import
    integer(c_int) :: size
    type(c_ptr), value :: v_obj
  end function gen_vertex_particles_out_size
end interface
```

(HepMC interface: public)+≡

```
public :: hepmc_vertex_get_n_in
public :: hepmc_vertex_get_n_out
```

(HepMC interface: procedures)+≡

```
function hepmc_vertex_get_n_in (v) result (n_in)
  integer :: n_in
  type(hepmc_vertex_t), intent(in) :: v
  n_in = gen_vertex_particles_in_size (v%obj)
end function hepmc_vertex_get_n_in

function hepmc_vertex_get_n_out (v) result (n_out)
  integer :: n_out
  type(hepmc_vertex_t), intent(in) :: v
  n_out = gen_vertex_particles_out_size (v%obj)
end function hepmc_vertex_get_n_out
```

8.3.6 Vertex-particle-in iterator

This iterator iterates over all incoming particles in an vertex. We store a pointer to the vertex in addition to the iterator. This allows for simple end checking.

The iterator is actually a constant iterator; it can only read.

(HepMC interface: public)+≡

```
public :: hepmc_vertex_particle_in_iterator_t
```

(HepMC interface: types)+≡

```
type :: hepmc_vertex_particle_in_iterator_t
  private
  type(c_ptr) :: obj
  type(c_ptr) :: v_obj
end type hepmc_vertex_particle_in_iterator_t
```

Constructor. The iterator is initialized at the first particle in the vertex.

```

<HepMC interface: interfaces>+≡
  interface
    type(c_ptr) function &
      new_vertex_particles_in_const_iterator (v_obj) bind(C)
    import
      type(c_ptr), value :: v_obj
    end function new_vertex_particles_in_const_iterator
  end interface
<HepMC interface: public>+≡
  public :: hepmc_vertex_particle_in_iterator_init
<HepMC interface: procedures>+≡
  subroutine hepmc_vertex_particle_in_iterator_init (it, v)
    type(hepmc_vertex_particle_in_iterator_t), intent(out) :: it
    type(hepmc_vertex_t), intent(in) :: v
    it%obj = new_vertex_particles_in_const_iterator (v%obj)
    it%v_obj = v%obj
  end subroutine hepmc_vertex_particle_in_iterator_init

```

Destructor. Necessary because the iterator is allocated on the heap.

```

<HepMC interface: interfaces>+≡
  interface
    subroutine vertex_particles_in_const_iterator_delete (it_obj) bind(C)
    import
      type(c_ptr), value :: it_obj
    end subroutine vertex_particles_in_const_iterator_delete
  end interface
<HepMC interface: public>+≡
  public :: hepmc_vertex_particle_in_iterator_final
<HepMC interface: procedures>+≡
  subroutine hepmc_vertex_particle_in_iterator_final (it)
    type(hepmc_vertex_particle_in_iterator_t), intent(inout) :: it
    call vertex_particles_in_const_iterator_delete (it%obj)
  end subroutine hepmc_vertex_particle_in_iterator_final

```

Increment

```

<HepMC interface: interfaces>+≡
  interface
    subroutine vertex_particles_in_const_iterator_advance (it_obj) bind(C)
    import
      type(c_ptr), value :: it_obj
    end subroutine vertex_particles_in_const_iterator_advance
  end interface
<HepMC interface: public>+≡
  public :: hepmc_vertex_particle_in_iterator_advance
<HepMC interface: procedures>+≡
  subroutine hepmc_vertex_particle_in_iterator_advance (it)
    type(hepmc_vertex_particle_in_iterator_t), intent(inout) :: it
    call vertex_particles_in_const_iterator_advance (it%obj)
  end subroutine hepmc_vertex_particle_in_iterator_advance

```

Reset to the beginning

```
<HepMC interface: interfaces>+≡
  interface
    subroutine vertex_particles_in_const_iterator_reset &
      (it_obj, v_obj) bind(C)
    import
      type(c_ptr), value :: it_obj, v_obj
    end subroutine vertex_particles_in_const_iterator_reset
  end interface

<HepMC interface: public>+≡
  public :: hepmc_vertex_particle_in_iterator_reset

<HepMC interface: procedures>+≡
  subroutine hepmc_vertex_particle_in_iterator_reset (it)
    type(hepmc_vertex_particle_in_iterator_t), intent(inout) :: it
    call vertex_particles_in_const_iterator_reset (it%obj, it%v_obj)
  end subroutine hepmc_vertex_particle_in_iterator_reset
```

Test: return true as long as we are not past the end.

```
<HepMC interface: interfaces>+≡
  interface
    function vertex_particles_in_const_iterator_is_valid &
      (it_obj, v_obj) result (flag) bind(C)
    import
      logical(c_bool) :: flag
      type(c_ptr), value :: it_obj, v_obj
    end function vertex_particles_in_const_iterator_is_valid
  end interface

<HepMC interface: public>+≡
  public :: hepmc_vertex_particle_in_iterator_is_valid

<HepMC interface: procedures>+≡
  function hepmc_vertex_particle_in_iterator_is_valid (it) result (flag)
    logical :: flag
    type(hepmc_vertex_particle_in_iterator_t), intent(in) :: it
    flag = vertex_particles_in_const_iterator_is_valid (it%obj, it%v_obj)
  end function hepmc_vertex_particle_in_iterator_is_valid
```

Return the particle pointed to by the iterator. (The particle object should not be finalized, since it contains merely a pointer to the particle which is owned by the vertex.)

```
<HepMC interface: interfaces>+≡
  interface
    type(c_ptr) function &
      vertex_particles_in_const_iterator_get (it_obj) bind(C)
    import
      type(c_ptr), value :: it_obj
    end function vertex_particles_in_const_iterator_get
  end interface

<HepMC interface: public>+≡
  public :: hepmc_vertex_particle_in_iterator_get
```

```

<HepMC interface: procedures>+≡
function hepmc_vertex_particle_in_iterator_get (it) result (prt)
  type(hepmc_particle_t) :: prt
  type(hepmc_vertex_particle_in_iterator_t), intent(in) :: it
  prt%obj = vertex_particles_in_const_iterator_get (it%obj)
end function hepmc_vertex_particle_in_iterator_get

```

8.3.7 Vertex-particle-out iterator

This iterator iterates over all incoming particles in an vertex. We store a pointer to the vertex in addition to the iterator. This allows for simple end checking.

The iterator is actually a constant iterator; it can only read.

```

<HepMC interface: public>+≡
public :: hepmc_vertex_particle_out_iterator_t

<HepMC interface: types>+≡
type :: hepmc_vertex_particle_out_iterator_t
private
  type(c_ptr) :: obj
  type(c_ptr) :: v_obj
end type hepmc_vertex_particle_out_iterator_t

```

Constructor. The iterator is initialized at the first particle in the vertex.

```

<HepMC interface: interfaces>+≡
interface
  type(c_ptr) function &
    new_vertex_particles_out_const_iterator (v_obj) bind(C)
  import
    type(c_ptr), value :: v_obj
  end function new_vertex_particles_out_const_iterator
end interface

<HepMC interface: public>+≡
public :: hepmc_vertex_particle_out_iterator_init

<HepMC interface: procedures>+≡
subroutine hepmc_vertex_particle_out_iterator_init (it, v)
  type(hepmc_vertex_particle_out_iterator_t), intent(out) :: it
  type(hepmc_vertex_t), intent(in) :: v
  it%obj = new_vertex_particles_out_const_iterator (v%obj)
  it%v_obj = v%obj
end subroutine hepmc_vertex_particle_out_iterator_init

```

Destructor. Necessary because the iterator is allocated on the heap.

```

<HepMC interface: interfaces>+≡
interface
  subroutine vertex_particles_out_const_iterator_delete (it_obj) bind(C)
  import
    type(c_ptr), value :: it_obj
  end subroutine vertex_particles_out_const_iterator_delete
end interface

```

```

<HepMC interface: public>+≡
    public :: hepmc_vertex_particle_out_iterator_final
<HepMC interface: procedures>+≡
    subroutine hepmc_vertex_particle_out_iterator_final (it)
        type(hepmc_vertex_particle_out_iterator_t), intent(inout) :: it
        call vertex_particles_out_const_iterator_delete (it%obj)
    end subroutine hepmc_vertex_particle_out_iterator_final

```

Increment

```

<HepMC interface: interfaces>+≡
    interface
        subroutine vertex_particles_out_const_iterator_advance (it_obj) bind(C)
            import
            type(c_ptr), value :: it_obj
        end subroutine vertex_particles_out_const_iterator_advance
    end interface
<HepMC interface: public>+≡
    public :: hepmc_vertex_particle_out_iterator_advance
<HepMC interface: procedures>+≡
    subroutine hepmc_vertex_particle_out_iterator_advance (it)
        type(hepmc_vertex_particle_out_iterator_t), intent(inout) :: it
        call vertex_particles_out_const_iterator_advance (it%obj)
    end subroutine hepmc_vertex_particle_out_iterator_advance

```

Reset to the beginning

```

<HepMC interface: interfaces>+≡
    interface
        subroutine vertex_particles_out_const_iterator_reset &
            (it_obj, v_obj) bind(C)
            import
            type(c_ptr), value :: it_obj, v_obj
        end subroutine vertex_particles_out_const_iterator_reset
    end interface
<HepMC interface: public>+≡
    public :: hepmc_vertex_particle_out_iterator_reset
<HepMC interface: procedures>+≡
    subroutine hepmc_vertex_particle_out_iterator_reset (it)
        type(hepmc_vertex_particle_out_iterator_t), intent(inout) :: it
        call vertex_particles_out_const_iterator_reset (it%obj, it%v_obj)
    end subroutine hepmc_vertex_particle_out_iterator_reset

```

Test: return true as long as we are not past the end.

```

<HepMC interface: interfaces>+≡
    interface
        function vertex_particles_out_const_iterator_is_valid &
            (it_obj, v_obj) result (flag) bind(C)
            import
            logical(c_bool) :: flag
            type(c_ptr), value :: it_obj, v_obj
        end function vertex_particles_out_const_iterator_is_valid
    end interface

```

```

<HepMC interface: public>+≡
    public :: hepmc_vertex_particle_out_iterator_is_valid
<HepMC interface: procedures>+≡
    function hepmc_vertex_particle_out_iterator_is_valid (it) result (flag)
        logical :: flag
        type(hepmc_vertex_particle_out_iterator_t), intent(in) :: it
        flag = vertex_particles_out_const_iterator_is_valid (it%obj, it%v_obj)
    end function hepmc_vertex_particle_out_iterator_is_valid

```

Return the particle pointed to by the iterator. (The particle object should not be finalized, since it contains merely a pointer to the particle which is owned by the vertex.)

```

<HepMC interface: interfaces>+≡
    interface
        type(c_ptr) function &
            vertex_particles_out_const_iterator_get (it_obj) bind(C)
        import
        type(c_ptr), value :: it_obj
    end function vertex_particles_out_const_iterator_get
    end interface
<HepMC interface: public>+≡
    public :: hepmc_vertex_particle_out_iterator_get
<HepMC interface: procedures>+≡
    function hepmc_vertex_particle_out_iterator_get (it) result (prt)
        type(hepmc_particle_t) :: prt
        type(hepmc_vertex_particle_out_iterator_t), intent(in) :: it
        prt%obj = vertex_particles_out_const_iterator_get (it%obj)
    end function hepmc_vertex_particle_out_iterator_get

```

8.3.8 GenEvent

The main object of HepMC is a GenEvent. The object is filled by GenVertex objects, which in turn contain GenParticle objects.

```

<HepMC interface: public>+≡
    public :: hepmc_event_t
<HepMC interface: types>+≡
    type :: hepmc_event_t
    private
    type(c_ptr) :: obj
    end type hepmc_event_t

```

Constructor. Arguments are process ID (integer) and event ID (integer).

The Fortran version has initializer form.

```

<HepMC interface: interfaces>+≡
    interface
        type(c_ptr) function new_gen_event (proc_id, event_id) bind(C)
        import
        integer(c_int), value :: proc_id, event_id
    end function new_gen_event
    end interface

```

```

<HepMC interface: public>+≡
  public :: hepmc_event_init

<HepMC interface: procedures>+≡
  subroutine hepmc_event_init (evt, proc_id, event_id)
    type(hepmc_event_t), intent(out) :: evt
    integer, intent(in), optional :: proc_id, event_id
    integer(c_int) :: pid, eid
    pid = 0; if (present (proc_id)) pid = proc_id
    eid = 0; if (present (event_id)) eid = event_id
    evt%obj = new_gen_event (pid, eid)
  end subroutine hepmc_event_init

```

Destructor.

```

<HepMC interface: interfaces>+≡
  interface
    subroutine gen_event_delete (evt_obj) bind(C)
      import
      type(c_ptr), value :: evt_obj
    end subroutine gen_event_delete
  end interface

<HepMC interface: public>+≡
  public :: hepmc_event_final

<HepMC interface: procedures>+≡
  subroutine hepmc_event_final (evt)
    type(hepmc_event_t), intent(inout) :: evt
    call gen_event_delete (evt%obj)
  end subroutine hepmc_event_final

```

Screen output. Printing to file is possible in principle (using a C++ output channel), by allowing an argument. Printing to an open Fortran unit is obviously not possible.

```

<HepMC interface: interfaces>+≡
  interface
    subroutine gen_event_print (evt_obj) bind(C)
      import
      type(c_ptr), value :: evt_obj
    end subroutine gen_event_print
  end interface

<HepMC interface: public>+≡
  public :: hepmc_event_print

<HepMC interface: procedures>+≡
  subroutine hepmc_event_print (evt)
    type(hepmc_event_t), intent(in) :: evt
    call gen_event_print (evt%obj)
  end subroutine hepmc_event_print

```

Add a vertex to the event container.

```

<HepMC interface: interfaces>+≡
  interface

```

```

        subroutine gen_event_add_vertex (evt_obj, v_obj) bind(C)
            import
            type(c_ptr), value :: evt_obj
            type(c_ptr), value :: v_obj
        end subroutine gen_event_add_vertex
    end interface

    <HepMC interface: public>+≡
    public :: hepmc_event_add_vertex

    <HepMC interface: procedures>+≡
    subroutine hepmc_event_add_vertex (evt, v)
        type(hepmc_event_t), intent(inout) :: evt
        type(hepmc_vertex_t), intent(in) :: v
        call gen_event_add_vertex (evt%obj, v%obj)
    end subroutine hepmc_event_add_vertex

```

Mark a particular vertex as the signal process (hard interaction).

```

    <HepMC interface: interfaces>+≡
    interface
        subroutine gen_event_set_signal_process_vertex (evt_obj, v_obj) bind(C)
            import
            type(c_ptr), value :: evt_obj
            type(c_ptr), value :: v_obj
        end subroutine gen_event_set_signal_process_vertex
    end interface

    <HepMC interface: public>+≡
    public :: hepmc_event_set_signal_process_vertex

    <HepMC interface: procedures>+≡
    subroutine hepmc_event_set_signal_process_vertex (evt, v)
        type(hepmc_event_t), intent(inout) :: evt
        type(hepmc_vertex_t), intent(in) :: v
        call gen_event_set_signal_process_vertex (evt%obj, v%obj)
    end subroutine hepmc_event_set_signal_process_vertex

```

8.3.9 Event-particle iterator

This iterator iterates over all particles in an event. We store a pointer to the event in addition to the iterator. This allows for simple end checking.

The iterator is actually a constant iterator; it can only read.

```

    <HepMC interface: public>+≡
    public :: hepmc_event_particle_iterator_t

    <HepMC interface: types>+≡
    type :: hepmc_event_particle_iterator_t
    private
    type(c_ptr) :: obj
    type(c_ptr) :: evt_obj
    end type hepmc_event_particle_iterator_t

```

Constructor. The iterator is initialized at the first particle in the event.

```

<HepMC interface: interfaces>+≡
  interface
    type(c_ptr) function new_event_particle_const_iterator (evt_obj) bind(C)
    import
    type(c_ptr), value :: evt_obj
    end function new_event_particle_const_iterator
  end interface
<HepMC interface: public>+≡
  public :: hepmc_event_particle_iterator_init
<HepMC interface: procedures>+≡
  subroutine hepmc_event_particle_iterator_init (it, evt)
    type(hepmc_event_particle_iterator_t), intent(out) :: it
    type(hepmc_event_t), intent(in) :: evt
    it%obj = new_event_particle_const_iterator (evt%obj)
    it%evt_obj = evt%obj
  end subroutine hepmc_event_particle_iterator_init

```

Destructor. Necessary because the iterator is allocated on the heap.

```

<HepMC interface: interfaces>+≡
  interface
    subroutine event_particle_const_iterator_delete (it_obj) bind(C)
    import
    type(c_ptr), value :: it_obj
    end subroutine event_particle_const_iterator_delete
  end interface
<HepMC interface: public>+≡
  public :: hepmc_event_particle_iterator_final
<HepMC interface: procedures>+≡
  subroutine hepmc_event_particle_iterator_final (it)
    type(hepmc_event_particle_iterator_t), intent(inout) :: it
    call event_particle_const_iterator_delete (it%obj)
  end subroutine hepmc_event_particle_iterator_final

```

Increment

```

<HepMC interface: interfaces>+≡
  interface
    subroutine event_particle_const_iterator_advance (it_obj) bind(C)
    import
    type(c_ptr), value :: it_obj
    end subroutine event_particle_const_iterator_advance
  end interface
<HepMC interface: public>+≡
  public :: hepmc_event_particle_iterator_advance
<HepMC interface: procedures>+≡
  subroutine hepmc_event_particle_iterator_advance (it)
    type(hepmc_event_particle_iterator_t), intent(inout) :: it
    call event_particle_const_iterator_advance (it%obj)
  end subroutine hepmc_event_particle_iterator_advance

```

Reset to the beginning

```

<HepMC interface: interfaces>+≡
  interface
    subroutine event_particle_const_iterator_reset (it_obj, evt_obj) bind(C)
      import
      type(c_ptr), value :: it_obj, evt_obj
    end subroutine event_particle_const_iterator_reset
  end interface

<HepMC interface: public>+≡
  public :: hepmc_event_particle_iterator_reset

<HepMC interface: procedures>+≡
  subroutine hepmc_event_particle_iterator_reset (it)
    type(hepmc_event_particle_iterator_t), intent(inout) :: it
    call event_particle_const_iterator_reset (it%obj, it%evt_obj)
  end subroutine hepmc_event_particle_iterator_reset

```

Test: return true as long as we are not past the end.

```

<HepMC interface: interfaces>+≡
  interface
    function event_particle_const_iterator_is_valid &
      (it_obj, evt_obj) result (flag) bind(C)
      import
      logical(c_bool) :: flag
      type(c_ptr), value :: it_obj, evt_obj
    end function event_particle_const_iterator_is_valid
  end interface

<HepMC interface: public>+≡
  public :: hepmc_event_particle_iterator_is_valid

<HepMC interface: procedures>+≡
  function hepmc_event_particle_iterator_is_valid (it) result (flag)
    logical :: flag
    type(hepmc_event_particle_iterator_t), intent(in) :: it
    flag = event_particle_const_iterator_is_valid (it%obj, it%evt_obj)
  end function hepmc_event_particle_iterator_is_valid

```

Return the particle pointed to by the iterator. (The particle object should not be finalized, since it contains merely a pointer to the particle which is owned by the vertex.)

```

<HepMC interface: interfaces>+≡
  interface
    type(c_ptr) function event_particle_const_iterator_get (it_obj) bind(C)
      import
      type(c_ptr), value :: it_obj
    end function event_particle_const_iterator_get
  end interface

<HepMC interface: public>+≡
  public :: hepmc_event_particle_iterator_get

```

```

<HepMC interface: procedures>+≡
  function hepmc_event_particle_iterator_get (it) result (prt)
    type(hepmc_particle_t) :: prt
    type(hepmc_event_particle_iterator_t), intent(in) :: it
    prt%obj = event_particle_const_iterator_get (it%obj)
  end function hepmc_event_particle_iterator_get

```

8.3.10 I/O streams

There is a specific I/O stream type for handling the output of GenEvent objects (i.e., Monte Carlo event samples) to file. Opening the file is done by the constructor, closing by the destructor.

```

<HepMC interface: public>+≡
  public :: hepmc_iostream_t

<HepMC interface: types>+≡
  type :: hepmc_iostream_t
  private
  type(c_ptr) :: obj
  end type hepmc_iostream_t

```

Constructor for an output stream associated to a file.

```

<HepMC interface: interfaces>+≡
  interface
    type(c_ptr) function new_io_gen_event_out (filename) bind(C)
    import
    character(c_char), dimension(*), intent(in) :: filename
    end function new_io_gen_event_out
  end interface

<HepMC interface: public>+≡
  public :: hepmc_iostream_open_out

<HepMC interface: procedures>+≡
  subroutine hepmc_iostream_open_out (iostream, filename)
    type(hepmc_iostream_t), intent(out) :: iostream
    type(string_t), intent(in) :: filename
    iostream%obj = new_io_gen_event_out (char (filename) // c_null_char)
  end subroutine hepmc_iostream_open_out

```

Constructor for an input stream associated to a file.

```

<HepMC interface: interfaces>+≡
  interface
    type(c_ptr) function new_io_gen_event_in (filename) bind(C)
    import
    character(c_char), dimension(*), intent(in) :: filename
    end function new_io_gen_event_in
  end interface

<HepMC interface: public>+≡
  public :: hepmc_iostream_open_in

```

```

<HepMC interface: procedures>+≡
  subroutine hepmc_iostream_open_in (iostream, filename)
    type(hepmc_iostream_t), intent(out) :: iostream
    type(string_t), intent(in) :: filename
    iostream%obj = new_io_gen_event_in (char (filename) // c_null_char)
  end subroutine hepmc_iostream_open_in

```

Destructor:

```

<HepMC interface: interfaces>+≡
  interface
    subroutine io_gen_event_delete (io_obj) bind(C)
      import
      type(c_ptr), value :: io_obj
    end subroutine io_gen_event_delete
  end interface

```

```

<HepMC interface: public>+≡
  public :: hepmc_iostream_close

```

```

<HepMC interface: procedures>+≡
  subroutine hepmc_iostream_close (iostream)
    type(hepmc_iostream_t), intent(inout) :: iostream
    call io_gen_event_delete (iostream%obj)
  end subroutine hepmc_iostream_close

```

Write a single event to the I/O stream.

```

<HepMC interface: interfaces>+≡
  interface
    subroutine io_gen_event_write_event (io_obj, evt_obj) bind(C)
      import
      type(c_ptr), value :: io_obj, evt_obj
    end subroutine io_gen_event_write_event
  end interface

```

```

<HepMC interface: public>+≡
  public :: hepmc_iostream_write_event

```

```

<HepMC interface: procedures>+≡
  subroutine hepmc_iostream_write_event (iostream, evt)
    type(hepmc_iostream_t), intent(inout) :: iostream
    type(hepmc_event_t), intent(in) :: evt
    call io_gen_event_write_event (iostream%obj, evt%obj)
  end subroutine hepmc_iostream_write_event

```

Read a single event from the I/O stream.

```

<HepMC interface: interfaces>+≡
  interface
    subroutine io_gen_event_read_event (io_obj, evt_obj) bind(C)
      import
      type(c_ptr), value :: io_obj, evt_obj
    end subroutine io_gen_event_read_event
  end interface

```

```

<HepMC interface: public>+≡
  public :: hepmc_iostream_read_event

```

```

<HepMC interface: procedures>+≡
  subroutine hepmc_iostream_read_event (iostream, evt)
    type(hepmc_iostream_t), intent(inout) :: iostream
    type(hepmc_event_t), intent(in) :: evt
    call io_gen_event_read_event (iostream%obj, evt%obj)
  end subroutine hepmc_iostream_read_event

```

8.3.11 Test

This test example is an abridged version from the build-from-scratch example in the HepMC distribution. We create two vertices for $p \rightarrow q$ PDF splitting, then a vertex for a $qq \rightarrow W^- g$ hard-interaction process, and finally a vertex for $W^- \rightarrow qq$ decay. The setup is for LHC kinematics.

Extending the original example, we set color flow for the incoming quarks and polarization for the outgoing photon. For the latter, we have to define a particle-data object for the photon, so a flavor object can be correctly initialized.

```

<HepMC interface: public>+≡
  public :: hepmc_test

<HepMC interface: procedures>+≡
  subroutine hepmc_test
    type(hepmc_event_t) :: evt
    type(hepmc_vertex_t) :: v1, v2, v3, v4
    type(hepmc_particle_t) :: prt1, prt2, prt3, prt4, prt5, prt6, prt7, prt8
    type(hepmc_iostream_t) :: iostream
    type(flavor_t) :: flv
    type(color_t) :: col
    type(polarization_t) :: pol
    type(particle_data_t), target :: photon_data

    ! Initialize a photon flavor object and some polarization
    call particle_data_init (photon_data, var_str ("PHOTON"), 22)
    call particle_data_set (photon_data, spin_type=VECTOR)
    call particle_data_freeze (photon_data)
    call flavor_init (flv, photon_data)
    call polarization_init_angles &
      (pol, flv, 0.6_default, 1._default, 0.5_default)

    ! Event initialization
    call hepmc_event_init (evt, 20, 1)

    ! $p\to q$ splittings
    call hepmc_vertex_init (v1)
    call hepmc_event_add_vertex (evt, v1)
    call hepmc_vertex_init (v2)
    call hepmc_event_add_vertex (evt, v2)
    call particle_init (prt1, &
      0._default, 0._default, 7000._default, 7000._default, &
      2212, 3)
    call hepmc_vertex_add_particle_in (v1, prt1)
    call particle_init (prt2, &
      0._default, 0._default, -7000._default, 7000._default, &

```

```

2212, 3)
call hepmc_vertex_add_particle_in (v2, prt2)
call particle_init (prt3, &
    .750_default, -1.569_default, 32.191_default, 32.238_default, &
    1, 3)
call color_init_from_array (col, (/501/))
call hepmc_particle_set_color (prt3, col)
call hepmc_vertex_add_particle_out (v1, prt3)
call particle_init (prt4, &
    -3.047_default, -19._default, -54.629_default, 57.920_default, &
    -2, 3)
call color_init_from_array (col, (/501/))
call hepmc_particle_set_color (prt4, col)
call hepmc_vertex_add_particle_out (v2, prt4)

! Hard interaction
call hepmc_vertex_init (v3)
call hepmc_event_add_vertex (evt, v3)
call hepmc_vertex_add_particle_in (v3, prt3)
call hepmc_vertex_add_particle_in (v3, prt4)
call particle_init (prt6, &
    -3.813_default, 0.113_default, -1.833_default, 4.233_default, &
    22, 1)
call hepmc_particle_set_polarization (prt6, pol)
call hepmc_vertex_add_particle_out (v3, prt6)
call particle_init (prt5, &
    1.517_default, -20.68_default, -20.605_default, 85.925_default, &
    -24, 3)
call hepmc_vertex_add_particle_out (v3, prt5)
call hepmc_event_set_signal_process_vertex (evt, v3)

! $W^-$ decay
call vertex_init_pos (v4, &
    0.12_default, -0.3_default, 0.05_default, 0.004_default)
call hepmc_event_add_vertex (evt, v4)
call hepmc_vertex_add_particle_in (v4, prt5)
call particle_init (prt7, &
    -2.445_default, 28.816_default, 6.082_default, 29.552_default, &
    1, 1)
call hepmc_vertex_add_particle_out (v4, prt7)
call particle_init (prt8, &
    3.962_default, -49.498_default, -26.687_default, 56.373_default, &
    -2, 1)
call hepmc_vertex_add_particle_out (v4, prt8)

! Event output
call hepmc_event_print (evt)
print *, "Writing to file 'hepmc_test.hepmc.dat'"
call hepmc_iostream_open_out (iostream, var_str ("hepmc_test.hepmc.dat"))
call hepmc_iostream_write_event (iostream, evt)
call hepmc_iostream_close (iostream)
print *, "Write completed"

! Wrapup

```

```

call polarization_final (pol)
call hepmc_event_final (evt)

contains

subroutine vertex_init_pos (v, x, y, z, t)
  type(hepmc_vertex_t), intent(out) :: v
  real(default), intent(in) :: x, y, z, t
  type(vector4_t) :: xx
  xx = vector4_moving (t, vector3_moving ((/x, y, z/)))
  call hepmc_vertex_init (v, xx)
end subroutine vertex_init_pos

subroutine particle_init (prt, px, py, pz, E, pdg, status)
  type(hepmc_particle_t), intent(out) :: prt
  real(default), intent(in) :: px, py, pz, E
  integer, intent(in) :: pdg, status
  type(vector4_t) :: p
  p = vector4_moving (E, vector3_moving ((/px, py, pz/)))
  call hepmc_particle_init (prt, p, pdg, status)
end subroutine particle_init

end subroutine hepmc_test

```

8.4 Particles

This module defines the `particle_t` object type, and the methods and operations that deal with it.

`<particles.f90>`≡
<File header>

```

module particles

  <Use kinds>
  <Use strings>
  <Use file utils>
  use lorentz !NODEP!
  use prt_lists
  use expressions
  use models
  use flavors
  use colors
  use helicities
  use quantum_numbers
  use state_matrices
  use interactions
  use evaluators
  use polarizations
  use les_houches_events
  use hepmc_interface

```

⟨Standard module head⟩

⟨Particles: public⟩

⟨Particles: parameters⟩

⟨Particles: types⟩

⟨Particles: interfaces⟩

contains

⟨Particles: procedures⟩

end module particles

8.4.1 The particle type

Particle status codes

The overall status codes (incoming/outgoing etc.) are inherited from the module `prt_lists`.

Polarization status:

⟨Particles: parameters⟩≡

integer, parameter :: PRT_UNPOLARIZED = 0

integer, parameter :: PRT_DEFINITE_HELICITY = 1

integer, parameter :: PRT_GENERIC_POLARIZATION = 2

Definition

The quantum numbers are flavor (from which invariant particle properties can be derived), color, and polarization. The particle may be unpolarized. In this case, `hel` and `pol` are unspecified. If it has a definite helicity, the `hel` component is defined. If it has a generic polarization, the `pol` component is defined. For each particle we store the four-momentum and the invariant mass squared, i.e., the squared norm of the four-momentum. There is also an optional list of parent and child particles, for bookkeeping in physical events.

⟨Particles: types⟩≡

type :: particle_t

private

integer :: status = PRT_UNDEFINED

integer :: polarization = PRT_UNPOLARIZED

type(flavor_t) :: flv

type(color_t) :: col

type(helicity_t) :: hel

type(polarization_t) :: pol

type(vector4_t) :: p = vector4_null

real(default) :: p2 = 0

integer, dimension(:), allocatable :: parent

integer, dimension(:), allocatable :: child

end type particle_t

Particle initializers:

(Particles: interfaces)≡

```
interface particle_init
  module procedure particle_init_state
  module procedure particle_init_hepmc
end interface
```

Initialize a particle using a single-particle state matrix which determines flavor, color, and polarization. The state matrix must have unique flavor and color. The factorization mode determines whether the particle is unpolarized, has definite helicity, or generic polarization. This mode is translated into the polarization status.

(Particles: procedures)≡

```
subroutine particle_init_state (prt, state, status, mode)
  type(particle_t), intent(out) :: prt
  type(state_matrix_t), intent(in) :: state
  integer, intent(in) :: status, mode
  type(state_iterator_t) :: it
  prt%status = status
  call state_iterator_init (it, state)
  prt%flv = state_iterator_get_flavor (it, 1)
  prt%col = state_iterator_get_color (it, 1)
  select case (mode)
  case (FM_SELECT_HELICITY)
    prt%hel = state_iterator_get_helicity (it, 1)
    prt%polarization = PRT_DEFINITE_HELICITY
  case (FM_FACTOR_HELICITY)
    call polarization_init_state_matrix (prt%pol, state)
    prt%polarization = PRT_GENERIC_POLARIZATION
  end select
end subroutine particle_init_state
```

Initialize a particle from a HepMC particle object. The model is necessary for making a fully qualified flavor component. We have the additional flag `polarized` which tells whether the polarization information should be interpreted or ignored, and the lookup array of barcodes. Note that the lookup array is searched linearly, a possible bottleneck for large particle arrays. If necessary, the barcode array could be replaced by a hash table.

(Particles: procedures)+≡

```
subroutine particle_init_hepmc (prt, hprt, model, polarization, barcode)
  type(particle_t), intent(out) :: prt
  type(hepmc_particle_t), intent(in) :: hprt
  type(model_t), intent(in), target :: model
  integer, intent(in) :: polarization
  integer, dimension(:), intent(in) :: barcode
  type(hepmc_polarization_t) :: hpol
  integer :: n_parents, n_children
  integer, dimension(:), allocatable :: parent_barcode, child_barcode
  integer :: i
  select case (hepmc_particle_get_status (hprt))
  case (1); prt%status = PRT_OUTGOING
  case (2); prt%status = PRT_RESONANT
  case (3); prt%status = PRT_VIRTUAL
```

```

end select
call flavor_init (prt%flv, hepmc_particle_get_pdg (hpvt), model)
call color_init (prt%col, hepmc_particle_get_color (hpvt))
prt%polarization = polarization
select case (polarization)
case (PRT_DEFINITE_HELICITY)
    hpvt = hepmc_particle_get_polarization (hpvt)
    call hepmc_polarization_to_hel (hpvt, prt%flv, prt%hel)
    call hepmc_polarization_final (hpvt)
case (PRT_GENERIC_POLARIZATION)
    hpvt = hepmc_particle_get_polarization (hpvt)
    call hepmc_polarization_to_pol (hpvt, prt%flv, prt%pol)
    call hepmc_polarization_final (hpvt)
end select
prt%p = hepmc_particle_get_momentum (hpvt)
prt%p2 = hepmc_particle_get_mass_squared (hpvt)
n_parents = hepmc_particle_get_n_parents (hpvt)
n_children = hepmc_particle_get_n_children (hpvt)
allocate (parent_barcode (n_parents), prt%parent (n_parents))
allocate (child_barcode (n_children), prt%child (n_children))
parent_barcode = hepmc_particle_get_parent_barcodes (hpvt)
child_barcode = hepmc_particle_get_child_barcodes (hpvt)
do i = 1, size (barcode)
    where (parent_barcode == barcode(i)) prt%parent = i
    where (child_barcode == barcode(i)) prt%child = i
end do
if (prt%status == PRT_VIRTUAL .and. n_parents == 0) &
    prt%status = PRT_INCOMING
end subroutine particle_init_hepmc

```

Finalizer. The polarization component has pointers allocated.

```

<Particles: procedures>+≡
    elemental subroutine particle_final (prt)
        type(particle_t), intent(inout) :: prt
        call polarization_final (prt%pol)
    end subroutine particle_final

```

I/O

```

<Particles: procedures>+≡
    subroutine particle_write (prt, unit)
        type(particle_t), intent(in) :: prt
        integer, intent(in), optional :: unit
        integer :: u
        u = output_unit (unit); if (u < 0) return
        select case (prt%status)
        case (PRT_UNDEFINED); write (u, "(1x, A)", advance="no") "[-]"
        case (PRT_INCOMING); write (u, "(1x, A)", advance="no") "[i]"
        case (PRT_OUTGOING); write (u, "(1x, A)", advance="no") "[o]"
        case (PRT_VIRTUAL); write (u, "(1x, A)", advance="no") "[v]"
        case (PRT_RESONANT); write (u, "(1x, A)", advance="no") "[r]"
        end select
    end subroutine

```

```

write (u, "(1x)", advance="no")
call flavor_write (prt%flv, unit)
call color_write (prt%col, unit)
select case (prt%polarization)
case (PRT_DEFINITE_HELICITY)
    call helicity_write (prt%hel, unit)
    write (u, *)
case (PRT_GENERIC_POLARIZATION)
    write (u, *)
    call polarization_write (prt%pol, unit)
case default
    write (u, *)
end select
write (u, *) "Momentum:"
call vector4_write (prt%p, unit)
write (u, "(1x,A)", advance="no") "T = "
write (u, *) prt%p2
if (allocated (prt%parent)) then
    if (size (prt%parent) /= 0) then
        write (u, "(1x,A,40(1x,I0))") "Parents:", prt%parent
    end if
end if
if (allocated (prt%child)) then
    if (size (prt%child) /= 0) then
        write (u, "(1x,A,40(1x,I0))") "Children:", prt%child
    end if
end if
end subroutine particle_write

```

Binary I/O:

$\langle \text{Particles: procedures} \rangle + \equiv$

```

subroutine particle_write_raw (prt, u)
type(particle_t), intent(in) :: prt
integer, intent(in) :: u
write (u) prt%status, prt%polarization
call flavor_write_raw (prt%flv, u)
call color_write_raw (prt%col, u)
select case (prt%polarization)
case (PRT_DEFINITE_HELICITY)
    call helicity_write_raw (prt%hel, u)
case (PRT_GENERIC_POLARIZATION)
    call polarization_write_raw (prt%pol, u)
end select
call vector4_write_raw (prt%p, u)
write (u) prt%p2
write (u) allocated (prt%parent)
if (allocated (prt%parent)) then
    write (u) size (prt%parent)
    write (u) prt%parent
end if
write (u) allocated (prt%child)
if (allocated (prt%child)) then
    write (u) size (prt%child)

```

```

        write (u) prt%child
    end if
end subroutine particle_write_raw

subroutine particle_read_raw (prt, u, iostat)
    type(particle_t), intent(out) :: prt
    integer, intent(in) :: u
    integer, intent(out), optional :: iostat
    logical :: allocated_parent, allocated_child
    integer :: size_parent, size_child
    read (u, iostat=iostat) prt%status, prt%polarization
    call flavor_read_raw (prt%flv, u, iostat=iostat)
    call color_read_raw (prt%col, u, iostat=iostat)
    select case (prt%polarization)
    case (PRT_DEFINITE_HELICITY)
        call helicity_read_raw (prt%hel, u, iostat=iostat)
    case (PRT_GENERIC_POLARIZATION)
        call polarization_read_raw (prt%pol, u, iostat=iostat)
    end select
    call vector4_read_raw (prt%p, u, iostat=iostat)
    read (u, iostat=iostat) prt%p2
    read (u, iostat=iostat) allocated_parent
    if (allocated_parent) then
        read (u, iostat=iostat) size_parent
        allocate (prt%parent (size_parent))
        read (u, iostat=iostat) prt%parent
    end if
    read (u, iostat=iostat) allocated_child
    if (allocated_child) then
        read (u, iostat=iostat) size_child
        allocate (prt%child (size_child))
        read (u, iostat=iostat) prt%child
    end if
end subroutine particle_read_raw

```

Transform a particle into a `hepmc_particle` object, including color and polarization. The HepMC status is equivalent to the HEPEVT status, in particular: 0 = null entry, 1 = physical particle, 2 = decayed/fragmented particle, 3 = other unphysical particle entry.

(Particles: procedures)+≡

```

subroutine particle_to_hepmc (prt, hprt)
    type(particle_t), intent(in) :: prt
    type(hepmc_particle_t), intent(out) :: hprt
    integer :: hepmc_status
    select case (prt%status)
    case (PRT_UNDEFINED)
        hepmc_status = 0
    case (PRT_OUTGOING)
        hepmc_status = 1
    case (PRT_RESONANT)
        hepmc_status = 2
    case default
        hepmc_status = 3
    end select
end subroutine particle_to_hepmc

```

```

end select
call hepmc_particle_init &
    (hprrt, prt%p, flavor_get_pdg (prt%flv), hepmc_status)
call hepmc_particle_set_color (hprrt, prt%col)
select case (prt%polarization)
case (PRT_DEFINITE_HELICITY)
    call hepmc_particle_set_polarization (hprrt, prt%hel)
case (PRT_GENERIC_POLARIZATION)
    call hepmc_particle_set_polarization (hprrt, prt%pol)
end select
end subroutine particle_to_hepmc

```

Setting contents

The momentum is set independent of the quantum numbers.

(Particles: procedures)+≡

```

elemental subroutine particle_set_momentum (prt, p)
    type(particle_t), intent(inout) :: prt
    type(vector4_t), intent(in) :: p
    prt%p = p
    prt%p2 = p ** 2
end subroutine particle_set_momentum

```

Set resonance information. This should be done after momentum assignment, because we need to know whether the particle is spacelike or timelike. The resonance flag is defined only for virtual particles.

(Particles: procedures)+≡

```

elemental subroutine particle_set_resonance_flag (prt, resonant)
    type(particle_t), intent(inout) :: prt
    logical, intent(in) :: resonant
    select case (prt%status)
    case (PRT_VIRTUAL)
        if (resonant) prt%status = PRT_RESONANT
    end select
end subroutine particle_set_resonance_flag

```

Set children and parents information.

(Particles: procedures)+≡

```

subroutine particle_set_children (prt, idx)
    type(particle_t), intent(inout) :: prt
    integer, dimension(:), intent(in) :: idx
    allocate (prt%child (size (idx)))
    prt%child = idx
end subroutine particle_set_children

subroutine particle_set_parents (prt, idx)
    type(particle_t), intent(inout) :: prt
    integer, dimension(:), intent(in) :: idx
    allocate (prt%parent (size (idx)))
    prt%parent = idx
end subroutine particle_set_parents

```

Accessing contents

The status code.

```
(Particles: procedures)+≡  
  function particle_get_status (prt) result (status)  
    integer :: status  
    type(particle_t), intent(in) :: prt  
    status = prt%status  
  end function particle_get_status
```

Polarization status.

```
(Particles: procedures)+≡  
  function particle_get_polarization_status (prt) result (status)  
    integer :: status  
    type(particle_t), intent(in) :: prt  
    status = prt%polarization  
  end function particle_get_polarization_status
```

Return the PDG code from the flavor component directly.

```
(Particles: procedures)+≡  
  function particle_get_pdg (prt) result (pdg)  
    integer :: pdg  
    type(particle_t), intent(in) :: prt  
    pdg = flavor_get_pdg (prt%flv)  
  end function particle_get_pdg
```

Return the polarization density matrix (as a shallow copy).

```
(Particles: procedures)+≡  
  function particle_get_polarization (prt) result (pol)  
    type(polarization_t) :: pol  
    type(particle_t), intent(in) :: prt  
    pol = prt%pol  
  end function particle_get_polarization
```

Return the number of children/parents

```
(Particles: procedures)+≡  
  function particle_get_n_parents (prt) result (n)  
    integer :: n  
    type(particle_t), intent(in) :: prt  
    if (allocated (prt%parent)) then  
      n = size (prt%parent)  
    else  
      n = 0  
    end if  
  end function particle_get_n_parents  
  
  function particle_get_n_children (prt) result (n)  
    integer :: n  
    type(particle_t), intent(in) :: prt  
    if (allocated (prt%child)) then  
      n = size (prt%child)  
    else
```

```

        n = 0
    end if
end function particle_get_n_children

```

Return the array of parents/children.

(Particles: procedures)+≡

```

function particle_get_parents (prt) result (parent)
    type(particle_t), intent(in) :: prt
    integer, dimension(:), allocatable :: parent
    if (allocated (prt%parent)) then
        allocate (parent (size (prt%parent)))
        parent = prt%parent
    else
        allocate (parent (0))
    end if
end function particle_get_parents

function particle_get_children (prt) result (child)
    type(particle_t), intent(in) :: prt
    integer, dimension(:), allocatable :: child
    if (allocated (prt%child)) then
        allocate (child (size (prt%child)))
        child = prt%child
    else
        allocate (child (0))
    end if
end function particle_get_children

```

Return momentum and momentum squared.

(Particles: procedures)+≡

```

function particle_get_momentum (prt) result (p)
    type(vector4_t) :: p
    type(particle_t), intent(in) :: prt
    p = prt%p
end function particle_get_momentum

function particle_get_p2 (prt) result (p2)
    real(default) :: p2
    type(particle_t), intent(in) :: prt
    p2 = prt%p2
end function particle_get_p2

```

8.4.2 Particle sets

A particle set is what is usually called an event: an array of particles. The individual particle entries carry momentum, quantum numbers, polarization, and optionally connections. There is (also optionally) a correlated state-density matrix that maintains spin correlations that are lost in the individual particle entries.

(Particles: public)≡

```

public :: particle_set_t

```

```

<Particles: types>+≡
  type :: particle_set_t
  private
    integer :: n_in = 0
    integer :: n_vir = 0
    integer :: n_out = 0
    integer :: n_tot = 0
    type(particle_t), dimension(:), allocatable :: prt
    type(state_matrix_t) :: correlated_state
  end type particle_set_t

```

A particle set can be initialized from an interaction or from a HepMC event record.

```

<Particles: public>+≡
  public :: particle_set_init

<Particles: interfaces>+≡
  interface particle_set_init
    module procedure particle_set_init_interaction
    module procedure particle_set_init_hepmc
  end interface

```

When a particle set is initialized from a given interaction, we have to determine the branch within the original state matrix that fixes the particle quantum numbers. This is done with the appropriate probabilities, based on a random number `x`. The `mode` determines whether the individual particles become unpolarized, or take a definite (diagonal) helicity, or acquire single-particle polarization matrices. The flag `keep_correlations` tells whether the spin-correlation matrix is to be calculated and stored in addition to the particles. The flag `keep_virtual` tells whether virtual particles should be dropped. Note that if virtual particles are dropped, the spin-correlation matrix makes no sense, and parent-child relations are not set.

For a correct disentangling of color and flavor (in the presence of helicity), we consider two interactions. `int` has no color information, and is used to select a flavor state. Consequently, we trace over helicities here. `int_flows` contains color-flow and potentially helicity information, but is useful only after the flavor combination has been chosen. So this interaction is used to select helicity and color, but restricted to the selected flavor combination.

`int` and `int_flows` may be identical if there is only a single (or no) color flow. If there is just a single flavor combination, `x(1)` can be set to zero.

The current algorithm of evaluator convolution requires that the beam particles are assumed outgoing (in the beam interaction) and become virtual in all derived interactions. In the particle set they should be re-identified as incoming. The optional integer `n_incoming` can be used to perform this correction.

```

<Particles: procedures>+≡
  subroutine particle_set_init_interaction &
    (particle_set, int, int_flows, mode, x, &
     keep_correlations, keep_virtual, n_incoming)
    type(particle_set_t), intent(out) :: particle_set
    type(interaction_t), intent(in), target :: int, int_flows
    integer, intent(in) :: mode

```

```

real(default), dimension(2), intent(in) :: x
logical, intent(in) :: keep_correlations, keep_virtual
integer, intent(in), optional :: n_incoming
type(state_matrix_t), dimension(:), allocatable, target :: flavor_state
type(state_matrix_t), dimension(:), allocatable, target :: single_state
integer :: n_in, n_vir, n_out, n_tot
type(quantum_numbers_t), dimension(:,:), allocatable :: qn
integer :: i, j
if (present (n_incoming)) then
    n_in = n_incoming
    n_vir = interaction_get_n_vir (int) - n_incoming
else
    n_in = interaction_get_n_in (int)
    n_vir = interaction_get_n_vir (int)
end if
n_out = interaction_get_n_out (int)
n_tot = interaction_get_n_tot (int)
particle_set%n_in = n_in
particle_set%n_out = n_out
if (keep_virtual) then
    particle_set%n_vir = n_vir
    particle_set%n_tot = n_tot
else
    particle_set%n_vir = 0
    particle_set%n_tot = n_in + n_out
end if
call interaction_factorize (int, FM_IGNORE_HELICITY, x(1), flavor_state)
allocate (qn (n_tot,1))
do i = 1, n_tot
    qn(i,:) = state_matrix_get_quantum_numbers (flavor_state(i), 1)
end do
if (keep_correlations .and. keep_virtual) then
    call interaction_factorize (int_flows, &
        mode, x(2), single_state, particle_set%correlated_state, qn(:,1))
else
    call interaction_factorize (int_flows, &
        mode, x(2), single_state, qn_in=qn(:,1))
end if
allocate (particle_set%prt (particle_set%n_tot))
j = 1
do i = 1, n_tot
    if (i <= n_in) then
        call particle_init &
            (particle_set%prt(j), single_state(i), PRT_INCOMING, mode)
    else if (i <= n_in + n_vir) then
        if (.not. keep_virtual) cycle
        call particle_init &
            (particle_set%prt(j), single_state(i), PRT_VIRTUAL, mode)
    else
        call particle_init &
            (particle_set%prt(j), single_state(i), PRT_OUTGOING, mode)
    end if
    call particle_set_momentum &
        (particle_set%prt(j), interaction_get_momentum (int, i))

```

```

        if (keep_virtual) then
            call particle_set_children &
                (particle_set%prt(j), interaction_get_children (int, i))
            call particle_set_parents &
                (particle_set%prt(j), interaction_get_parents (int, i))
        end if
        j = j + 1
    end do
    if (keep_virtual) then
        call particle_set_resonance_flag &
            (particle_set%prt, interaction_get_resonance_flags (int))
    end if
    call state_matrix_final (flavor_state)
    call state_matrix_final (single_state)
end subroutine particle_set_init_interaction

```

If a particle set is initialized from a HepMC event record, we have to specify the treatment of polarization (unpolarized or density matrix) which is common to all particles. Correlated polarization information is not available.

(Particles: procedures)+≡

```

subroutine particle_set_init_hepmc (particle_set, evt, model, polarization)
    type(particle_set_t), intent(out) :: particle_set
    type(hepmc_event_t), intent(in) :: evt
    type(model_t), intent(in), target :: model
    integer, intent(in) :: polarization
    type(hepmc_event_particle_iterator_t) :: it
    type(hepmc_particle_t) :: prt
    integer, dimension(:), allocatable :: barcode
    integer :: n_tot, i
    n_tot = 0
    call hepmc_event_particle_iterator_init (it, evt)
    do while (hepmc_event_particle_iterator_is_valid (it))
        n_tot = n_tot + 1
        call hepmc_event_particle_iterator_advance (it)
    end do
    allocate (barcode (n_tot))
    call hepmc_event_particle_iterator_reset (it)
    do i = 1, n_tot
        barcode(i) = hepmc_particle_get_barcode &
            (hepmc_event_particle_iterator_get (it))
        call hepmc_event_particle_iterator_advance (it)
    end do
    allocate (particle_set%prt (n_tot))
    call hepmc_event_particle_iterator_reset (it)
    do i = 1, n_tot
        prt = hepmc_event_particle_iterator_get (it)
        call particle_init (particle_set%prt(i), &
            prt, model, polarization, barcode)
        call hepmc_event_particle_iterator_advance (it)
    end do
    call hepmc_event_particle_iterator_final (it)
    particle_set%n_tot = n_tot
end subroutine particle_set_init_hepmc

```

Pointer components are hidden inside the particle polarization, and in the correlated state matrix.

```

<Particles: public>+≡
    public :: particle_set_final

<Particles: procedures>+≡
    subroutine particle_set_final (particle_set)
        type(particle_set_t), intent(inout) :: particle_set
        if (allocated (particle_set%prt)) call particle_final (particle_set%prt)
        call state_matrix_final (particle_set%correlated_state)
    end subroutine particle_set_final

```

Output (default format)

```

<Particles: public>+≡
    public :: particle_set_write

<Particles: procedures>+≡
    subroutine particle_set_write (particle_set, unit)
        type(particle_set_t), intent(in) :: particle_set
        integer, intent(in), optional :: unit
        integer :: u, i
        u = output_unit (unit); if (u < 0) return
        write (u, "(1x,A)") "Particle set:"
        if (particle_set%n_tot /= 0) then
            do i = 1, particle_set%n_tot
                write (u, "(1x,A,1x,I0)", advance="no") "Particle", i
                call particle_write (particle_set%prt(i), u)
            end do
            if (state_matrix_is_defined (particle_set%correlated_state)) then
                write (u, *) "Correlated state density matrix:"
                call state_matrix_write (particle_set%correlated_state, u)
            end if
        else
            write (u, "(3x,A)") "[empty]"
        end if
    end subroutine particle_set_write

```

8.4.3 I/O formats

Here, we define input/output of particle sets in various formats. This is the right place since particle sets contain most of the event information.

All write/read routines take as first argument the object, as second argument the I/O unit which in this case is a mandatory argument. Then follow further event data.

Internal binary format

This format is supposed to contain the complete information, so the particle data set can be fully reconstructed. The exception is the model part of the particle flavors; this is unassigned for the flavor values read from file.

```

<Particles: public>+≡

```

```

public :: particle_set_write_raw
public :: particle_set_read_raw

<Particles: procedures>+≡
subroutine particle_set_write_raw (particle_set, u)
  type(particle_set_t), intent(in) :: particle_set
  integer, intent(in) :: u
  integer :: i
  write (u) particle_set%n_in, particle_set%n_vir, particle_set%n_out
  write (u) particle_set%n_tot
  do i = 1, particle_set%n_tot
    call particle_write_raw (particle_set%prt(i), u)
  end do
  call state_matrix_write_raw (particle_set%correlated_state, u)
end subroutine particle_set_write_raw

subroutine particle_set_read_raw (particle_set, u, iostat)
  type(particle_set_t), intent(out) :: particle_set
  integer, intent(in) :: u
  integer, intent(out), optional :: iostat
  integer :: i
  read (u, iostat=iostat) &
    particle_set%n_in, particle_set%n_vir, particle_set%n_out
  read (u, iostat=iostat) particle_set%n_tot
  allocate (particle_set%prt (particle_set%n_tot))
  do i = 1, size (particle_set%prt)
    call particle_read_raw (particle_set%prt(i), u, iostat=iostat)
  end do
  call state_matrix_read_raw (particle_set%correlated_state, u, iostat=iostat)
end subroutine particle_set_read_raw

```

Les Houches event format

This format consists of two common blocks and a file format. The actual interface is put in a separate module `les_houches_events`.

We first fill the common block. Event information such as process ID and weight is not transferred here; this has to be done by the caller. The spin information is set only if the particle has a unique mother, and if its polarization is fully defined.

```

<Particles: public>+≡
public :: particle_set_fill_hepeup

<Particles: procedures>+≡
subroutine particle_set_fill_hepeup (particle_set)
  type(particle_set_t), intent(in), target :: particle_set
  type(particle_t), pointer :: prt
  integer :: i, n_parents
  integer, dimension(1) :: i_mother
  call hepeup_init (particle_set%n_tot)
  do i = 1, particle_set%n_tot
    prt => particle_set%prt(i)
    call hepeup_set_particle (i, &
      particle_get_pdg (prt), &

```

```

        particle_get_status (prt), &
        particle_get_parents (prt), &
        particle_get_momentum (prt), &
        particle_get_p2 (prt))
    n_parents = particle_get_n_parents (prt)
    if (n_parents == 1) then
        i_mother = particle_get_parents (prt)
        select case (particle_get_polarization_status (prt))
        case (PRT_GENERIC_POLARIZATION)
            call hepeup_set_particle_spin (i, &
                particle_get_momentum (prt), &
                particle_get_polarization (prt), &
                particle_get_momentum (particle_set%prt(i_mother(1))))
        end select
    end if
end do
end subroutine particle_set_fill_hepeup

```

HepMC format

The master output function fills a HepMC GenEvent object that is already initialized, but has no vertices in it.

We first set up the vertex lists and enter the vertices into the HepMC event. Then, we assign first all incoming particles and then all outgoing particles to their associated vertices. Particles which have neither parent nor children entries (this should not happen) are dropped.

```

<Particles: public>+≡
    public :: particle_set_fill_hepmc_event

<Particles: procedures>+≡
    subroutine particle_set_fill_hepmc_event (particle_set, evt)
        type(particle_set_t), intent(in) :: particle_set
        type(hepmc_event_t), intent(inout) :: evt
        type(hepmc_vertex_t), dimension(:), allocatable :: v
        type(hepmc_particle_t), dimension(:), allocatable :: hpvt
        integer, dimension(:), allocatable :: v_from, v_to
        integer :: n_vertices, i
        allocate (v_from (particle_set%n_tot), v_to (particle_set%n_tot))
        call particle_set_assign_vertices (particle_set, v_from, v_to, n_vertices)
        allocate (v (n_vertices))
        do i = 1, n_vertices
            call hepmc_vertex_init (v(i))
            call hepmc_event_add_vertex (evt, v(i))
        end do
        allocate (hpvt (particle_set%n_tot))
        do i = 1, particle_set%n_tot
            if (v_to(i) /= 0 .or. v_from(i) /= 0) then
                call particle_to_hepmc (particle_set%prt(i), hpvt(i))
            end if
        end do
        do i = 1, particle_set%n_tot
            if (v_to(i) /= 0) then
                call hepmc_vertex_add_particle_in (v(v_to(i)), hpvt(i))
            end if
        end do
    end subroutine particle_set_fill_hepmc_event

```

```

        end if
    end do
    do i = 1, particle_set%n_tot
        if (v_from(i) /= 0) then
            call hepmc_vertex_add_particle_out (v(v_from(i)), hpvt(i))
        end if
    end do
end subroutine particle_set_fill_hepmc_event

```

Tools

This procedure reconstructs an array of vertex indices from the parent-child information in the particle entries, according to the HepMC scheme. For each particle, we determine which vertex it comes from and which vertex it goes to. We return the two arrays and the maximum vertex index.

For each particle in the list, we first check its parents. If for any parent the vertex where it goes to is already known, this vertex index is assigned as the current 'from' vertex. Otherwise, a new index is created, assigned as the current 'from' vertex, and as the 'to' vertex for all parents.

Then, the analogous procedure is done for the children.

(Particles: procedures)+≡

```

subroutine particle_set_assign_vertices &
    (particle_set, v_from, v_to, n_vertices)
type(particle_set_t), intent(in) :: particle_set
integer, dimension(:), intent(out) :: v_from, v_to
integer, intent(out) :: n_vertices
integer, dimension(:), allocatable :: parent, child
integer :: n_parents, n_children, vf, vt
integer :: i, j, v
v_from = 0
v_to = 0
vf = 0
vt = 0
do i = 1, particle_set%n_tot
    n_parents = particle_get_n_parents (particle_set%prt(i))
    if (n_parents /= 0) then
        allocate (parent (n_parents))
        parent = particle_get_parents (particle_set%prt(i))
        SCAN_PARENTS: do j = 1, size (parent)
            v = v_to(parent(j))
            if (v /= 0) then
                v_from(i) = v; exit SCAN_PARENTS
            end if
        end do SCAN_PARENTS
        if (v_from(i) == 0) then
            vf = vf + 1; v_from(i) = vf
            v_to(parent) = vf
        end if
        deallocate (parent)
    end if
    n_children = particle_get_n_children (particle_set%prt(i))
    if (n_children /= 0) then

```

```

allocate (child (n_children))
child = particle_get_children (particle_set%prt(i))
SCAN_CHILDREN: do j = 1, size (child)
  v = v_from(child(j))
  if (v /= 0) then
    v_to(i) = v; exit SCAN_CHILDREN
  end if
end do SCAN_CHILDREN
if (v_to(i) == 0) then
  vt = vt + 1; v_to(i) = vt
  v_from(child) = vt
end if
deallocate (child)
end if
end do
n_vertices = max (vf, vt)
end subroutine particle_set_assign_vertices

```

8.4.4 Expression interface

This converts a `particle_set` object as defined here to a more concise `prt_list` object that can be used as the event root of an expression. In particular, the latter lacks virtual particles, spin correlations and parent-child relations.

TODO: The `prt_list` also lacks helicity/pol info.

```

(Particles: public) +=
  public :: particle_set_to_prt_list

(Particles: procedures) +=
  subroutine particle_set_to_prt_list (particle_set, prt_list)
    type(particle_set_t), intent(in), target :: particle_set
    type(prt_list_t), intent(out) :: prt_list
    type(particle_t), pointer :: prt
    integer :: i, k
    call prt_list_init (prt_list)
    call prt_list_reset (prt_list, particle_set%n_in + particle_set%n_out)
    k = 0
    do i = 1, particle_set%n_tot
      prt => particle_set%prt(i)
      select case (particle_get_status (prt))
        case (PRT_INCOMING)
          k = k + 1
          call prt_list_set_incoming (prt_list, k, &
            particle_get_pdg (prt), &
            particle_get_momentum (prt), &
            particle_get_p2 (prt))
        case (PRT_OUTGOING)
          k = k + 1
          call prt_list_set_outgoing (prt_list, k, &
            particle_get_pdg (prt), &
            particle_get_momentum (prt), &
            particle_get_p2 (prt))
      end select
    end do
  end do

```

```
end subroutine particle_set_to_prt_list
```

8.4.5 Test

Set up a chain of production and decay and factorize the result into particles.
The process is $d\bar{d} \rightarrow Z \rightarrow q\bar{q}$.

(Particles: public)+≡

```
public :: particles_test
```

(Particles: procedures)+≡

```
subroutine particles_test
  use os_interface, only: os_data_t
  type(os_data_t) :: os_data
  type(model_t), pointer :: model
  type(flavor_t), dimension(3) :: flv
  type(color_t), dimension(3) :: col
  type(helicity_t), dimension(3) :: hel
  type(quantum_numbers_t), dimension(3) :: qn
  type(vector4_t), dimension(3) :: p
  type(interaction_t), target :: int1, int2
  type(quantum_numbers_mask_t) :: qn_mask_conn, qn_rest
  type(evaluator_t), target :: eval
  type(interaction_t), pointer :: int
  type(particle_set_t) :: particle_set1, particle_set2
  type(particle_set_t) :: particle_set3, particle_set4
  type(hepmc_event_t) :: hepmc_event
  type(hepmc_iostream_t) :: iostream
  type(prt_list_t) :: prt_list
  integer :: u
  print *, "*** Read model file"
  call syntax_model_file_init ()
  call model_list_read_model &
    (var_str("QCD"), var_str("test.mdl"), os_data, model)
  print *
  print *, "*** Setup production process ***"
  call interaction_init (int1, 2, 0, 1, set_relations=.true.)
  call flavor_init (flv, (/1, -1, 23/), model)
  call helicity_init (hel(3), 1, 1)
  call quantum_numbers_init (qn, flv, hel)
  call interaction_add_state (int1, qn, value=(0.25_default, 0._default))
  call helicity_init (hel(3), 1,-1)
  call quantum_numbers_init (qn, flv, hel)
  call interaction_add_state (int1, qn, value=(0._default, 0.25_default))
  call helicity_init (hel(3),-1, 1)
  call quantum_numbers_init (qn, flv, hel)
  call interaction_add_state (int1, qn, value=(0._default,-0.25_default))
  call helicity_init (hel(3),-1,-1)
  call quantum_numbers_init (qn, flv, hel)
  call interaction_add_state (int1, qn, value=(0.25_default, 0._default))
  call helicity_init (hel(3), 0, 0)
  call quantum_numbers_init (qn, flv, hel)
  call interaction_add_state (int1, qn, value=(0.5_default, 0._default))
  call interaction_freeze (int1)
```

```

p(1) = vector4_moving (45._default, 45._default, 3)
p(2) = vector4_moving (45._default,-45._default, 3)
p(3) = p(1) + p(2)
call interaction_set_momenta (int1, p)
print *
print *, "*** Setup decay process ***"
call interaction_init (int2, 1, 0, 2, set_relations=.true.)
call flavor_init (flv, (/23, 1, -1/), model)
call color_init_col_acl (col, (/ 0, 501, 0 /), (/ 0, 0, 501 /))
call helicity_init (hel, (/ 1, 1, 1/), (/ 1, 1, 1/))
call quantum_numbers_init (qn, flv, col, hel)
call interaction_add_state (int2, qn, value=(1._default, 0._default))
call helicity_init (hel, (/ 1, 1, 1/), (/ -1, -1, -1/))
call quantum_numbers_init (qn, flv, col, hel)
call interaction_add_state (int2, qn, value=(0._default, 0.1_default))
call helicity_init (hel, (/ -1, -1, -1/), (/ 1, 1, 1/))
call quantum_numbers_init (qn, flv, col, hel)
call interaction_add_state (int2, qn, value=(0._default, -0.1_default))
call helicity_init (hel, (/ -1, -1, -1/), (/ -1, -1, -1/))
call quantum_numbers_init (qn, flv, col, hel)
call interaction_add_state (int2, qn, value=(1._default, 0._default))
call helicity_init (hel, (/ 0, 1, -1/), (/ 0, 1, -1/))
call quantum_numbers_init (qn, flv, col, hel)
call interaction_add_state (int2, qn, value=(4._default, 0._default))
call helicity_init (hel, (/ 0, -1, 1/), (/ 0, 1, -1/))
call quantum_numbers_init (qn, flv, col, hel)
call interaction_add_state (int2, qn, value=(2._default, 0._default))
call helicity_init (hel, (/ 0, 1, -1/), (/ 0, -1, 1/))
call quantum_numbers_init (qn, flv, col, hel)
call interaction_add_state (int2, qn, value=(2._default, 0._default))
call helicity_init (hel, (/ 0, -1, 1/), (/ 0, -1, 1/))
call quantum_numbers_init (qn, flv, col, hel)
call interaction_add_state (int2, qn, value=(4._default, 0._default))
call flavor_init (flv, (/23, 2, -2/), model)
call helicity_init (hel, (/ 0, 1, -1/), (/ 0, 1, -1/))
call quantum_numbers_init (qn, flv, col, hel)
call interaction_add_state (int2, qn, value=(0.5_default, 0._default))
call helicity_init (hel, (/ 0, -1, 1/), (/ 0, -1, 1/))
call quantum_numbers_init (qn, flv, col, hel)
call interaction_add_state (int2, qn, value=(0.5_default, 0._default))
call interaction_freeze (int2)
p(2) = vector4_moving (45._default, 45._default, 2)
p(3) = vector4_moving (45._default,-45._default, 2)
call interaction_set_momenta (int2, p)
call interaction_set_source_link (int2, 1, int1, 3)
call interaction_write (int1)
call interaction_write (int2)
print *
print *, "*** Concatenate production and decay ***"
call evaluator_init_product (eval, int1, int2, qn_mask_conn, &
connections_are_resonant=.true.)
call evaluator_receive_momenta (eval)
call evaluator_evaluate (eval)
call evaluator_write (eval)

```

```

print *
print *, "*** Factorize as particle list (complete, polarized) ***"
int => evaluator_get_int_ptr (eval)
call particle_set_init &
    (particle_set1, int, int, FM_FACTOR_HELICITY, &
    (/0.2_default, 0.2_default/), .false., .true.)
call particle_set_write (particle_set1)
print *
print *, "*** Write this to HEPEUP and print as LHEF format ***"
call les_houches_events_write_header ()
call heprup_init ((/2212, 2212/), (/7.e3_default, 7.e3_default/), &
    n_processes=1, unweighted=.true., negative_weights=.false.)
call heprup_set_process_parameters (1, 1)
call heprup_write_lhef ()
call particle_set_fill_hepeup (particle_set1)
call hepeup_write_lhef ()
call les_houches_events_write_footer ()
print *
print *, "*** Factorize as particle list (in/out only, selected helicity) ***"
int => evaluator_get_int_ptr (eval)
call particle_set_init &
    (particle_set2, int, int, FM_SELECT_HELICITY, &
    (/0.9_default, 0.9_default/), .false., .false.)
call particle_set_write (particle_set2)
call particle_set_final (particle_set2)
print *
print *, "*** Factorize as particle list (complete, selected helicity) ***"
int => evaluator_get_int_ptr (eval)
call particle_set_init &
    (particle_set2, int, int, FM_SELECT_HELICITY, &
    (/0.7_default, 0.7_default/), .false., .true.)
call particle_set_write (particle_set2)
print *
print *, "*** Write to HepMC, print, and output to particles_test.hepmc.dat ***"
call hepmc_event_init (hepmc_event, 11, 127)
call particle_set_fill_hepmc_event (particle_set2, hepmc_event)
call hepmc_event_print (hepmc_event)
call hepmc_iostream_open_out &
    (iostream , var_str ("particles_test.hepmc.dat"))
call hepmc_iostream_write_event (iostream, hepmc_event)
call hepmc_iostream_close (iostream)
print *
print *, "*** Recover from HepMC file ***"
call particle_set_final (particle_set2)
call hepmc_event_final (hepmc_event)
call hepmc_event_init (hepmc_event)
call hepmc_iostream_open_in &
    (iostream , var_str ("particles_test.hepmc.dat"))
call hepmc_iostream_read_event (iostream, hepmc_event)
call hepmc_iostream_close (iostream)
call particle_set_init (particle_set2, &
    hepmc_event, model, PRT_DEFINITE_HELICITY)
call particle_set_write (particle_set2)
print *

```

```

print *, "*** Factorize (complete, polarized, correlated); write and read again ***"
int => evaluator_get_int_ptr (eval)
call particle_set_init &
    (particle_set3, int, int, FM_FACTOR_HELICITY, &
    (/0.7_default, 0.7_default/), .true., .true.)
call particle_set_write (particle_set3)
u = free_unit ()
open (u, action="readwrite", form="unformatted", status="scratch")
call particle_set_write_raw (particle_set3, u)
rewind (u)
call particle_set_read_raw (particle_set4, u)
close (u)
print *
call particle_set_write (particle_set4)
print *
print *, "*** Transform to a prt_list object ***"
call particle_set_to_prt_list (particle_set4, prt_list)
call prt_list_write (prt_list)
print *
print *, "*** Cleanup ***"
call particle_set_final (particle_set1)
call particle_set_final (particle_set2)
call particle_set_final (particle_set3)
call particle_set_final (particle_set4)
call evaluator_final (eval)
call interaction_final (int1)
call interaction_final (int2)
call hepmc_event_final (hepmc_event)
end subroutine particles_test

```

Chapter 9

Initial State

9.1 Beams for collisions and decays

```
<beams.f90>≡  
  <File header>  
  
  module beams  
  
    <Use kinds>  
    <Use strings>  
    use constants !NODEP!  
    <Use file utils>  
    use diagnostics !NODEP!  
    use lorentz !NODEP!  
    use md5  
    use models  
    use flavors  
    use colors  
    use polarizations  
    use quantum_numbers  
    use state_matrices  
    use interactions  
  
    <Standard module head>  
  
    <Beams: public>  
  
    <Beams: types>  
  
    <Beams: interfaces>  
  
    contains  
  
    <Beams: procedures>  
  
  end module beams
```

9.1.1 Beam data

The beam data type contains beam data for one or two beams, depending on whether we are dealing with beam collisions or particle decay. In addition, it holds the c.m. energy `sqrts`, the Lorentz transformation `L` that transforms the c.m. system into the lab system, and the pair of c.m. momenta.

```

(Beams: public)≡
    public :: beam_data_t

(Beams: types)≡
    type :: beam_data_t
        logical :: initialized = .false.
        integer :: n
        type(flavor_t), dimension(:), allocatable :: flv
        real(default), dimension(:), allocatable :: mass
        type(polarization_t), dimension(:), allocatable :: pol
        logical :: lab_is_cm_frame = .true.
        type(vector4_t), dimension(:), allocatable :: p_cm
        type(vector4_t), dimension(:), allocatable :: p
        type(lorentz_transformation_t), pointer :: L_cm_to_lab => null ()
        real(default) :: sqrts
        character(32) :: md5sum = ""
    end type beam_data_t

```

Generic initializer. This is called by the specific initializers below. Initialize either for decay or for collision.

```

(Beams: procedures)≡
    subroutine beam_data_init (beam_data, n)
        type(beam_data_t), intent(out) :: beam_data
        integer, intent(in) :: n
        beam_data%n = n
        allocate (beam_data%flv (n))
        allocate (beam_data%mass (n))
        allocate (beam_data%pol (n))
        allocate (beam_data%p_cm (n))
        allocate (beam_data%p (n))
        beam_data%initialized = .true.
    end subroutine beam_data_init

```

Finalizer: needed for the polarization components of the beams.

```

(Beams: public)+≡
    public :: beam_data_final

(Beams: procedures)+≡
    subroutine beam_data_final (beam_data)
        type(beam_data_t), intent(inout) :: beam_data
        beam_data%initialized = .false.
        if (allocated (beam_data%pol)) call polarization_final (beam_data%pol)
        if (associated (beam_data%L_cm_to_lab)) deallocate (beam_data%L_cm_to_lab)
    end subroutine beam_data_final

```

The verbose (default) version is for debugging. The short version is for screen output in the UI.

<Beams: public>+≡

public :: beam_data_write

<Beams: procedures>+≡

```
subroutine beam_data_write (beam_data, unit, verbose, write_md5sum)
  type(beam_data_t), intent(in) :: beam_data
  integer, intent(in), optional :: unit
  logical, intent(in), optional :: verbose, write_md5sum
  integer :: prt_name_len
  logical :: verb, write_md5
  integer :: u
  u = output_unit (unit); if (u < 0) return
  verb = .true.; if (present (verbose)) verb = verbose
  write_md5 = verb; if (present (write_md5sum)) write_md5 = write_md5sum
  if (.not. beam_data%initialized) then
    write (u, "(A)") "Beam data: [undefined]"
    return
  end if
  prt_name_len = maxval (len (flavor_get_name (beam_data%flv)))
  select case (beam_data%n)
  case (1)
    write (u, "(A)") "Beam data (decay):"
    if (verb) then
      call write_prt (1)
      call polarization_write (beam_data%pol(1), u)
      write (u, *) "R.f. momentum:"
      call vector4_write (beam_data%p_cm(1), u)
      write (u, *) "Lab momentum:"
      call vector4_write (beam_data%p(1), u)
    else
      call write_prt (1)
    end if
  case (2)
    write (u, "(A)") "Beam data (collision):"
    if (verb) then
      call write_prt (1)
      call polarization_write (beam_data%pol(1), u)
      call write_prt (2)
      call polarization_write (beam_data%pol(2), u)
      call write_sqrts
      write (u, *) "C.m. momenta:"
      call vector4_write (beam_data%p_cm(1), u)
      call vector4_write (beam_data%p_cm(2), u)
      write (u, *) "Lab momenta:"
      call vector4_write (beam_data%p(1), u)
      call vector4_write (beam_data%p(2), u)
    else
      call write_prt (1)
      call write_prt (2)
      call write_sqrts
    end if
  end select
```

```

    if (associated (beam_data%L_cm_to_lab)) &
        call lorentz_transformation_write (beam_data%L_cm_to_lab, u)
    if (write_md5) then
        write (u, *) "MD5 sum: ", beam_data%md5sum
    end if
contains
    subroutine write_sqrts
        character(80) :: sqrts_str
        write (sqrts_str, "(1PG21.15)") beam_data%sqrts
        write (u, "(1x,A)") "sqrts = " // trim (adjustl (sqrts_str)) // " GeV"
    end subroutine write_sqrts
    subroutine write_prt (i)
        integer, intent(in) :: i
        character(80) :: name_str, mass_str
        write (name_str, "(A)") char (flavor_get_name (beam_data%flv(i)))
        write (mass_str, "(1PG15.8)") beam_data%mass(i)
        write (u, "(1x,A)") name_str(:prt_name_len) // " (mass = " &
            // trim (adjustl (mass_str)) // " GeV)"
    end subroutine write_prt
end subroutine beam_data_write

```

Return initialization status:

```

(Beams: public)+≡
    public :: beam_data_are_valid

(Beams: procedures)+≡
    function beam_data_are_valid (beam_data) result (flag)
        logical :: flag
        type(beam_data_t), intent(in) :: beam_data
        flag = beam_data%initialized
    end function beam_data_are_valid

```

Return the number of beams (1 for decays, 2 for collisions).

```

(Beams: public)+≡
    public :: beam_data_get_n_in

(Beams: procedures)+≡
    function beam_data_get_n_in (beam_data) result (n_in)
        integer :: n_in
        type(beam_data_t), intent(in) :: beam_data
        n_in = beam_data%n
    end function beam_data_get_n_in

```

Return the beam energies

```

(Beams: public)+≡
    public :: beam_data_get_energy

(Beams: procedures)+≡
    function beam_data_get_energy (beam_data) result (e)
        real(default), dimension(:), allocatable :: e
        type(beam_data_t), intent(in) :: beam_data
        allocate (e (beam_data%n))
        if (beam_data%initialized) then
            e = energy (beam_data%p)
        end if
    end function beam_data_get_energy

```

```

    else
        e = 0
    end if
end function beam_data_get_energy

```

Return a MD5 checksum for beam data. If no checksum is present (because beams have not been initialized), compute the checksum of the sqrts value.

```

(Beams: public)+≡
    public :: beam_data_get_md5sum

(Beams: procedures)+≡
    function beam_data_get_md5sum (beam_data, sqrts) result (md5sum_beams)
        type(beam_data_t), intent(in) :: beam_data
        real(default), intent(in) :: sqrts
        character(32) :: md5sum_beams
        character(80) :: buffer
        if (beam_data%md5sum /= "") then
            md5sum_beams = beam_data%md5sum
        else
            write (buffer, *) sqrts
            md5sum_beams = md5sum (buffer)
        end if
    end function beam_data_get_md5sum

```

9.1.2 Initializers: collisions

This is the simplest one: just the two flavors, c.m. energy, polarization. Color is inferred from flavor. Beam momenta and c.m. momenta coincide.

```

(Beams: public)+≡
    public :: beam_data_init_sqrts

(Beams: procedures)+≡
    subroutine beam_data_init_sqrts &
        (beam_data, sqrts, flv, pol, p_cm, p_cm_theta, p_cm_phi)
        type(beam_data_t), intent(out) :: beam_data
        real(default), intent(in) :: sqrts
        type(flavor_t), dimension(:), intent(in) :: flv
        type(polarization_t), dimension(:), intent(in), optional :: pol
        real(default), intent(in), optional :: p_cm, p_cm_theta, p_cm_phi
        real(default), dimension(size(flv)) :: E, p
        integer :: i
        call beam_data_init (beam_data, size (flv))
        beam_data%sqrts = sqrts
        beam_data%lab_is_cm_frame = &
            .not. present (p_cm) .and. .not. present (p_cm_theta)
        select case (beam_data%n)
        case (1)
            if (present (p_cm)) then
                E = sqrt (sqrts**2 + p_cm**2)
                p = p_cm
            else
                E = sqrts; p = 0
            end if
        end select
    end subroutine beam_data_init_sqrts

```

```

        end if
        beam_data%p_cm = vector4_moving (E, p, 3)
    case (2)
        beam_data%p_cm = colliding_momenta (sqrts, flavor_get_mass (flv), p_cm)
    end select
    if (present (p_cm_theta)) then
        beam_data%p_cm = rotation (p_cm_theta, 2) * beam_data%p_cm
        if (present (p_cm_phi)) then
            beam_data%p_cm = rotation (p_cm_phi, 3) * beam_data%p_cm
        end if
    end if
    do i = 1, beam_data%n
        beam_data%flv(i) = flv(i)
        beam_data%mass(i) = flavor_get_mass (flv(i))
        beam_data%p(i) = beam_data%p_cm(i)
        if (present (pol)) then
            beam_data%pol(i) = pol(i)
        else
            call polarization_init_unpolarized (beam_data%pol(i), flv(i))
        end if
    end do
    call beam_data_compute_md5sum (beam_data)
end subroutine beam_data_init_sqrts

```

9.1.3 Initializers: decays

This is the simplest one: decay in rest frame. We need just flavor and polarization. Color is inferred from flavor. Beam momentum and c.m. momentum coincide.

```

(Beams: public)+≡
    public :: beam_data_init_decay

(Beams: procedures)+≡
    subroutine beam_data_init_decay &
        (beam_data, flv, pol, p_cm, p_cm_theta, p_cm_phi)
        type(beam_data_t), intent(out) :: beam_data
        type(flavor_t), dimension(1), intent(in) :: flv
        type(polarization_t), dimension(1), intent(in), optional :: pol
        real(default), intent(in), optional :: p_cm, p_cm_theta, p_cm_phi
        real(default), dimension(1) :: m
        type(polarization_t), dimension(1) :: polarization
        m = flavor_get_mass (flv)
        if (present (pol)) then
            call beam_data_init_sqrts &
                (beam_data, m(1), flv, pol, p_cm, p_cm_theta, p_cm_phi)
        else
            call polarization_init_trivial (polarization(1), flv(1))
            call beam_data_init_sqrts &
                (beam_data, m(1), flv, polarization, p_cm, p_cm_theta, p_cm_phi)
        end if
    end subroutine beam_data_init_decay

```

9.1.4 Compute MD5 sum

The MD5 sum is stored within the beam-data record, so it can be checked for integrity in subsequent runs.

```
<Beams: procedures>+≡
  subroutine beam_data_compute_md5sum (beam_data)
    type(beam_data_t), intent(inout) :: beam_data
    integer :: unit
    unit = free_unit ()
    open (unit = unit, status = "scratch", action = "readwrite")
    call beam_data_write (beam_data, unit, write_md5sum = .false.)
    rewind (unit)
    beam_data%md5sum = md5sum (unit)
    close (unit)
  end subroutine beam_data_compute_md5sum
```

9.1.5 Sanity check

After the beams have been set, the initial-particle masses may have been modified. This can be checked here.

```
<Beams: public>+≡
  public :: beam_data_masses_are_consistent

<Beams: procedures>+≡
  function beam_data_masses_are_consistent (beam_data) result (flag)
    logical :: flag
    type(beam_data_t), intent(in) :: beam_data
    flag = all (beam_data%mass == flavor_get_mass (beam_data%flv))
  end function beam_data_masses_are_consistent
```

9.1.6 The beams type

Beam objects are interaction objects that contain the actual beam data including polarization and density matrix. For collisions, the beam object actually contains two beams.

```
<Beams: public>+≡
  public :: beam_t

<Beams: types>+≡
  type :: beam_t
    private
    type(interaction_t) :: int
  end type beam_t
```

The constructor contains code that converts beam data into the (entangled) particle-pair quantum state. First, we set the number of particles and polarization mask. (The polarization mask is handed over to all later interactions, so if helicity is diagonal or absent, this fact is used when constructing the hard-interaction events.) Then, we construct the entangled state that combines helicity, flavor and color of the two particles (where flavor and color are unique,

while several helicity states are possible). Then, we transfer this state together with the associated values from the spin density matrix into the `interaction_t` object.

```

(Beams: public)+≡
    public :: beam_init

(Beams: procedures)+≡
    subroutine beam_init (beam, beam_data)
        type(beam_t), intent(out) :: beam
        type(beam_data_t), intent(in), target :: beam_data
        type(quantum_numbers_mask_t), dimension(beam_data%n) :: mask
        type(state_matrix_t), target :: state_hel, state_fc, state_tmp
        type(state_iterator_t) :: it_hel, it_tmp
        type(quantum_numbers_t), dimension(:), allocatable :: qn
        mask = new_quantum_numbers_mask (.false., .false., &
            .not. polarization_is_polarized (beam_data%pol), &
            mask_hd = polarization_is_diagonal (beam_data%pol))
        call interaction_init &
            (beam%int, 0, 0, beam_data%n, mask=mask, store_values=.true.)
        call combine_polarization_states (beam_data%pol, state_hel)
        allocate (qn (beam_data%n))
        call quantum_numbers_init &
            (qn, beam_data%flv, color_from_flavor (beam_data%flv))
        call state_matrix_init (state_fc)
        call state_matrix_add_state (state_fc, qn)
        call merge_state_matrices (state_hel, state_fc, state_tmp)
        call state_iterator_init (it_hel, state_hel)
        call state_iterator_init (it_tmp, state_tmp)
        do while (state_iterator_is_valid (it_hel))
            call interaction_add_state (beam%int, &
                state_iterator_get_quantum_numbers (it_tmp), &
                value=state_iterator_get_matrix_element (it_hel))
            call state_iterator_advance (it_hel)
            call state_iterator_advance (it_tmp)
        end do
        call interaction_freeze (beam%int)
        call interaction_set_momenta &
            (beam%int, beam_data%p, outgoing = .true.)
        call state_matrix_final (state_hel)
        call state_matrix_final (state_fc)
        call state_matrix_final (state_tmp)
    end subroutine beam_init

```

Finalizer:

```

(Beams: public)+≡
    public :: beam_final

(Beams: procedures)+≡
    elemental subroutine beam_final (beam)
        type(beam_t), intent(inout) :: beam
        call interaction_final (beam%int)
    end subroutine beam_final

```

I/O:

```
<Beams: public>+≡
    public :: beam_write

<Beams: procedures>+≡
    subroutine beam_write (beam, unit, verbose, show_momentum_sum, show_mass)
        type(beam_t), intent(in) :: beam
        integer, intent(in), optional :: unit
        logical, intent(in), optional :: verbose, show_momentum_sum, show_mass
        integer :: u
        u = output_unit (unit); if (u < 0) return
        select case (interaction_get_n_out (beam%int))
        case (1); write (u, *) "Decaying particle:"
        case (2); write (u, *) "Colliding beams:"
        end select
        call interaction_write &
            (beam%int, unit, verbose, show_momentum_sum, show_mass)
    end subroutine beam_write
```

Defined assignment: deep copy

```
<Beams: public>+≡
    public :: assignment(=)

<Beams: interfaces>≡
    interface assignment(=)
        module procedure beam_assign
    end interface

<Beams: procedures>+≡
    subroutine beam_assign (beam_out, beam_in)
        type(beam_t), intent(out) :: beam_out
        type(beam_t), intent(in) :: beam_in
        beam_out%int = beam_in%int
    end subroutine beam_assign
```

9.1.7 Inherited procedures

```
<Beams: public>+≡
    public :: interaction_set_source_link

<Beams: interfaces>+≡
    interface interaction_set_source_link
        module procedure interaction_set_source_link_beam
    end interface

<Beams: procedures>+≡
    subroutine interaction_set_source_link_beam (int, i, beam1, i1)
        type(interaction_t), intent(inout) :: int
        type(beam_t), intent(in), target :: beam1
        integer, intent(in) :: i, i1
        call interaction_set_source_link (int, i, beam1%int, i1)
    end subroutine interaction_set_source_link_beam
```

9.1.8 Accessing contents

Return the interaction component – as a pointer, to avoid any copying.

```
<Beams: public>+≡
    public :: beam_get_int_ptr

<Beams: procedures>+≡
    function beam_get_int_ptr (beam) result (int)
        type(interaction_t), pointer :: int
        type(beam_t), intent(in), target :: beam
        int => beam%int
    end function beam_get_int_ptr
```

Set beam momenta directly. (Used for cascade decays.)

```
<Beams: public>+≡
    public :: beam_set_momenta

<Beams: procedures>+≡
    subroutine beam_set_momenta (beam, p)
        type(beam_t), intent(inout) :: beam
        type(vector4_t), dimension(:), intent(in) :: p
        call interaction_set_momenta (beam%int, p)
    end subroutine beam_set_momenta
```

9.1.9 Test

```
<Beams: public>+≡
    public :: beam_test

<Beams: procedures>+≡
    subroutine beam_test ()
        use os_interface, only: os_data_t
        type(os_data_t) :: os_data
        type(beam_data_t), target :: beam_data
        type(beam_t) :: beam
        real(default) :: sqrts
        type(flavor_t), dimension(2) :: flv
        type(polarization_t), dimension(2) :: pol
        type(model_t), pointer :: model
        print *, "*** Read model file"
        call syntax_model_file_init ()
        call model_list_read_model &
            (var_str("QCD"), var_str("test.mdl"), os_data, model)
        call syntax_model_file_final ()
        print *
        print *, "*** Scattering"
        sqrts = 500
        call flavor_init (flv, ((/1,-1/)), model)
        call polarization_init_circular (pol(1), flv(1), 0.5_default)
        call polarization_init_transversal (pol(2), flv(2), 0._default, 1._default)
        call beam_data_init_sqrts (beam_data, sqrts, flv, pol)
        call beam_data_write (beam_data)
        print *
        call beam_init (beam, beam_data)
```

```

call beam_write (beam)
call beam_final (beam)
call beam_data_final (beam_data)
print *
print *, "*** Decay"
call flavor_init (flv(1), 23, model)
call polarization_init_longitudinal (pol(1), flv(1), 0.4_default)
call beam_data_init_decay (beam_data, flv(1:1), pol(1:1))
call beam_data_write (beam_data)
print *
call beam_init (beam, beam_data)
call beam_write (beam)
call beam_final (beam)
call beam_data_final (beam_data)
end subroutine beam_test

```

Chapter 10

Spectra and structure functions

Each type of spectrum and structure function gets its own module with a common API; all modules are collected and accessed via the wrapper module `spectra`.

10.1 Tools

This module contains auxiliary procedures that can be accessed by the structure function code.

```
<sf_aux.f90>≡  
  <File header>  
  
  module sf_aux  
  
    <Use kinds>  
    use constants, only: twopi !NODEP!  
    <Use file utils>  
    use lorentz !NODEP!  
  
    <Standard module head>  
  
    <SF aux: public>  
  
    <SF aux: parameters>  
  
    <SF aux: types>  
  
    contains  
  
    <SF aux: procedures>  
  
  end module sf_aux
```

10.1.1 Momentum splitting

Let us consider first an incoming parton with momentum k and invariant mass squared $s = k^2$ that splits into two partons with momenta q, p and invariant masses $t = q^2$ and $u = p^2$. (This is an abuse of the Mandelstam notation. t is actually the momentum transfer, assuming that p is radiated and q initiates the hard process.) The energy is split among the partons such that if $E = k^0$, we have $q^0 = xE$ and $p^0 = \bar{x}E$, where $\bar{x} \equiv 1 - x$.

We define the angle θ as the polar angle of p w.r.t. the momentum axis of the incoming momentum k . Ignoring azimuthal angle, we can write the four-momenta in the basis (E, p_T, p_L) as

$$k = \begin{pmatrix} E \\ 0 \\ p \end{pmatrix}, \quad p = \begin{pmatrix} \bar{x}E \\ \bar{x}\bar{p}\sin\theta \\ \bar{x}\bar{p}\cos\theta \end{pmatrix}, \quad q = \begin{pmatrix} xE \\ -\bar{x}\bar{p}\sin\theta \\ p - \bar{x}\bar{p}\cos\theta \end{pmatrix}, \quad (10.1)$$

where the first two mass-shell conditions are

$$p^2 = E^2 - s, \quad \bar{p}^2 = E^2 - \frac{u}{\bar{x}^2}. \quad (10.2)$$

The second condition implies that, for positive u , $\bar{x}^2 > u/E^2$, or equivalently

$$x < 1 - \sqrt{u}/E. \quad (10.3)$$

We are interested in the third mass-shell conditions: s and u are fixed, so we need t as a function of $\cos\theta$:

$$t = -2\bar{x}(E^2 - p\bar{p}\cos\theta) + s + u. \quad (10.4)$$

Solving for $\cos\theta$, we get

$$\cos\theta = \frac{2\bar{x}E^2 + t - s - u}{2\bar{x}p\bar{p}}. \quad (10.5)$$

We can compute $\sin^2\theta$ numerically as $\sin^2\theta = 1 - \cos^2\theta$, but it is important to reexpress this in view of numerical stability. To this end, we first determine the bounds for t . The cosine must be between -1 and 1 , so the bounds are

$$t_0 = -2\bar{x}(E^2 + p\bar{p}) + s + u, \quad (10.6)$$

$$t_1 = -2\bar{x}(E^2 - p\bar{p}) + s + u. \quad (10.7)$$

Computing $\sin^2\theta$ from $\cos\theta$ above, we observe that the numerator is a quadratic polynomial in t which has the zeros t_0 and t_1 , while the common denominator is given by $(2\bar{x}p\bar{p})^2$. Hence, we can write

$$\sin^2\theta = -\frac{(t - t_0)(t - t_1)}{(2\bar{x}p\bar{p})^2} \quad \text{and} \quad \cos\theta = \frac{(t - t_0) + (t - t_1)}{4\bar{x}p\bar{p}}, \quad (10.8)$$

which is free of large cancellations near $t = t_0$ or $t = t_1$.

If all is massless, i.e., $s = u = 0$, this simplifies to

$$t_0 = -4\bar{x}E^2, \quad t_1 = 0, \quad (10.9)$$

$$\sin^2\theta = -\frac{t}{\bar{x}E^2} \left(1 + \frac{t}{4\bar{x}E^2}\right), \quad \cos\theta = 1 + \frac{t}{2\bar{x}E^2}. \quad (10.10)$$

Here is the implementation. First, we define a container for the kinematical integration limits and some further data.

```

<SF aux: public>≡
  public :: splitting_data_t

<SF aux: types>≡
  type :: splitting_data_t
  private
    real(default) :: x0 = 0
    real(default) :: x1
    real(default) :: t0
    real(default) :: t1
    real(default) :: phi0 = 0
    real(default) :: phi1 = twopi
    real(default) :: E, p, s, u, m2
    real(default) :: x, xb, pb
    real(default) :: t, phi
  end type splitting_data_t

```

This is the initializer for the data. The input consists of the incoming momentum, its invariant mass squared, and the invariant mass squared of the radiated particle. m is the *physical* mass of the outgoing particle. The t bounds depend on the chosen x value and cannot be determined yet.

```

<SF aux: public>+≡
  public :: new_splitting_data

<SF aux: procedures>≡
  function new_splitting_data (k, mk2, mr2, m) result (d)
    type(splitting_data_t) :: d
    type(vector4_t), intent(in) :: k
    real(default), intent(in) :: mk2, mr2, m
    d%E = energy (k)
    d%x1 = 1 - sqrt (max (mr2, 0._default)) / d%E
    d%p = sqrt (d%E**2 - mk2)
    d%s = mk2
    d%u = mr2
    d%m2 = m**2
  end function new_splitting_data

```

I/O for debugging:

```

<SF aux: public>+≡
  public :: splitting_data_write

<SF aux: procedures>+≡
  subroutine splitting_data_write (d, unit)
    type(splitting_data_t), intent(in) :: d
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write (u, *) "Splitting data:"
    write (u, *) " x0   =", d%x0
    write (u, *) " x    =", d%x
    write (u, *) " xb   =", d%xb
    write (u, *) " x1   =", d%x1

```

```

write (u, *) " t0   =", d%t0
write (u, *) " t    =", d%t
write (u, *) " t1   =", d%t1
write (u, *) " phi0 =", d%phi0
write (u, *) " phi  =", d%phi
write (u, *) " phi1 =", d%phi1
write (u, *) " E    =", d%E
write (u, *) " p    =", d%p
write (u, *) " pb   =", d%pb
write (u, *) " s    =", d%s
write (u, *) " u    =", d%u
write (u, *) " m2   =", d%m2
end subroutine splitting_data_write

```

Retrieve the x bounds, if needed for x sampling. Generating an x value is done by the caller, since this is the part that depends on the nature of the structure function.

```

<SF aux: public>+≡
public :: splitting_get_x_bounds

<SF aux: procedures>+≡
function splitting_get_x_bounds (d) result (x)
  real(default), dimension(2) :: x
  type(splitting_data_t), intent(in) :: d
  x = (/ d%x0, d%x1 /)
end function splitting_get_x_bounds

```

Now set the momentum fraction and compute t_0 and t_1 .

```

<SF aux: public>+≡
public :: splitting_set_t_bounds

<SF aux: procedures>+≡
subroutine splitting_set_t_bounds (d, x, xb)
  type(splitting_data_t), intent(inout) :: d
  real(default), intent(in) :: x, xb
  real(default) :: tp, tm
  d%x = x
  d%xb = xb
  d%pb = sqrt (d%E**2 - d%u / xb**2)
  tp = -2 * xb * d%E**2 + d%s + d%u
  tm = -2 * xb * d%p * d%pb
  d%t0 = tp + tm
  d%t1 = tp - tm
end subroutine splitting_set_t_bounds

```

These bounds may be narrowed by external cutoffs. Necessary in particular, if $m = 0$ and $t_1 = 0$.

```

<SF aux: public>+≡
public :: splitting_narrow_t_bounds

<SF aux: procedures>+≡
subroutine splitting_narrow_t_bounds (d, qmin, qmax)
  type(splitting_data_t), intent(inout) :: d

```

```

real(default), intent(in), optional :: qmin, qmax
if (present (qmax)) d%t0 = max (d%t0, - qmax ** 2)
if (present (qmin)) d%t1 = min (d%t1, - qmin ** 2)
end subroutine splitting_narrow_t_bounds

```

Compute a value for the momentum transfer t , using a random number r . We assume a logarithmic distribution for $t - m^2$, corresponding to the propagator $1/(t - m^2)$ with the physical mass m for the outgoing particle. Optionally, we can narrow the kinematical bounds.

```

<SF aux: public>+≡
public :: splitting_sample_t

<SF aux: procedures>+≡
subroutine splitting_sample_t (d, r, t0, t1)
type(splitting_data_t), intent(inout) :: d
real(default), intent(in) :: r
real(default), intent(in), optional :: t0, t1
real(default) :: tt0, tt1
tt0 = d%t0; if (present (t0)) tt0 = max (t0, tt0)
tt1 = d%t1; if (present (t1)) tt1 = min (t1, tt1)
d%t = d%m2 + (tt0 - d%m2) * exp (r * log ((tt1 - d%m2) / (tt0 - d%m2)))
end subroutine splitting_sample_t

```

State that we can ignore recoil. The momentum transfer t is set to its upper limit (which is zero for massless particles).

```

<SF aux: public>+≡
public :: splitting_set_collinear

<SF aux: procedures>+≡
subroutine splitting_set_collinear (d)
type(splitting_data_t), intent(inout) :: d
d%t = d%t1
end subroutine splitting_set_collinear

```

This is trivial, but provided for convenience:

```

<SF aux: public>+≡
public :: splitting_sample_phi

<SF aux: procedures>+≡
subroutine splitting_sample_phi (d, r)
type(splitting_data_t), intent(inout) :: d
real(default), intent(in) :: r
d%phi = (1-r) * d%phi0 + r * d%phi1
end subroutine splitting_sample_phi

```

In this function, we actually perform the splitting. Apart from the splitting data, we need the incoming momentum k , the momentum transfer t , and the azimuthal angle ϕ . The momentum fraction x is already known here.

Alternatively, we can split without recoil. The azimuthal angle is irrelevant, and the momentum transfer is always equal to the upper limit t_1 , so the polar angle is zero. Still, we have to account for nonvanishing invariant masses.

```

<SF aux: public>+≡
public :: split_momentum

```

```

<SF aux: procedures>+≡
function split_momentum (k, d) result (q)
  type(vector4_t), dimension(2) :: q
  type(vector4_t), intent(in) :: k
  type(splitting_data_t), intent(in) :: d
  real(default) :: ct, st, cp, sp
  type(lorentz_transformation_t) :: rot
  real(default) :: tt0, tt1, den
  type(vector3_t) :: kk, q1, q2
  if (d%t < d%t1) then
    tt0 = d%t - d%t0
    tt1 = d%t - d%t1
    den = 2 * d%xb * d%p * d%pb
    ct = (tt0 + tt1) / (2 * den)
    st = - (tt0 * tt1) / den**2
    cp = cos (d%phi)
    sp = sin (d%phi)
    rot = rotation_to_2nd (3, space_part (k))
    q1 = vector3_moving (d%xb * d%pb * (/ st * cp, st * sp, ct /))
    q2 = vector3_moving (d%p, 3) - q1
    q(1) = rot * vector4_moving (d%xb * d%E, q1)
    q(2) = rot * vector4_moving (d%x * d%E, q2)
  else if (d%s /= 0 .or. d%u /= 0) then
    kk = space_part (k)
    q1 = d%xb * (d%pb / d%p) * kk
    q2 = kk - q1
    q(1) = vector4_moving (d%xb * d%E, q1)
    q(2) = vector4_moving (d%x * d%E, q2)
  else
    q(1) = d%xb * k
    q(2) = d%x * k
  end if
end function split_momentum

```

10.1.2 Mass-shell projection

Momenta generated by splitting will in general be off-shell. They are on-shell only if they are collinear and massless. This subroutine puts them on shell by brute force, violating either momentum or energy conservation. The direction of three-momentum is always retained.

```

<SF aux: parameters>≡
integer, parameter, public :: KEEP_ENERGY = 0, KEEP_MOMENTUM = 1

<SF aux: public>+≡
public :: on_shell

<SF aux: procedures>+≡
elemental subroutine on_shell (p, mass, keep)
  type(vector4_t), intent(inout) :: p
  real(default), intent(in) :: mass
  integer, intent(in) :: keep
  real(default) :: E, pn
  select case (keep)

```

```

case (KEEP_ENERGY)
  E = energy (p)
  pn = sqrt (max (E**2 - mass**2, 0._default))
  p = vector4_moving (E, pn * direction (space_part (p)))
case (KEEP_MOMENTUM)
  E = sqrt (space_part (p) ** 2 + mass **2)
  p = vector4_moving (E, space_part (p))
end select
end subroutine on_shell

```

10.2 Photon radiation: ISR

```

⟨sf_isr.f90⟩≡
  ⟨File header⟩

  module sf_isr

    ⟨Use kinds⟩
    ⟨Use strings⟩
    use constants, only: pi !NODEP!
    ⟨Use file utils⟩
    use diagnostics !NODEP!
    use lorentz !NODEP!
    use sm_physics, only: Li2 !NODEP!
    use models
    use flavors
    use colors
    use quantum_numbers
    use state_matrices
    use polarizations
    use interactions
    use sf_aux

    ⟨Standard module head⟩

    ⟨ISR: public⟩

    ⟨ISR: parameters⟩

    ⟨ISR: types⟩

    contains

    ⟨ISR: procedures⟩

  end module sf_isr

```

10.2.1 Physics

The ISR structure function is in the most crude approximation (LLA without α corrections, i.e. ϵ^0)

$$f_0(x) = \epsilon(1-x)^{-1+\epsilon} \quad \text{with} \quad \epsilon = \frac{\alpha}{\pi} q_e^2 \ln \frac{s}{m^2}, \quad (10.11)$$

where m is the mass of the incoming (and outgoing) particle, which is initially assumed on-shell.

Here, the form of ϵ results from the kinematical bounds for the momentum squared of the outgoing particle, which in the limit $m^2 \ll s$ are given by

$$t_0 = -2\bar{x}E(E+p) + m^2 \approx -\bar{x}s, \quad (10.12)$$

$$t_1 = -2\bar{x}E(E-p) + m^2 \approx xm^2, \quad (10.13)$$

so the integration over the propagator $1/(t - m^2)$ yields

$$\ln \frac{t_0 - m^2}{t_1 - m^2} = \ln \frac{s}{m^2}. \quad (10.14)$$

In $f_0(x)$, there is an integrable singularity at $x = 1$ which does not spoil the integration, but would lead to an unbounded f_{\max} . Therefore, we map this singularity like

$$x = 1 - (1 - x')^{1/\epsilon} \quad (10.15)$$

such that

$$\int dx f_0(x) = \int dx' \quad (10.16)$$

The structure function has three parameters: α , m_{in} of the incoming particle and s , the hard scale. Internally, we store the exponent ϵ which is the relevant parameter. (In conventional notation, $\epsilon = \beta/2$.) As defaults, we take the actual values of α (which is probably $\alpha(s)$), the actual mass m_{in} and the squared total c.m. energy s .

Including ϵ , ϵ^2 , and ϵ^3 corrections, the successive approximation of the ISR structure function read

$$f_0(x) = \epsilon(1 - x)^{-1+\epsilon} \quad (10.17)$$

$$f_1(x) = g_1(\epsilon) f_0(x) - \frac{\epsilon}{2}(1 + x) \quad (10.18)$$

$$f_2(x) = g_2(\epsilon) f_0(x) - \frac{\epsilon}{2}(1 + x) - \frac{\epsilon^2}{8} \left(\frac{1 + 3x^2}{1 - x} \ln x + 4(1 + x) \ln(1 - x) + 5 + x \right) \quad (10.19)$$

$$\begin{aligned} f_3(x) = & g_3(\epsilon) f_0(x) - \frac{\epsilon}{2}(1 + x) \\ & - \frac{\epsilon^2}{8} \left(\frac{1 + 3x^2}{1 - x} \ln x + 4(1 + x) \ln(1 - x) + 5 + x \right) \\ & - \frac{\epsilon^3}{48} \left((1 + x) [6 \text{Li}_2(x) + 12 \ln^2(1 - x) - 3\pi^2] + 6(x + 5) \ln(1 - x) \right. \\ & \quad \left. + \frac{1}{1 - x} \left[\frac{3}{2}(1 + 8x + 3x^2) \ln x + 12(1 + x^2) \ln x \ln(1 - x) \right. \right. \\ & \quad \left. \left. - \frac{1}{2}(1 + 7x^2) \ln^2 x + \frac{1}{4}(39 - 24x - 15x^2) \right] \right) \end{aligned} \quad (10.20)$$

where the successive approximations to the prefactor of the leading singularity

$$g(\epsilon) = \frac{\exp\left(\epsilon(-\gamma_E + \frac{3}{4})\right)}{\Gamma(1 + \epsilon)}, \quad (10.21)$$

are given by

$$g_0(\epsilon) = 1 \quad (10.22)$$

$$g_1(\epsilon) = 1 + \frac{3}{4}\epsilon \quad (10.23)$$

$$g_2(\epsilon) = 1 + \frac{3}{4}\epsilon + \frac{27 - 8\pi^2}{96}\epsilon^2 \quad (10.24)$$

$$g_3(\epsilon) = 1 + \frac{3}{4}\epsilon + \frac{27 - 8\pi^2}{96}\epsilon^2 + \frac{27 - 24\pi^2 + 128\zeta(3)}{384}\epsilon^3, \quad (10.25)$$

where, numerically

$$\zeta(3) = 1.20205690315959428539973816151\dots \quad (10.26)$$

Although one could calculate the function $g(\epsilon)$ exactly, truncating its Taylor expansion ensures the exact normalization of the truncated structure function at each given order:

$$\int_0^1 dx f_i(x) = 1 \quad \text{for all } i. \quad (10.27)$$

Effectively, the $O(\epsilon)$ correction reduces the low- x tail of the structure function by 50% while increasing the coefficient of the singularity by $O(\epsilon)$. Relative to this, the $O(\epsilon^2)$ correction slightly enhances $x > \frac{1}{2}$ compared to $x < \frac{1}{2}$. At $x = 0$, $f_2(x)$ introduces a logarithmic singularity which should be cut off at $x_0 = O(e^{-1/\epsilon})$: for lower x the perturbative series breaks down. The f_3 correction is slightly positive for low x values and negative near $x = 1$, where the Li_2 piece slightly softens the singularity at $x = 1$.

Instead of the definition for ϵ given above, it is customary to include a universal nonlogarithmic piece:

$$\epsilon = \frac{\alpha}{\pi} q_e^2 \left(\ln \frac{s}{m^2} - 1 \right) \quad (10.28)$$

10.2.2 Implementation

In the concrete implementation, the zeroth order mapping (10.15) is implemented, and the Jacobian is equal to $f_i(x)/f_0(x)$. This can be written as

$$\frac{f_0(x)}{f_0(x)} = 1 \quad (10.29)$$

$$\frac{f_1(x)}{f_0(x)} = 1 + \frac{3}{4}\epsilon - \frac{1 - x^2}{2(1 - x')} \quad (10.30)$$

$$\begin{aligned} \frac{f_2(x)}{f_0(x)} = 1 + \frac{3}{4}\epsilon + \frac{27 - 8\pi^2}{96}\epsilon^2 - \frac{1 - x^2}{2(1 - x')} \\ - \frac{(1 + 3x^2) \ln x + (1 - x)(4(1 + x) \ln(1 - x) + 5 + x)}{8(1 - x')} \epsilon \end{aligned} \quad (10.31)$$

For $x = 1$ (i.e., numerically indistinguishable from 1), this reduces to

$$\frac{f_0(x)}{f_0(x)} = 1 \quad (10.32)$$

$$\frac{f_1(x)}{f_0(x)} = 1 + \frac{3}{4}\epsilon \quad (10.33)$$

$$\frac{f_2(x)}{f_0(x)} = 1 + \frac{3}{4}\epsilon + \frac{27 - 8\pi^2}{96}\epsilon^2 \quad (10.34)$$

The last line in (10.31) is zero for

$$x_{\min} = 0.00714053329734592839549810275603 \quad (10.35)$$

(Mathematica result), independent of ϵ . For x values less than this we ignore this correction because of the logarithmic singularity which should in principle be resummed.

10.2.3 The ISR data block

```

<ISR: public>≡
  public :: isr_data_t
<ISR: types>≡
  type :: isr_data_t
    private
      type(model_t), pointer :: model => null ()
      type(flavor_t) :: flv
      real(default) :: alpha = 0
      real(default) :: q_max = 0
      real(default) :: real_mass = 0
      real(default) :: mass = 0
      real(default) :: eps = 0
      real(default) :: log = 0
      integer :: order = 3
      integer :: error = NONE
  end type isr_data_t

```

Error codes

```

<ISR: parameters>≡
  integer, parameter :: NONE = 0
  integer, parameter :: ZERO_MASS = 1
  integer, parameter :: Q_MAX_TOO_SMALL = 2
  integer, parameter :: EPS_TOO_LARGE = 3
  integer, parameter :: INVALID_ORDER = 4

```

Generate flavor-dependent ISR data:

```

<ISR: public>+≡
  public :: isr_data_init
<ISR: procedures>≡
  subroutine isr_data_init (data, model, flv, alpha, q_max, mass)
    type(isr_data_t), intent(out) :: data
    type(model_t), intent(in), target :: model
    type(flavor_t), intent(in) :: flv

```

```

real(default), intent(in) :: alpha
real(default), intent(in) :: q_max
real(default), intent(in), optional :: mass
data%model => model
data%flv = flv
data%alpha = alpha
data%q_max = q_max
data%real_mass = flavor_get_mass (flv)
if (present (mass)) then
  if (mass > 0) then
    data%mass = mass
  else
    data%mass = data%real_mass
  end if
else
  data%mass = data%real_mass
end if
if (data%mass == 0) then
  data%error = ZERO_MASS; return
else if (data%mass >= data%q_max) then
  data%error = Q_MAX_TOO_SMALL; return
end if
data%log = log (1 + (data%q_max / data%mass)**2)
data%eps = data%alpha / pi &
  * flavor_get_charge (data%flv)**2 &
  * (2 * log (data%q_max / data%mass) - 1)
if (data%eps > 1) then
  data%error = EPS_TOO_LARGE; return
end if
end subroutine isr_data_init

```

Explicitly set ISR order

```

<ISR: public>+≡
  public :: isr_data_set_order

<ISR: procedures>+≡
  elemental subroutine isr_data_set_order (data, order)
    type(isr_data_t), intent(inout) :: data
    integer, intent(in) :: order
    if (order < 0 .or. order > 3) then
      data%error = INVALID_ORDER
    else
      data%order = order
    end if
  end subroutine isr_data_set_order

```

Handle error conditions. Should always be done after initialization, unless we are sure everything is ok.

```

<ISR: public>+≡
  public :: isr_data_check

<ISR: procedures>+≡
  subroutine isr_data_check (data)
    type(isr_data_t), intent(in) :: data

```

```

select case (data%error)
case (ZERO_MASS)
  call msg_fatal (" ISR: Particle mass is zero")
case (Q_MAX_TOO_SMALL)
  call msg_fatal (" ISR: Particle mass exceeds Qmax")
case (EPS_TOO_LARGE)
  call msg_fatal (" ISR: Expansion parameter too large, perturbative expansion breaks down")
case (INVALID_ORDER)
  call msg_error (" ISR: LLA order invalid (valid values are 0,1,2,3)")
end select
end subroutine isr_data_check

```

Output

<ISR: public>+≡

```
public :: isr_data_write
```

<ISR: procedures>+≡

```

subroutine isr_data_write (data, unit)
  type(isr_data_t), intent(in) :: data
  integer, intent(in), optional :: unit
  integer :: u
  u = output_unit (unit); if (u < 0) return
  write (u, *) "ISR data:"
  write (u, *) " prt  = ", char (flavor_get_name (data%flv))
  write (u, *) " alpha = ", data%alpha
  write (u, *) " q_max = ", data%q_max
  write (u, *) " mass  = ", data%mass
  write (u, *) " eps   = ", data%eps
  write (u, *) " log   = ", data%log
  write (u, *) " order = ", data%order
end subroutine isr_data_write

```

10.2.4 The ISR object

The `isr_t` data type is a $1 \rightarrow 2$ interaction, i.e., we allow for single-photon emission only (but use the multi-photon resummed radiator function). The particles are ordered as (incoming, photon, outgoing).

There is no need to handle several flavors (and data blocks) in parallel, since ISR is always applied immediately after beam collision. (ISR for partons is accounted for by the PDFs themselves.) Polarization is carried through, i.e., we retain the polarization of the incoming particle and treat the emitted photon as unpolarized. Color is trivially carried through. This implies that particles 1 and 3 should be locked together.

<ISR: public>+≡

```
public :: interaction_init_isr
```

<ISR: procedures>+≡

```

subroutine interaction_init_isr (int, data)
  type(interaction_t), intent(out) :: int
  type(isr_data_t), intent(in) :: data
  type(quantum_numbers_mask_t), dimension(3) :: mask
  integer, dimension(3) :: lock

```

```

type(polarization_t) :: pol
type(quantum_numbers_t), dimension(1) :: qn_fc, qn_hel
type(flavor_t) :: flv_photon
type(quantum_numbers_t) :: qn_photon, qn
type(state_iterator_t) :: it_hel
mask = new_quantum_numbers_mask (.false., .false., &
    mask_h = (/ .false., .true., .false. /))
lock = (/ 3, 0, 1 /)
call interaction_init (int, 1, 0, 2, mask=mask, lock=lock)
call flavor_init (flv_photon, PHOTON, data%model)
call quantum_numbers_init (qn_photon, flv_photon)
call polarization_init_generic (pol, data%flv)
call quantum_numbers_init (qn_fc(1), &
    flv = data%flv, col = color_from_flavor (data%flv))
call state_iterator_init (it_hel, pol%state)
do while (state_iterator_is_valid (it_hel))
    qn_hel = state_iterator_get_quantum_numbers (it_hel)
    qn = qn_hel(1) .merge. qn_fc(1)
    call interaction_add_state (int, (/ qn, qn_photon, qn /))
    call state_iterator_advance (it_hel)
end do
call polarization_final (pol)
call interaction_freeze (int)
end subroutine interaction_init_isr

```

10.2.5 ISR structure function

The ISR structure function allows for a straightforward mapping of the unit interval. So, to leading order, the structure function value is unity, but the x value is transformed. Higher orders affect the function value.

The structure function implementation applies the above mapping to the input (random) number r to generate the momentum fraction x and the function value f . For numerical stability reasons, we also output xb , which is $\bar{x} = 1 - x$. The mapping ensures that $f = 1$ at leading order, and the higher-order corrections are well-behaved.

(ISR: procedures) +=

```

subroutine strfun (f, x, xb, r, data)
    real(default), intent(out) :: f, x, xb
    real(default), intent(in) :: r
    type(isr_data_t), intent(in) :: data
    real(default) :: eps
    real(default) :: rb, log_x, log_xb, x_2
    real(default), parameter :: &
        & xmin = 0.00714053329734592839549810275603_default
    real(default), parameter :: &
        & zeta3 = 1.20205690315959428539973816151_default
    real(default), parameter :: &
        & g1 = 3._default / 4._default, &
        & g2 = (27 - 8*pi**2) / 96._default, &
        & g3 = (27 - 24*pi**2 + 128*zeta3) / 384._default
    eps = data%eps
    rb = 1 - r

```

```

if (rb < tiny(1._default)**eps) then
  xb = 0
else
  xb = rb**(1/eps)
end if
x = 1 - xb
if (data%order > 0) then
  f = 1 + g1 * eps
  x_2 = x*x
  if (rb>0) f = f - (1-x_2) / (2 * rb)
  if (data%order > 1) then
    f = f + g2 * eps**2
    if (rb>0 .and. xb>0 .and. x>xmin) then
      log_x = log (x)
      log_xb = log (xb)
      f = f - ((1+3*x_2)*log_x + xb * (4*(1+x)*log_xb + 5 + x)) &
        & / ( 8 * rb) * eps
    end if
    if (data%order > 2) then
      f = f + g3 * eps**3
      if (rb > 0 .and. xb > 0 .and. x > xmin) then
        f = f - ((1+x) * xb &
          * (6 * Li2(x) + 12 * log_xb**2 - 3 * pi**2) &
          + 1.5_default * (1 + 8*x + 3*x_2) * log_x &
          + 6 * (x+5) * xb * log_xb &
          + 12 * (1+x_2) * log_x * log_xb &
          - (1 + 7*x_2) * log_x**2 / 2 &
          + (39 - 24*x - 15*x_2) / 4) &
          / ( 48 * rb) * eps**2
      end if
    end if
  end if
else
  f = 1
end if
end subroutine strfun

```

10.2.6 ISR application

For ISR, we can compute kinematics and function value in a single step. This function works on a single beam, assuming that the input momentum has been set. We need four random numbers as input: one for x , one for Q^2 , and two for the polar and azimuthal angles. Alternatively, we can skip p_T generation; in this case, we only need one.

After splitting momenta, we set the outgoing momenta on-shell. We choose to conserve momentum, so energy conservation may be violated.

```

<ISR: public>+≡
  public :: interaction_apply_isr

<ISR: procedures>+≡
  subroutine interaction_apply_isr (int, r, isr_data)
    type(interaction_t), intent(inout) :: int

```

```

real(default), dimension(:), intent(in) :: r
type(isr_data_t), intent(in) :: isr_data
type(vector4_t) :: k
type(splitting_data_t) :: sd
real(default) :: f, x, xb
k = interaction_get_momentum (int, 1)
sd = new_splitting_data (k, k**2, 0._default, isr_data%mass)
call strfun (f, x, xb, r(1), isr_data)
call interaction_set_matrix_element (int, cmplx (f, kind=default))
call splitting_set_t_bounds (sd, x, xb)
select case (size (r))
case (1)
    call splitting_set_collinear (sd)
case (3)
    call splitting_sample_t (sd, r(2))
    call splitting_sample_phi (sd, r(3))
case default
    print *, "n_rand = ", size (r)
    call msg_bug (" ISR: number of random numbers must be 1 or 3")
end select
call interaction_set_momenta &
    (int, split_momentum (k, sd), outgoing=.true.)
end subroutine interaction_apply_isr

```

10.3 EPA

```

⟨sf_epa.f90⟩≡
  ⟨File header⟩

  module sf_epa

    ⟨Use kinds⟩
    ⟨Use strings⟩
    use constants, only: pi !NODEP!
    ⟨Use file utils⟩
    use diagnostics !NODEP!
    use lorentz !NODEP!
    use models
    use flavors
    use colors
    use quantum_numbers
    use state_matrices
    use polarizations
    use interactions
    use sf_aux

    ⟨Standard module head⟩

    ⟨EPA: public⟩

    ⟨EPA: parameters⟩

    ⟨EPA: types⟩

    contains

    ⟨EPA: procedures⟩

  end module sf_epa

```

10.3.1 Physics

The EPA structure function for a photon inside an (elementary) particle p with energy E , mass m and charge q_p (e.g., electron) is given by ($\bar{x} \equiv 1 - x$)

$$f(x) = \frac{\alpha}{\pi} q_p^2 \frac{1}{x} \left[\left(\bar{x} + \frac{x^2}{2} \right) \ln \frac{Q_{\max}^2}{Q_{\min}^2} - \left(1 - \frac{x}{2} \right)^2 \ln \frac{x^2 + \frac{Q_{\max}^2}{E^2}}{x^2 + \frac{Q_{\min}^2}{E^2}} - x^2 \frac{m^2}{Q_{\min}^2} \left(1 - \frac{Q_{\min}^2}{Q_{\max}^2} \right) \right]. \quad (10.36)$$

If no explicit Q bounds are provided, the kinematical bounds are

$$-Q_{\max}^2 = t_0 = -2\bar{x}(E^2 + p\bar{p}) + 2m^2 \approx -4\bar{x}E^2, \quad (10.37)$$

$$-Q_{\min}^2 = t_1 = -2\bar{x}(E^2 - p\bar{p}) + 2m^2 \approx -\frac{x^2}{\bar{x}}m^2. \quad (10.38)$$

The second and third terms in (10.36) are negative definite (and subleading). Noting that $\bar{x} + x^2/2$ is bounded between $1/2$ and 1 , we derive that $f(x)$ is always

smaller than

$$\bar{f}(x) = \frac{\alpha}{\pi} q_p^2 \frac{L - 2 \ln x}{x} \quad \text{where} \quad L = \ln \frac{\min(4E_{\max}^2, Q_{\max}^2)}{\max(m^2, Q_{\min}^2)}, \quad (10.39)$$

where we allow for explicit Q bounds that narrow the kinematical range. Therefore, we generate this distribution:

$$\int_{x_0}^{x_1} dx \bar{f}(x) = C(x_0, x_1) \int_0^1 dx' \quad (10.40)$$

We set

$$\ln x = \frac{1}{2} \left\{ L - \sqrt{L^2 - 4 [x' \ln x_1 (L - \ln x_1) + \bar{x}' \ln x_0 (L - \ln x_0)]} \right\} \quad (10.41)$$

such that $x(0) = x_0$ and $x(1) = x_1$ and

$$\frac{dx}{dx'} = \left(\frac{\alpha}{\pi} \right)^{-1} x \frac{C(x_0, x_1)}{L - 2 \ln x} \quad (10.42)$$

with

$$C(x_0, x_1) = \frac{\alpha}{\pi} q_p^2 [\ln x_1 (L - \ln x_1) - \ln x_0 (L - \ln x_0)] \quad (10.43)$$

such that (10.40) is satisfied. Finally, we have

$$\int_{x_0}^{x_1} dx f(x) = C(x_0, x_1) \int_0^1 dx' \frac{f(x(x'))}{\bar{f}(x(x'))} \quad (10.44)$$

where x' is calculated from x via (10.41)

10.3.2 The EPA data block

The EPA parameters are: α , E_{\max} , m , Q_{\min} , and x_{\min} . Instead of m we can use the incoming particle PDG code as input; from this we can deduce the mass and charge.

Internally we store in addition $C_{0/1} = \frac{\alpha}{\pi} q_e^2 \ln x_{0/1} (L - \ln x_{0/1})$, the c.m. energy squared and the incoming particle mass.

```

<EPA: public>≡
  public :: epa_data_t
<EPA: types>≡
  type :: epa_data_t
    private
    type(model_t), pointer :: model => null ()
    type(flavor_t) :: flv
    real(default) :: alpha
    real(default) :: x_min
    real(default) :: x_max
    real(default) :: q_min
    real(default) :: q_max
    real(default) :: E_max
    real(default) :: mass
    real(default) :: log
    real(default) :: c0
    real(default) :: c1
    integer :: error = 0
  end type epa_data_t

```

Error codes

```

(EPA: parameters)≡
    integer, parameter :: NONE = 0
    integer, parameter :: ZERO_QMIN = 1
    integer, parameter :: Q_MAX_TOO_SMALL = 2
    integer, parameter :: ZERO_XMIN = 3

(EPA: public)+≡
    public :: epa_data_init

(EPA: procedures)≡
    subroutine epa_data_init (data, model, flv, alpha, x_min, q_min, E_max, mass)
        type(epa_data_t), intent(inout) :: data
        type(model_t), intent(in), target :: model
        type(flavor_t), intent(in) :: flv
        real(default), intent(in) :: alpha, x_min, q_min, E_max
        real(default), intent(in), optional :: mass
        data%model => model
        data%flv = flv
        data%alpha = alpha
        data%E_max = E_max
        data%x_min = x_min
        data%x_max = 1
        if (data%x_min == 0) then
            data%error = ZERO_XMIN; return
        end if
        data%q_min = q_min
        data%q_max = 2 * data%E_max
        if (present (mass)) then
            data%mass = mass
        else
            data%mass = flavor_get_mass (flv)
        end if
        if (max (data%mass, data%q_min) == 0) then
            data%error = ZERO_QMIN; return
        else if (max (data%mass, data%q_min) >= data%E_max) then
            data%error = Q_MAX_TOO_SMALL; return
        end if
        data%log = log (4 * (data%E_max / max (data%mass, data%q_min)) ** 2 )
        data%c0 = data%alpha / pi &
            * flavor_get_charge (data%flv)**2 &
            * log (data%x_min) * (data%log - log (data%x_min))
        data%c1 = data%alpha / pi &
            * flavor_get_charge (data%flv)**2 &
            * log (data%x_max) * (data%log - log (data%x_max))
    end subroutine epa_data_init

```

Handle error conditions. Should always be done after initialization, unless we are sure everything is ok.

```

(EPA: public)+≡
    public :: epa_data_check

(EPA: procedures)+≡
    subroutine epa_data_check (data)
        type(epa_data_t), intent(in) :: data

```

```

select case (data%error)
case (ZERO_QMIN)
  call msg_fatal (" EPA: Particle mass is zero")
case (Q_MAX_TOO_SMALL)
  call msg_fatal (" EPA: Particle mass exceeds Qmax")
case (ZERO_XMIN)
  call msg_fatal (" EPA: x_min must be larger than zero")
end select
end subroutine epa_data_check

```

Output

(EPA: public)+≡

```
public :: epa_data_write
```

(EPA: procedures)+≡

```

subroutine epa_data_write (data, unit)
  type(epa_data_t), intent(in) :: data
  integer, intent(in), optional :: unit
  integer :: u
  u = output_unit (unit); if (u < 0) return
  write (u, *) "EPA data:"
  write (u, *) " prt  = ", char (flavor_get_name (data%flv))
  write (u, *) " alpha = ", data%alpha
  write (u, *) " x_min = ", data%x_min
  write (u, *) " x_max = ", data%x_max
  write (u, *) " q_min = ", data%q_min
  write (u, *) " q_max = ", data%q_max
  write (u, *) " E_max = ", data%q_max
  write (u, *) " mass  = ", data%mass
  write (u, *) " log   = ", data%log
  write (u, *) " c0    = ", data%c0
  write (u, *) " c1    = ", data%c1
end subroutine epa_data_write

```

10.3.3 The EPA object

The `epa_t` data type is a $1 \rightarrow 2$ interaction. We should be able to handle several flavors in parallel, since EPA is not necessarily applied immediately after beam collision: Photons may be radiated from quarks. In that case, the partons are massless and q_{\min} applies instead, so we do not need to generate several kinematical configurations in parallel.

The particles are ordered as (incoming, radiated, photon), where the photon initiates the hard interaction.

We generate an unpolarized photon and transfer initial polarization to the radiated parton. Color is transferred in the same way.

(EPA: public)+≡

```
public :: interaction_init_epa
```

(EPA: procedures)+≡

```

subroutine interaction_init_epa (int, data)
  type(interaction_t), intent(out) :: int
  type(epa_data_t), intent(in) :: data

```

```

type(quantum_numbers_mask_t), dimension(3) :: mask
integer, dimension(3) :: lock
type(polarization_t) :: pol
type(quantum_numbers_t), dimension(1) :: qn_fc, qn_hel
type(flavor_t) :: flv_photon
type(quantum_numbers_t) :: qn_photon, qn
type(state_iterator_t) :: it_hel
integer :: i
mask = new_quantum_numbers_mask (.false., .false., &
    mask_h = (/ .false., .false., .true. /))
lock = (/ 2, 1, 0 /)
call interaction_init (int, 1, 0, 2, mask=mask, lock=lock)
call flavor_init (flv_photon, PHOTON, data%model)
call quantum_numbers_init (qn_photon, flv_photon)
call polarization_init_generic (pol, data%flv)
call quantum_numbers_init (qn_fc(1), &
    flv = data%flv, col = color_from_flavor (data%flv))
call state_iterator_init (it_hel, pol%state)
do while (state_iterator_is_valid (it_hel))
    qn_hel = state_iterator_get_quantum_numbers (it_hel)
    qn = qn_hel(1) .merge. qn_fc(1)
    call interaction_add_state (int, (/ qn, qn, qn_photon /))
    call state_iterator_advance (it_hel)
end do
call polarization_final (pol)
call interaction_freeze (int)
end subroutine interaction_init_epa

```

10.3.4 EPA structure function

The EPA structure function allows for a straightforward mapping of the unit interval. So, to leading order, the structure function value is unity, but the x value is transformed. Higher orders affect the function value.

The structure function implementation applies the above mapping to the input (random) number r to generate the momentum fraction x and the function value f . For numerical stability reasons, we also output xb , which is $\bar{x} = 1 - x$. The mapping ensures that $f = 1$ at leading order, and the higher-order corrections are well-behaved.

(EPA: procedures)+≡

```

elemental subroutine strfun (f, x, xb, r, E, data)
    real(default), intent(out) :: f, x, xb
    real(default), intent(in) :: r, E
    type(epa_data_t), intent(in) :: data
    real(default) :: rb, lx0, lx1, lx, d, den
    real(default) :: qmaxsq, qminsq
    f = 0
    rb = 1 - r
    lx0 = log (data%x_min)
    lx1 = log (data%x_max)
    d = data%log ** 2 &
        - 4 * (r * lx1 * (data%log - lx1) + rb * lx0 * (data%log - lx0))
    if (d <= 0) then

```

```

        return
    else
        lx = (data%log - sqrt (d)) / 2
    end if
    x = exp (lx)
    xb = 1 - x
    den = data%log - 2 * lx
    if (den <= 0) return
    qminsq = max (x ** 2 / xb * data%mass ** 2, data%q_min ** 2)
    qmaxsq = min (4 * E ** 2, data%q_max ** 2)
    if (qminsq < qmaxsq) then
        f = ((xb + x ** 2 / 2) * (qmaxsq / qminsq) &
            - (1 - x / 2) ** 2 &
            * log ((x**2 + qmaxsq / E ** 2) / (x**2 + qminsq / E ** 2)) &
            - xb ** 2 * data%mass ** 2 / qminsq * (1 - qminsq / qmaxsq)) &
            * ( data%c1 - data%c0 ) / den
    end if
end subroutine strfun

```

10.3.5 EPA application

For EPA, we can compute kinematics and function value in a single step. This function works on a single beam, assuming that the input momentum has been set. We need four random numbers as input: one for x , one for Q^2 , and two for the polar and azimuthal angles. Alternatively, we can skip p_T generation; in this case, we only need one.

For obtaining splitting kinematics, we rely on the assumption that all in-particles are mass-degenerate (or there is only one), so the generated x values are identical.

```

(EPA: public)+≡
    public :: interaction_apply_epa

(EPA: procedures)+≡
    subroutine interaction_apply_epa (int, r, epa_data)
        type(interaction_t), intent(inout) :: int
        real(default), dimension(:), intent(in) :: r
        type(epa_data_t), dimension(:), intent(in) :: epa_data
        type(vector4_t) :: k
        type(splitting_data_t) :: sd
        real(default), dimension(size(epa_data)) :: f, x, xb
        k = interaction_get_momentum (int, 1)
        sd = new_splitting_data (k, k**2, epa_data(1)%mass**2, 0._default)
        call strfun (f, x, xb, r(1), energy (k), epa_data)
        call interaction_set_flavored_values &
            (int, cmplx (f, kind=default), epa_data%flv, 2)
        call splitting_set_t_bounds (sd, x(1), xb(1))
        call splitting_narrow_t_bounds (sd, epa_data(1)%q_min, epa_data(1)%q_max)
        select case (size (r))
        case (1)
            call splitting_set_collinear (sd)
        case (3)
            call splitting_sample_t (sd, r(2))

```

```

        call splitting_sample_phi (sd, r(3))
case default
    print *, "n_rand = ", size (r)
    call msg_bug (" EPA: number of random numbers must be 1 or 3")
end select
call interaction_set_momenta &
    (int, split_momentum (k, sd), outgoing=.true.)
end subroutine interaction_apply_epa

```

10.4 EWA

```

⟨sf_ewa.f90⟩≡
  ⟨File header⟩

  module sf_ewa

    ⟨Use kinds⟩
    ⟨Use strings⟩
    ⟨Use file utils⟩
    use diagnostics !NODEP!
    use lorentz !NODEP!
    use models
    use flavors
    use colors
    use quantum_numbers
    use state_matrices
    use polarizations
    use interactions
    use sf_aux

    ⟨Standard module head⟩

    ⟨EWA: public⟩

    ⟨EWA: parameters⟩

    ⟨EWA: types⟩

    contains

    ⟨EWA: procedures⟩

  end module sf_ewa

```

10.4.1 Physics

The EWA structure function for a Z or W inside a fermion (lepton or quark) depends on the vector-boson polarization. We distinguish transversal (\pm) and longitudinal (0) polarization.

$$F_+(x) = \frac{1}{16\pi^2} \frac{(v-a)^2 + (v+a)^2 \bar{x}^2}{x} \left[\ln \left(\frac{p_{\perp,\max}^2 + \bar{x}M^2}{\bar{x}M^2} \right) - \frac{p_{\perp,\max}^2}{p_{\perp,\max}^2 + \bar{x}M^2} \right] \quad (10.45)$$

$$F_-(x) = \frac{1}{16\pi^2} \frac{(v+a)^2 + (v-a)^2 \bar{x}^2}{x} \left[\ln \left(\frac{p_{\perp,\max}^2 + \bar{x}M^2}{\bar{x}M^2} \right) - \frac{p_{\perp,\max}^2}{p_{\perp,\max}^2 + \bar{x}M^2} \right] \quad (10.46)$$

$$F_0(x) = \frac{v^2 + a^2}{8\pi^2} \frac{2\bar{x}}{x} \frac{p_{\perp,\max}^2}{p_{\perp,\max}^2 + \bar{x}M^2} \quad (10.47)$$

where $p_{\perp,\max}$ is the cutoff in transversal momentum, M is the vector-boson mass, v and a are the vector and axial-vector couplings, and $\bar{x} \equiv 1-x$. Note that the longitudinal structure function is finite for large cutoff, while the transversal structure function is logarithmically divergent.

The maximal transverse momentum is given by the kinematical limit, it is

$$p_{\perp,\max} = \bar{x}\sqrt{s}/2. \quad (10.48)$$

The vector and axial couplings for a fermion branching into a W are

$$v_W = \frac{g}{2\sqrt{2}}, \quad a_W = \frac{g}{2\sqrt{2}}. \quad (10.49)$$

For Z emission, this is replaced by

$$v_Z = \frac{g}{2\cos\theta_w} (t_3 - 2q\sin^2\theta_w), \quad a_Z = \frac{g}{2\cos\theta_w} t_3, \quad (10.50)$$

where $t_3 = \pm\frac{1}{2}$ is the fermion isospin, and q its charge.

For an initial antifermion, the signs of the axial couplings are inverted. Note that a common sign change of v and a is irrelevant.

The EWA depends on the parameters g , $\sin^2\theta_w$, M_W , and M_Z . These can all be taken from the SM input, and the prefactors are calculated from those and the incoming particle type.

Since these structure functions have a $1/x$ singularity (which is not really relevant in practice, however, since the vector boson mass is finite), we map this singularity allowing for nontrivial x bounds:

$$x = \exp(\bar{r} \ln x_0 + r \ln x_1) \quad (10.51)$$

such that

$$\int_{x_0}^{x_1} \frac{dx}{x} = (\ln x_1 - \ln x_0) \int_0^1 dr. \quad (10.52)$$

As a user parameter, we have the cutoff $p_{\perp,\max}$. The divergence $1/x$ also requires a x_0 cutoff; and for completeness we introduce a corresponding x_1 . Physically, the minimal sensible value of x is M^2/s , although the approximation loses its value already at higher x values.

10.4.2 The EWA data block

The EPA parameters are: $p_{T,\max}$, c_V , c_A , and m . Instead of m we can use the incoming particle PDG code as input; from this we can deduce the mass and charges.

```

(EWA: public)≡
  public :: ewa_data_t

(EWA: types)≡
  type :: ewa_data_t
  private
  type(model_t), pointer :: model => null ()
  !!! Do we need this for the EWA?
  type(flavor_t) :: flv
  real(default) :: pt_max

```

```

        real(default) :: x_0
        real(default) :: x_1
        real(default) :: mass
        real(default) :: cv
        real(default) :: ca
        real(default) :: coeff
        integer :: error = 0
    end type ewa_data_t

```

Error codes

(EWA: parameters)≡

```

        integer, parameter :: NONE = 0
        integer, parameter :: ZERO_QMIN = 1
        integer, parameter :: Q_MAX_TOO_SMALL = 2
        integer, parameter :: ZERO_XMIN = 3

```

(EWA: public)+≡

```

        public :: ewa_data_init

```

(EWA: procedures)≡

```

        subroutine ewa_data_init (data, model, flv, x_0, x_1, pt_max, mass)
            type(ewa_data_t), intent(inout) :: data
            type(model_t), intent(in), target :: model
            type(flavor_t), intent(in) :: flv
            real(default), intent(in) :: x_0, x_1, pt_max
            real(default), intent(in), optional :: mass
            data%model => model
            data%flv = flv
            data%pt_max = pt_max
            data%x_0 = x_0
            data%x_1 = x_1
            !!! data%cv = cv
            !!! data%ca = ca
            if (present (mass)) then
                data%mass = mass
            else
                data%mass = flavor_get_mass (flv)
            end if
            !!!
            !!! INCOMPLETE
            !!!
            !!!if (max (data%mass, data%q_min) == 0) then
            !!!    data%error = ZERO_QMIN; return
            !!!else if (max (data%mass, data%q_min) >= data%E_max) then
            !!!    data%error = Q_MAX_TOO_SMALL; return
            !!!end if
            !!!data%log = log (4 * (data%E_max / max (data%mass, data%q_min)) ** 2 )
            !!!data%c0 = data%alpha / pi &
            !!!    * flavor_get_charge (data%flv)**2 &
            !!!    * log (data%x_min) * (data%log - log (data%x_min))
            !!!data%c1 = data%alpha / pi &
            !!!    * flavor_get_charge (data%flv)**2 &
            !!!    * log (data%x_max) * (data%log - log (data%x_max))
        end subroutine ewa_data_init

```

Handle error conditions. Should always be done after initialization, unless we are sure everything is ok.

```

(EWA: procedures)+≡
subroutine ewa_data_check (data)
  type(ewa_data_t), intent(in) :: data
  select case (data%error)
  case (ZERO_QMIN)
    call msg_fatal (" EWA: Particle mass is zero")
  case (Q_MAX_TOO_SMALL)
    call msg_fatal (" EWA: Particle mass exceeds Qmax")
  case (ZERO_XMIN)
    call msg_fatal (" EWA: x_min must be larger than zero")
  end select
end subroutine ewa_data_check

```

Output

```

(EWA: public)+≡
public :: ewa_data_write

(EWA: procedures)+≡
subroutine ewa_data_write (data, unit)
  type(ewa_data_t), intent(in) :: data
  integer, intent(in), optional :: unit
  integer :: u
  u = output_unit (unit); if (u < 0) return
  write (u, *) "EWA data:"
  write (u, *) " prt   = ", char (flavor_get_name (data%flv))
  write (u, *) " x_0   = ", data%x_0
  write (u, *) " x_1   = ", data%x_1
  write (u, *) " pt_max = ", data%pt_max
  write (u, *) " mass   = ", data%mass
  write (u, *) " cv     = ", data%cv
  write (u, *) " ca     = ", data%ca
end subroutine ewa_data_write

```

10.4.3 The EWA object

The `ewa_t` data type is a $1 \rightarrow 2$ interaction. We should be able to handle several flavors in parallel, since EPA is not necessarily applied immediately after beam collision: Photons may be radiated from quarks. In that case, the partons are massless and q_{\min} applies instead, so we do not need to generate several kinematical configurations in parallel.

The particles are ordered as (incoming, radiated, photon), where the photon initiates the hard interaction.

We generate an unpolarized photon and transfer initial polarization to the radiated parton. Color is transferred in the same way.

```

(EWA: public)+≡
public :: interaction_init_ewa

(EWA: procedures)+≡
subroutine interaction_init_ewa (int, data)
  type(interaction_t), intent(out) :: int

```

```

type(ewa_data_t), dimension(:), intent(in) :: data
type(quantum_numbers_mask_t), dimension(3) :: mask
integer, dimension(3) :: lock
type(polarization_t) :: pol
type(quantum_numbers_t), dimension(1) :: qn_fc, qn_hel
type(flavor_t) :: flv_photon
type(quantum_numbers_t) :: qn_photon, qn
type(state_iterator_t) :: it_hel
integer :: i
mask = new_quantum_numbers_mask (.false., .false., &
    mask_h = (/ .false., .false., .true. /))
lock = (/ 2, 1, 0 /)
call interaction_init (int, 1, 0, 2, mask=mask, lock=lock)
call flavor_init (flv_photon, PHOTON, data(1)%model)
call quantum_numbers_init (qn_photon, flv_photon)
do i = 1, size (data)
    call polarization_init_generic (pol, data(i)%flv)
    call quantum_numbers_init (qn_fc(1), &
        flv = data(i)%flv, col = color_from_flavor (data(i)%flv))
    call state_iterator_init (it_hel, pol%state)
    do while (state_iterator_is_valid (it_hel))
        qn_hel = state_iterator_get_quantum_numbers (it_hel)
        qn = qn_hel(1) .merge. qn_fc(1)
        call interaction_add_state (int, (/ qn, qn, qn_photon /))
        call state_iterator_advance (it_hel)
    end do
    call polarization_final (pol)
end do
call interaction_freeze (int)
end subroutine interaction_init_ewa

```

10.4.4 EWA structure function

The EPA structure function allows for a straightforward mapping of the unit interval. So, to leading order, the structure function value is unity, but the x value is transformed. Higher orders affect the function value.

The structure function implementation applies the above mapping to the input (random) number r to generate the momentum fraction x and the function value f . For numerical stability reasons, we also output xb , which is $\bar{x} = 1 - x$. The mapping ensures that $f = 1$ at leading order, and the higher-order corrections are well-behaved.

(EWA: procedures)+≡

```

elemental subroutine strfun (f, x, xb, r, E, data)
    real(default), intent(out) :: f, x, xb
    real(default), intent(in) :: r, E
    type(ewa_data_t), intent(in) :: data
    real(default) :: rb, lx0, lx1, lx, d, den
    real(default) :: c1, c2, pt2
    real(default) :: fm, fp, fL, fsum
    !!! Here I assume we always do a mapping
    lx0 = log (data%x_0)
    lx1 = log (data%x_1)

```

```

lx = lx1 * x + lx0 * xb
x = exp(lx)
!!! I assume that the original (structure) function value should
!!! be 1
f = data%coeff * (lx1 - lx0)
!!! Still some parts missing, compare old implementation
!!! What's the equivalent of sqrts here???
pt2 = min ((data%pt_max)**2, (xb * E / 2)**2)
c1 = log (1 + pt2 / (xb * (data%mass)**2))
c2 = 1 / (1 + (xb * (data%mass)**2) / pt2)
fm = ((data%cv + data%ca)**2 + ((data%cv - data%ca) * &
xb)**2) / 2 * (c1 - c2)
fp = ((data%cv - data%ca)**2 + ((data%cv + data%ca) * &
xb)**2) / 2 * (c1 - c2)
fL = (data%cv**2 + data%ca**2) * 2 * xb * c2
fsum = fp + fm + fL
f = f * fsum
if (fsum /= 0) then
    fp = fp / fsum
    fm = fm / fsum
    fL = fL / fsum
end if
!!!
!!! INCOMPLETE
!!!
!!! f = 0
!!! rb = 1 - r
!!! d = data%log ** 2 &
!!!      - 4 * (r * lx1 * (data%log - lx1) + rb * lx0 * (data%log - lx0))
!!! if (d <= 0) then
!!!     return
!!! else
!!!     lx = (data%log - sqrt (d)) / 2
!!! end if
!!! x = exp (lx)
!!! xb = 1 - x
!!! den = data%log - 2 * lx
!!! if (den <= 0) return
!!! qminsq = max (x ** 2 / xb * data%mass ** 2, data%q_min ** 2)
!!! qmaxsq = min (4 * E ** 2, data%q_max ** 2)
!!! if (qminsq < qmaxsq) then
!!!     f = ((xb + x ** 2 / 2) * (qmaxsq / qminsq) &
!!!          - (1 - x / 2) ** 2 &
!!!          * log ((x**2 + qmaxsq / E ** 2) / (x**2 + qminsq / E ** 2)) &
!!!          - xb ** 2 * data%mass ** 2 / qminsq * (1 - qminsq / qmaxsq)) &
!!!          * ( data%c1 - data%c0 ) / den
!!! end if
end subroutine strfun

```

10.4.5 EWA application

For EPA, we can compute kinematics and function value in a single step. This function works on a single beam, assuming that the input momentum has been

set. We need four random numbers as input: one for x , one for Q^2 , and two for the polar and azimuthal angles. Alternatively, we can skip p_T generation; in this case, we only need one.

For obtaining splitting kinematics, we rely on the assumption that all in-particles are mass-degenerate (or there is only one), so the generated x values are identical.

```

(EWA: public)+≡
  public :: interaction_apply_ewa

(EWA: procedures)+≡
  subroutine interaction_apply_ewa (int, r, ewa_data)
    type(interaction_t), intent(inout) :: int
    real(default), dimension(:), intent(in) :: r
    type(ewa_data_t), dimension(:), intent(in) :: ewa_data
    type(vector4_t) :: k
    type(splitting_data_t) :: sd
    real(default), dimension(size(ewa_data)) :: f, x, xb
    k = interaction_get_momentum (int, 1)
    sd = new_splitting_data (k, k**2, ewa_data(1)%mass**2, 0._default)
    call strfun (f, x, xb, r(1), energy (k), ewa_data)
    call interaction_set_flavored_values &
      (int, cmplx (f, kind=default), ewa_data%flv, 2)
    call splitting_set_t_bounds (sd, x(1), xb(1))
    !!! JR: Call does not work like that
    !!! call splitting_narrow_t_bounds (sd, ewa_data(1)%q_min, ewa_data(1)%q_max)
    select case (size (r))
    case (1)
      call splitting_set_collinear (sd)
    case (3)
      call splitting_sample_t (sd, r(2))
      call splitting_sample_phi (sd, r(3))
    case default
      print *, "n_rand = ", size (r)
      call msg_bug (" EWA: number of random numbers must be 1 or 3")
    end select
    call interaction_set_momenta &
      (int, split_momentum (k, sd), outgoing=.true.)
  end subroutine interaction_apply_eWa

```

10.5 LHAPDF

Parton distribution functions (PDFs) are available via an interface to the LHAPDF standard library.

The default PDF for protons set is chosen to be CTEQ6ll (LO fit with LO α_s).

```
<Limits: public parameters>+≡
    character(*), parameter, public :: LHAPDF_DEFAULT_PROTON = "cteq6ll.LHpdf"
    character(*), parameter, public :: LHAPDF_DEFAULT_PION   = "ABFKWPI.LHgrid"
    character(*), parameter, public :: LHAPDF_DEFAULT_PHOTON = "GSG960.LHgrid"
```

10.5.1 The module

```
<(sf_lhapdf.f90)≡
<File header>

module sf_lhapdf

<Use kinds>
<Use strings>
    use system_dependencies, only: LHAPDF_PDFSETS_PATH !NODEP!
    use system_dependencies, only: LHAPDF_AVAILABLE !NODEP!
    use limits, only: LHAPDF_DEFAULT_PROTON !NODEP!
    use limits, only: LHAPDF_DEFAULT_PION !NODEP!
    use limits, only: LHAPDF_DEFAULT_PHOTON !NODEP!
<Use file utils>
    use diagnostics !NODEP!
    use lorentz !NODEP!
    use models
    use flavors
    use colors
    use quantum_numbers
    use state_matrices
    use polarizations
    use interactions
    use sf_aux

<Standard module head>

<LHAPDF: public>

<LHAPDF: types>

<LHAPDF: interfaces>

contains

<LHAPDF: procedures>

end module sf_lhapdf
```

10.5.2 LHAPDF library interface

Here we specify explicit interfaces for all LHAPDF routines that we use below.

$\langle \text{LHAPDF: interfaces} \rangle \equiv$

```
interface
  subroutine InitPDFsetM (set, file)
    integer, intent(in) :: set
    character(*), intent(in) :: file
  end subroutine InitPDFsetM
end interface
```

$\langle \text{LHAPDF: interfaces} \rangle + \equiv$

```
interface
  subroutine InitPDFM (set, mem)
    integer, intent(in) :: set, mem
  end subroutine InitPDFM
end interface
```

$\langle \text{LHAPDF: interfaces} \rangle + \equiv$

```
interface
  subroutine numberPDFM (set, n_members)
    integer, intent(in) :: set
    integer, intent(out) :: n_members
  end subroutine numberPDFM
end interface
```

$\langle \text{LHAPDF: interfaces} \rangle + \equiv$

```
interface
  subroutine evolvePDFM (set, x, q, ff)
    integer, intent(in) :: set
    double precision, intent(in) :: x, q
    double precision, dimension(-6:6), intent(out) :: ff
  end subroutine evolvePDFM
end interface
```

$\langle \text{LHAPDF: interfaces} \rangle + \equiv$

```
interface
  subroutine evolvePDFpM (set, x, q, s, scheme, ff)
    integer, intent(in) :: set
    double precision, intent(in) :: x, q, s
    integer, intent(in) :: scheme
    double precision, dimension(-6:6), intent(out) :: ff
  end subroutine evolvePDFpM
end interface
```

$\langle \text{LHAPDF: interfaces} \rangle + \equiv$

```
interface
  subroutine GetXminM (set, mem, xmin)
    integer, intent(in) :: set, mem
    double precision, intent(out) :: xmin
  end subroutine GetXminM
end interface
```

```

<LHAPDF: interfaces>+=
interface
  subroutine GetXmaxM (set, mem, xmax)
    integer, intent(in) :: set, mem
    double precision, intent(out) :: xmax
  end subroutine GetXmaxM
end interface

```

```

<LHAPDF: interfaces>+=
interface
  subroutine GetQ2minM (set, mem, q2min)
    integer, intent(in) :: set, mem
    double precision, intent(out) :: q2min
  end subroutine GetQ2minM
end interface

```

```

<LHAPDF: interfaces>+=
interface
  subroutine GetQ2maxM (set, mem, q2max)
    integer, intent(in) :: set, mem
    double precision, intent(out) :: q2max
  end subroutine GetQ2maxM
end interface

```

10.5.3 The LHAPDF status

This type holds the initialization status of the LHAPDF system.

```

<LHAPDF: public>=
public :: lhapdf_status_t

<LHAPDF: types>=
type :: lhapdf_status_t
  private
  logical, dimension(3) :: initialized = .false.
end type lhapdf_status_t

<LHAPDF: public>+=
public :: lhapdf_status_reset

<LHAPDF: procedures>=
subroutine lhapdf_status_reset (lhapdf_status)
  type(lhapdf_status_t), intent(inout) :: lhapdf_status
  lhapdf_status%initialized = .false.
end subroutine lhapdf_status_reset

<LHAPDF: procedures>+=
function lhapdf_status_is_initialized (lhapdf_status, set) result (flag)
  logical :: flag
  type(lhapdf_status_t), intent(in) :: lhapdf_status
  integer, intent(in), optional :: set
  if (present (set)) then
    select case (set)

```

```

        case (1:3);    flag = lhpdf_status%initialized(set)
        case default;  flag = .false.
        end select
    else
        flag = any (lhpdf_status%initialized)
    end if
end function lhpdf_status_is_initialized

```

```

<LHAPDF: procedures>+≡
subroutine lhpdf_status_set_initialized (lhpdf_status, set)
    type(lhpdf_status_t), intent(inout) :: lhpdf_status
    integer, intent(in) :: set
    lhpdf_status%initialized(set) = .true.
end subroutine lhpdf_status_set_initialized

```

10.5.4 LHAPDF initialization

Before using LHAPDF, we have to initialize it with a particular data set and member. This applies not just if we use structure functions, but also if we just use an α_s formula. The integer `set` should be 1 for proton, 2 for pion, and 3 for photon, but this is just convention.

If the particular set has already been initialized, do nothing. This implies that whenever we want to change the setup for a particular set, we have to reset the LHAPDF status.

```

<LHAPDF: public>+≡
public :: lhpdf_init

<LHAPDF: procedures>+≡
subroutine lhpdf_init (status, set, prefix, file, member)
    type(lhpdf_status_t), intent(inout) :: status
    integer, intent(in) :: set
    type(string_t), intent(in) :: prefix
    type(string_t), intent(inout) :: file
    integer, intent(inout) :: member
    if (lhpdf_status_is_initialized (status, set)) return
    if (file == "") then
        select case (set)
        case (1); file = LHAPDF_DEFAULT_PROTON
        case (2); file = LHAPDF_DEFAULT_PION
        case (3); file = LHAPDF_DEFAULT_PHOTON
        end select
    end if
    if (data_file_exists (prefix // file)) then
        call InitPDFsetM (set, char (prefix // file))
    else
        call msg_fatal ("LHAPDF: Data file '" // char (file) // "' not found.")
        return
    end if
    if (.not. dataset_member_exists (set, member)) then
        call msg_error (" LHAPDF: Chosen member does not exist for set '" &
            // char (file) // "', using default.")
        member = 0
    end if
end subroutine lhpdf_init

```

```

end if
call InitPDFM (set, member)
call lhpdf_status_set_initialized (status, set)
contains
function data_file_exists (fq_name) result (exist)
  type(string_t), intent(in) :: fq_name
  logical :: exist
  inquire (file = char(fq_name), exist = exist)
end function data_file_exists
function dataset_member_exists (set, member) result (exist)
  integer, intent(in) :: set, member
  logical :: exist
  integer :: n_members
  call numberPDFM (set, n_members)
  exist = member >= 0 .and. member <= n_members
end function dataset_member_exists
end subroutine lhpdf_init

```

10.5.5 The LHAPDF data block

The data block holds the incoming flavor (which has to be proton, pion, or photon), the corresponding pointer to the global access data (1, 2, or 3), the flag `invert` which is set for an antiproton, the bounds as returned by LHAPDF for the specified set, and a mask that determines which partons will be actually in use.

```

<LHAPDF: public>+≡
  public :: lhpdf_data_t

<LHAPDF: types>+≡
  type :: lhpdf_data_t
  private
  type(string_t) :: prefix
  type(string_t) :: file
  integer :: member = 0
  type(model_t), pointer :: model => null ()
  type(flavor_t) :: flv_in
  integer :: set = 0
  logical :: invert = .false.
  logical :: photon = .false.
  integer :: photon_scheme = 0
  real(default) :: xmin, xmax
  real(default) :: qmin, qmax
  logical, dimension(-6:6) :: mask = .true.
end type lhpdf_data_t

```

Generate PDF data. This is provided as a function, but it has the side-effect of initializing the requested PDF set. A finalizer is not needed.

The library uses double precision, so since the default precision may be quadruple, we use auxiliary variables for type casting.

```

<LHAPDF: public>+≡
  public :: lhpdf_data_init

```

```

<LHAPDF: procedures>+≡
subroutine lhpdf_data_init &
    (data, status, model, flv, file, member, photon_scheme)
    type(lhpdf_data_t), intent(out) :: data
    type(lhpdf_status_t), intent(inout) :: status
    type(model_t), intent(in), target :: model
    type(flavor_t), intent(in) :: flv
    type(string_t), intent(in), optional :: file
    integer, intent(in), optional :: member
    integer, intent(in), optional :: photon_scheme
    integer :: mem
    double precision :: xmin, xmax, q2min, q2max
    external :: InitPDFsetM, InitPDFM, numberPDFM
    external :: GetXminM, GetXmaxM, GetQ2minM, GetQ2maxM
    if (.not. LHAPDF_AVAILABLE) then
        call msg_fatal ("LHAPDF requested but library is not linked")
        return
    end if
    data%model => model
    data%flv_in = flv
    select case (flavor_get_pdg (flv))
    case (PROTON)
        data%set = 1
    case (-PROTON)
        data%set = 1
        data%invert = .true.
    case (PIPLUS)
        data%set = 2
    case (-PIPLUS)
        data%set = 2
        data%invert = .true.
    case (PHOTON)
        data%set = 3
        data%photon = .true.
        if (present (photon_scheme)) data%photon_scheme = photon_scheme
    case default
        call msg_fatal (" LHAPDF: " &
            // "incoming particle must be (anti)proton, pion, or photon.")
        return
    end select
    data%prefix = LHAPDF_PDFSETS_PATH // "/"
    if (present (file)) then
        data%file = file
    else
        data%file = ""
    end if
    call lhpdf_init (status, data%set, data%prefix, data%file, data%member)
    call GetXminM (data%set, data%member, data%xmin)
    call GetXmaxM (data%set, data%member, data%xmax)
    call GetQ2minM (data%set, data%member, q2min)
    call GetQ2maxM (data%set, data%member, q2max)
    data%xmin = xmin
    data%xmax = xmax
    data%qmin = sqrt (q2min)

```

```

    data%qmax = sqrt (q2max)
end subroutine lhpdf_data_init

```

Enable/disable partons explicitly. If a mask entry is true, applying the PDF will generate the corresponding flavor on output.

```

<LHAPDF: public>+≡
    public :: lhpdf_data_set_mask

<LHAPDF: procedures>+≡
    subroutine lhpdf_data_set_mask (data, mask)
        type(lhpdf_data_t), intent(inout) :: data
        logical, dimension(-6:6), intent(in) :: mask
        data%mask = mask
    end subroutine lhpdf_data_set_mask

```

Output

```

<LHAPDF: public>+≡
    public :: lhpdf_data_write

<LHAPDF: procedures>+≡
    subroutine lhpdf_data_write (data, unit)
        type(lhpdf_data_t), intent(in) :: data
        integer, intent(in), optional :: unit
        integer :: u
        u = output_unit (unit); if (u < 0) return
        write (u, *) "LHAPDF data:"
        if (data%set /= 0) then
            write (u, "(3x,A)", advance="no") "flavor      = "
            call flavor_write (data%flv_in, u); write (u, *)
            write (u, *) " prefix      = ", char (data%prefix)
            write (u, *) " file       = ", char (data%file)
            write (u, *) " member     = ", data%member
            write (u, *) " x(min)      = ", data%xmin
            write (u, *) " x(max)      = ", data%xmax
            write (u, *) " Q^2(min)    = ", data%qmin
            write (u, *) " Q^2(max)    = ", data%qmax
            write (u, *) " invert     = ", data%invert
            if (data%photon) write (u, *) " IP2 (scheme) = ", data%photon_scheme
            write (u, *) " mask       = ", &
                data%mask(-6:-1), " ", data%mask(0), " ", data%mask(1:6)
        else
            write (u, *) " [undefined]"
        end if
    end subroutine lhpdf_data_write

```

10.5.6 The LHAPDF object

The `lhpdf_t` data type is a $1 \rightarrow 2$ interaction which describes the splitting of an (anti)proton into a parton and a beam remnant. We stay in the strict forward-splitting limit, but allow some invariant mass for the beam remnant such that the outgoing parton is exactly massless. For a real event, we would

replace this by a parton cascade, where the outgoing partons have virtuality as dictated by parton-shower kinematics, and transverse momentum is generated.

This is the LHAPDF object which holds input data together with the interaction. We also store the x momentum fraction and the scale, since kinematics and function value are requested at different times.

The PDF application is a $1 \rightarrow 2$ splitting process, where the particles are ordered as (hadron, remnant, parton).

Polarization is ignored completely. The beam particle is colorless, while partons and beam remnant carry color. The remnant gets a special flavor code.

```

<LHAPDF: public>+≡
    public :: interaction_init_lhapdf

<LHAPDF: procedures>+≡
    subroutine interaction_init_lhapdf (int, data)
        type(interaction_t), intent(out) :: int
        type(lhapdf_data_t), intent(in) :: data
        type(quantum_numbers_mask_t), dimension(3) :: mask
        type(quantum_numbers_t) :: qn_beam, qn_remnant, qn_parton
        type(flavor_t) :: flv, flv_remnant
        integer :: i
        mask = new_quantum_numbers_mask (.false., .false., .true.)
        call interaction_init (int, 1, 0, 2, mask=mask)
        call quantum_numbers_init (qn_beam, flv = data%flv_in)
        do i = -6, 6
            if (data%mask(i)) then
                if (i == 0) then
                    call flavor_init (flv, GLUON, data%model)
                    call flavor_init (flv_remnant, HADRON_REMNANT_OCTET, data%model)
                else
                    call flavor_init (flv, i, data%model)
                    call flavor_init (flv_remnant, &
                        sign (HADRON_REMNANT_TRIPLET, -i), data%model)
                end if
                call quantum_numbers_init (qn_remnant, &
                    flv = flv_remnant, col = color_from_flavor (flv_remnant, 1))
                call quantum_numbers_init (qn_parton, &
                    flv = flv, col = color_from_flavor (flv, 1, reverse=.true.))
                call interaction_add_state (int, &
                    (/ qn_beam, qn_remnant, qn_parton /))
            end if
        end do
        call interaction_freeze (int)
    end subroutine interaction_init_lhapdf

```

10.5.7 Structure function

For the PDFs, we separate kinematics from dynamics. We first generate appropriate x values, independent of flavor and scale. This allows us to determine the momenta that initiate the hard scattering. Only when the hard process has been computed, we can be sure about the scattering scale and compute the structure function values.

For the x values, we can only apply a simple mapping that eliminates the $1/x$ singularity, i.e., we generate x on a logarithmic scale. This produces a Jacobian factor that we store along with the generated x value. The boundaries are used as returned by the LHAPDF library for the chosen PDF set.

```

<LHAPDF: procedures>+≡
  subroutine generate_x (x, f, r, lhpdf_data)
    real(default), intent(out) :: x, f
    real(default), intent(in)  :: r
    type(lhpdf_data_t), intent(in) :: lhpdf_data
    real(default) :: lg
    x = r
    f = 1
    !   lg = log (lhpdf_data% xmax / lhpdf_data% xmin)
    !   x = lhpdf_data% xmin * exp (r * lg)
    !   f = x * lg
  end subroutine generate_x

```

The previous routine is called here, so we can compute the complete kinematics:

```

<LHAPDF: public>+≡
  public :: interaction_set_kinematics_lhpdf

<LHAPDF: procedures>+≡
  subroutine interaction_set_kinematics_lhpdf (int, x, f, s, r, lhpdf_data)
    type(interaction_t), intent(inout) :: int
    real(default), intent(out) :: x, f, s
    real(default), intent(in)  :: r
    type(lhpdf_data_t), intent(in) :: lhpdf_data
    type(vector4_t) :: k
    type(splitting_data_t) :: sd
    call generate_x (x, f, r, lhpdf_data)
    k = interaction_get_momentum (int, 1)
    s = k**2
    sd = new_splitting_data (k, s, 0._default, 0._default)
    call splitting_set_t_bounds (sd, x, 1 - x)
    call splitting_set_collinear (sd)
    call interaction_set_momenta &
      (int, split_momentum (k, sd), outgoing=.true.)
  end subroutine interaction_set_kinematics_lhpdf

```

Once the scale is also known, we can actually call the library and set the values. If the scale is out of bounds, we reset it to the boundary. Account for the Jacobian.

We have to cast the LHAPDF arguments to/from double precision (possibly from/to quadruple precision), if necessary.

```

<LHAPDF: public>+≡
  public :: interaction_apply_lhpdf

<LHAPDF: procedures>+≡
  subroutine interaction_apply_lhpdf (int, scale, x, f, s, lhpdf_data)
    type(interaction_t), intent(inout) :: int
    real(default), intent(in) :: scale, x, f, s
    type(lhpdf_data_t), intent(in) :: lhpdf_data
    double precision :: xx, qq, ss

```

```

double precision, dimension(-6:6) :: ff
complex(default), dimension(:), allocatable :: fc
external :: evolvePDFM, evolvePDFpM
xx = x
qq = min (lhpdf_data% qmax, scale)
qq = max (lhpdf_data% qmin, qq)
if (.not. lhpdf_data% photon) then
  if (lhpdf_data% invert) then
    call evolvePDFM (lhpdf_data% set, xx, qq, ff(6:-6:-1))
  else
    call evolvePDFM (lhpdf_data% set, xx, qq, ff)
  end if
else
  ss = s
  call evolvePDFpM (lhpdf_data% set, xx, qq, &
    ss, lhpdf_data% photon_scheme, ff)
end if
allocate (fc (count (lhpdf_data% mask)))
fc = pack (ff / x, lhpdf_data% mask) * f
call interaction_set_matrix_element (int, fc)
end subroutine interaction_apply_lhpdf

```

10.6 Spectra and structure functions: wrapper

In this module, we collect, for each type of spectrum or structure function, the data, initialization routines, and applications.

```

<strfun.f90>≡
  <File header>

  module strfun

    <Use kinds>
    <Use strings>
    <Use file utils>
    use diagnostics !NODEP!
    use lorentz !NODEP!
    use models
    use quantum_numbers
    use interactions
    use evaluators
    use beams
    use sf_isr
    use sf_epa
    use sf_ewa
    use sf_lhpdf

    <Standard module head>

    <Strfun: public>

    <Strfun: parameters>

```

```

<Strfun: types>

<Strfun: interfaces>

contains

<Strfun: procedures>

end module strfun

```

10.6.1 The structure functions type

Definition

This contains the specific structure function data, much of which depends on the type. An extensible type would be appropriate. As long as this is not available in general, we emulate it by allocating the requested data explicitly.

```

<Strfun: public>≡
! public :: strfun_t

<Strfun: types>≡
type :: strfun_t
private
integer :: type = STRF_NONE
type(string_t) :: name
type(interaction_t) :: int
type(isr_data_t), dimension(:), allocatable :: isr_data
type(epa_data_t), dimension(:), allocatable :: epa_data
type(lhapdf_data_t), dimension(:), allocatable :: lhpdf_data
real(default) :: x, f, s
real(default) :: scale
end type strfun_t

```

The list of structure function codes:

```

<Strfun: parameters>≡
integer, parameter, public :: STRF_NONE = 0
integer, parameter, public :: STRF_ISR = 1, STRF_EPA = 2, STRF_LHAPDF = 3

```

The initializer assigns specific data and tags the interaction. The data block(s) have to be known already.

```

<Strfun: public>+≡
! public :: strfun_init

<Strfun: interfaces>≡
interface strfun_init
module procedure strfun_init_isr
module procedure strfun_init_epa
module procedure strfun_init_lhapdf
end interface

```

```

<Strfun: procedures>≡
  subroutine strfun_init_isr (strfun, isr_data)
    type(strfun_t), intent(out) :: strfun
    type(isr_data_t), intent(in) :: isr_data
    strfun%type = STRF_ISR
    strfun%name = "ISR"
    allocate (strfun%isr_data (1))
    strfun%isr_data = isr_data
    call interaction_init_isr (strfun%int, isr_data)
  end subroutine strfun_init_isr

  subroutine strfun_init_epa (strfun, epa_data)
    type(strfun_t), intent(out) :: strfun
    type(epa_data_t), intent(in) :: epa_data
    strfun%type = STRF_EPA
    strfun%name = "EPA"
    allocate (strfun%epa_data (1))
    strfun%epa_data = epa_data
    call interaction_init_epa (strfun%int, epa_data)
  end subroutine strfun_init_epa

  subroutine strfun_init_lhapdf (strfun, lhpdf_data)
    type(strfun_t), intent(out) :: strfun
    type(lhapdf_data_t), intent(in) :: lhpdf_data
    strfun%type = STRF_LHAPDF
    strfun%name = "LHAPDF"
    allocate (strfun%lhpdf_data (1))
    strfun%lhpdf_data = lhpdf_data
    call interaction_init_lhapdf (strfun%int, lhpdf_data)
  end subroutine strfun_init_lhapdf

```

Finalizer for the contained interaction:

```

<Strfun: public>+≡
  ! public :: strfun_final

<Strfun: procedures>+≡
  elemental subroutine strfun_final (strfun)
    type(strfun_t), intent(inout) :: strfun
    select case (strfun%type)
    case (STRF_ISR)
      deallocate (strfun%isr_data)
    case (STRF_EPA)
      deallocate (strfun%epa_data)
    case (STRF_LHAPDF)
      deallocate (strfun%lhpdf_data)
    end select
    call interaction_final (strfun%int)
    strfun%type = STRF_NONE
  end subroutine strfun_final

```

I/O

```

<Strfun: public>+≡

```

```

! public :: strfun_write
<Strfun: procedures>+≡
subroutine strfun_write (strfun, unit, verbose, show_momentum_sum, show_mass)
  type(strfun_t), intent(in) :: strfun
  integer, intent(in), optional :: unit
  logical, intent(in), optional :: verbose, show_momentum_sum, show_mass
  integer :: u
  u = output_unit (unit); if (u < 0) return
  if (strfun%type /= STRF_NONE) then
    write (u, *) char (strfun_get_name (strfun)) // " setup:"
    select case (strfun%type)
    case (STRF_ISR)
      call isr_data_write (strfun%isr_data(1), u)
    case (STRF_EPA)
      call epa_data_write (strfun%epa_data(1), u)
    case (STRF_LHAPDF)
      call lhpdf_data_write (strfun%lhpdf_data(1), u)
      write (u, *) "LHAPDF event data:"
      write (u, *) "  x      =", strfun%x
      write (u, *) "  f      =", strfun%f
      write (u, *) "  scale =", strfun%scale
      write (u, *) "  p2     =", strfun%s
    end select
    call interaction_write &
      (strfun%int, unit, verbose, show_momentum_sum, show_mass)
  else
    write (u, *) "Structure function setup: [empty]"
  end if
end subroutine strfun_write

```

Retrieve data

```

<Strfun: public>+≡
! public :: strfun_get_name
<Strfun: procedures>+≡
function strfun_get_name (strfun) result (name)
  type(string_t) :: name
  type(strfun_t), intent(in) :: strfun
  name = strfun%name
end function strfun_get_name

```

Apply structure function

Set kinematics using input random numbers. For some structure functions, we can already compute matrix elements.

```

<Strfun: public>+≡
! public :: strfun_set_kinematics

```

```

<Strfun: procedures>+≡
subroutine strfun_set_kinematics (strfun, r)
  type(strfun_t), intent(inout) :: strfun
  real(default), dimension(:), intent(in) :: r
  select case (strfun%type)
  case (STRF_ISR)
    call interaction_apply_isr (strfun%int, r, strfun%isr_data(1))
  case (STRF_EPA)
    call interaction_apply_epa (strfun%int, r, strfun%epa_data)
  case (STRF_LHAPDF)
    call interaction_set_kinematics_lhapdf (strfun%int, &
      strfun%x, strfun%f, strfun%s, r(1), strfun%lhpdf_data(1))
  end select
end subroutine strfun_set_kinematics

```

Set values where they depend on a separate energy scale:

```

<Strfun: public>+≡
! public :: strfun_apply

<Strfun: procedures>+≡
subroutine strfun_apply (strfun, scale)
  type(strfun_t), intent(inout) :: strfun
  real(default), intent(in) :: scale
  strfun%scale = scale
  select case (strfun%type)
  case (STRF_LHAPDF)
    call interaction_apply_lhapdf (strfun%int, scale, &
      strfun%x, strfun%f, strfun%s, strfun%lhpdf_data(1))
  end select
end subroutine strfun_apply

```

10.6.2 Mappings

Definition

Mappings for single structure functions may be defined in the individual sections, but pairwise mappings belong here. We define a mapping type that applies to an array of x parameters identified by their indices. The individual mapping types are identified by a `type` parameter. A mapping may depend on a set on real parameters.

```

<Strfun: parameters>+≡
integer, parameter, public :: SFM_NONE = 0
integer, parameter, public :: SFM_PDFPAIR = 1
integer, parameter, public :: SFM_ISRPAIR = 2
integer, parameter, public :: SFM_EPAPAIR = 3

<Strfun: types>+≡
type :: strfun_mapping_t
  private
  integer, dimension(:), allocatable :: index
  integer :: type = SFM_NONE
  real(default), dimension(:), allocatable :: par
end type strfun_mapping_t

```

Initialization:

```

(Strfun: procedures)+≡
  subroutine strfun_mapping_init (sf_mapping, index, type, par)
    type(strfun_mapping_t), intent(out) :: sf_mapping
    integer, dimension(:), intent(in) :: index
    integer, intent(in) :: type
    real(default), dimension(:), intent(in) :: par
    allocate (sf_mapping%index (size (index)))
    sf_mapping%index = index
    sf_mapping%type = type
    allocate (sf_mapping%par (size (par)))
    sf_mapping%par = par
  end subroutine strfun_mapping_init

```

Output

```

(Strfun: procedures)+≡
  subroutine strfun_mapping_write (sf_mapping, unit)
    type(strfun_mapping_t), intent(in) :: sf_mapping
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write (u, "(1x,A)", advance="no") "Strfun mapping for indices: "
    write (u, "(10(1x,I0))") sf_mapping%index
    write (u, "(1x,A,1x,I0)") "mapping type =", sf_mapping%type
    write (u, "(1x,A)", advance="no") "mapping pars ="
    write (u, *) sf_mapping%par
  end subroutine strfun_mapping_write

```

Evaluation

```

(Strfun: procedures)+≡
  subroutine strfun_mapping_apply (sf_mapping, x, factor)
    type(strfun_mapping_t), intent(in) :: sf_mapping
    real(default), dimension(:), intent(inout) :: x
    real(default), intent(inout) :: factor
    real(default), dimension(2) :: x2
    select case (sf_mapping%type)
    case (SFM_PDFPAIR)
      x2 = x(sf_mapping%index)
      call map_unit_square (x2, factor, sf_mapping%par(1))
      x(sf_mapping%index) = x2
    end select
  end subroutine strfun_mapping_apply

```

This mapping of the unit square is appropriate in particular for structure functions which are concentrated at the lower end. Instead of a rectangular grid, one set of grid lines corresponds to constant parton c.m. energy. The other set is chosen such that the jacobian is only mildly singular ($\ln x$ which is zero at $x = 1$), corresponding to an initial concentration of sampling points at the

maximum energy. If `power` is greater than one (the default), points are also concentrated at the lower end.

<Strfun: procedures>+≡

```
subroutine map_unit_square (x, factor, power)
  real(kind=default), dimension(2), intent(inout) :: x
  real(kind=default), intent(inout) :: factor
  real(kind=default), intent(in), optional :: power
  real(kind=default) :: xx, yy
  xx = x(1)
  yy = x(2)
  if (present(power)) then
    if (x(1) > 0 .and. power > 1) then
      xx = x(1)**power
      factor = factor * power * xx / x(1)
    end if
  end if
  if (xx /= 0) then
    x(1) = xx ** yy
    x(2) = xx / x(1)
    factor = factor * abs (log (xx))
  else
    x = 0
  end if
end subroutine map_unit_square
```

10.6.3 Structure function chains

Definition

The structure function chain contains an array of structure functions, where each one has one or more free parameters. For each structure function there is an interaction, an image of the interaction within the `strfun` object, which is needed when quantum numbers are reduced. Furthermore, an array of evaluators which cumulatively multiply the structure functions. The last evaluator is connected to the hard matrix element.

The `last_strfun` and `out_index` index (pairs) identify, for each beam, the last structure function and the outgoing particle. The `coll_index` (pair) identifies the outgoing particles in the last evaluator.

For a decay, this structure is also used, but normally there are no structure functions besides the “beam” object.

<Strfun: public>+≡

```
public :: strfun_chain_t
```

<Strfun: types>+≡

```
type :: strfun_chain_t
  private
  type(beam_t) :: beam
  integer :: n_strfun, n_mapping
  type(strfun_t), dimension(:), allocatable :: strfun
  type(strfun_mapping_t), dimension(:), allocatable :: sf_mapping
  real(default) :: mapping_factor = 1
```

```

integer :: n_parameters_tot = 0
integer, dimension(:), allocatable :: n_parameters
type(evaluator_t), dimension(:), allocatable :: eval
integer, dimension(:), allocatable :: last_strfun
integer, dimension(:), allocatable :: out_index
integer, dimension(:), allocatable :: coll_index
end type strfun_chain_t

```

<Strfun: public>+≡

```
public :: strfun_chain_init
```

<Strfun: procedures>+≡

```

subroutine strfun_chain_init (sfchain, beam_data, n_strfun, n_mapping)
  type(strfun_chain_t), intent(out) :: sfchain
  type(beam_data_t), intent(in), target :: beam_data
  integer, intent(in) :: n_strfun, n_mapping
  integer :: i
  sfchain%n_strfun = n_strfun
  allocate (sfchain%strfun (n_strfun))
  allocate (sfchain%sf_mapping (n_mapping))
  allocate (sfchain%n_parameters (n_strfun))
  sfchain%n_parameters = 0
  allocate (sfchain%eval (n_strfun))
  call beam_init (sfchain%beam, beam_data)
  allocate (sfchain%last_strfun (beam_data%n))
  allocate (sfchain%out_index (beam_data%n))
  allocate (sfchain%coll_index (beam_data%n))
  sfchain%last_strfun = 0
  do i = 1, size (sfchain%out_index)
    sfchain%out_index(i) = i
    sfchain%coll_index(i) = i
  end do
end subroutine strfun_chain_init

```

Set beam momenta directly without changing anything else.

<Strfun: public>+≡

```
public :: strfun_chain_set_beam_momenta
```

<Strfun: procedures>+≡

```

subroutine strfun_chain_set_beam_momenta (sfchain, p)
  type(strfun_chain_t), intent(inout) :: sfchain
  type(vector4_t), dimension(:), intent(in) :: p
  call beam_set_momenta (sfchain%beam, p)
end subroutine strfun_chain_set_beam_momenta

```

<Strfun: public>+≡

```
public :: strfun_chain_final
```

<Strfun: procedures>+≡

```

subroutine strfun_chain_final (sfchain)
  type(strfun_chain_t), intent(inout) :: sfchain
  call beam_final (sfchain%beam)
  if (allocated (sfchain%strfun)) call strfun_final (sfchain%strfun)
  if (allocated (sfchain%eval)) call evaluator_final (sfchain%eval)

```

```
end subroutine strfun_chain_final
```

I/O

<Strfun: public>+≡

```
public :: strfun_chain_write
```

<Strfun: procedures>+≡

```
subroutine strfun_chain_write &
  (sfchain, unit, verbose, show_momentum_sum, show_mass)
  type(strfun_chain_t), intent(in) :: sfchain
  integer, intent(in), optional :: unit
  logical, intent(in), optional :: verbose, show_momentum_sum, show_mass
  integer :: u, i
  logical :: verb
  verb = .false.; if (present (verbose)) verb = verbose
  u = output_unit (unit); if (u < 0) return
  write (u, *) "Structure function chain:"
  write (u, *)
  call beam_write (sfchain%beam, unit, verbose, show_momentum_sum, show_mass)
  if (allocated (sfchain%strfun)) then
    do i = 1, size (sfchain%strfun)
      write (u, *)
      call strfun_write &
        (sfchain%strfun(i), unit, verbose, show_momentum_sum, show_mass)
      write (u, *) "number of parameters = ", sfchain%n_parameters(i)
    end do
  end if
  if (allocated (sfchain%sf_mapping)) then
    do i = 1, size (sfchain%sf_mapping)
      write (u, *)
      call strfun_mapping_write (sfchain%sf_mapping(i), unit)
    end do
  end if
  if (allocated (sfchain%eval)) then
    write (u, *)
    write (u, *) "Evaluators:"
    do i = 1, size (sfchain%eval)
      call evaluator_write &
        (sfchain%eval(i), unit, verbose, show_momentum_sum, show_mass)
    end do
  end if
  write (u, *)
  write (u, *) "Total number of parameters      = ", &
    sfchain%n_parameters_tot
  write (u, "(1x,A)", advance="no") "Last structure function (index) = "
  if (allocated (sfchain%last_strfun)) then
    write (u, *) sfchain%last_strfun
  else
    write (u, *) "[not allocated]"
  end if
  write (u, "(1x,A)", advance="no") "Outgoing particles (index)      = "
  if (allocated (sfchain%out_index)) then
```

```

        write (u, *) sfchain%out_index
    else
        write (u, *) "[not allocated]"
    end if
    write (u, "(1x,A)", advance="no") "Colliding particles (index)      = "
    if (allocated (sfchain%coll_index)) then
        write (u, *) sfchain%coll_index
    else
        write (u, *) "[not allocated]"
    end if
end subroutine strfun_chain_write

```

Defined assignment

Deep copy of all components.

```

<Strfun: public>+≡
    public :: assignment(=)

<Strfun: interfaces>+≡
    interface assignment(=)
        module procedure strfun_chain_assign
    end interface

<Strfun: procedures>+≡
    subroutine strfun_chain_assign (sfchain_out, sfchain_in)
        type(strfun_chain_t), intent(out) :: sfchain_out
        type(strfun_chain_t), intent(in)  :: sfchain_in
        sfchain_out%beam = sfchain_in%beam
        sfchain_out%n_strfun = sfchain_in%n_strfun
        sfchain_out%n_mapping = sfchain_in%n_mapping
        if (allocated (sfchain_in%strfun)) then
            allocate (sfchain_out%strfun (size (sfchain_in%strfun)))
            sfchain_out%strfun = sfchain_in%strfun
        end if
        if (allocated (sfchain_in%sf_mapping)) then
            allocate (sfchain_out%sf_mapping (size (sfchain_in%sf_mapping)))
            sfchain_out%sf_mapping = sfchain_in%sf_mapping
        end if
        sfchain_out%mapping_factor = sfchain_in%mapping_factor
        sfchain_out%n_parameters_tot = sfchain_in%n_parameters_tot
        if (allocated (sfchain_in%n_parameters)) then
            allocate (sfchain_out%n_parameters (size (sfchain_in%n_parameters)))
            sfchain_out%n_parameters = sfchain_in%n_parameters
        end if
        if (allocated (sfchain_in%eval)) then
            allocate (sfchain_out%eval (size (sfchain_in%eval)))
            sfchain_out%eval = sfchain_in%eval
        end if
        if (allocated (sfchain_in%last_strfun)) then
            allocate (sfchain_out%last_strfun (size (sfchain_in%last_strfun)))
            sfchain_out%last_strfun = sfchain_in%last_strfun
        end if
        if (allocated (sfchain_in%out_index)) then

```

```

        allocate (sfchain_out%out_index (size (sfchain_in%out_index)))
        sfchain_out%out_index = sfchain_in%out_index
    end if
    if (allocated (sfchain_in%coll_index)) then
        allocate (sfchain_out%coll_index (size (sfchain_in%coll_index)))
        sfchain_out%coll_index = sfchain_in%coll_index
    end if
end subroutine strfun_chain_assign

```

Accessing contents

<Strfun: public>+≡

```
public :: strfun_chain_get_n_strfun
```

<Strfun: procedures>+≡

```

function strfun_chain_get_n_strfun (sfchain) result (n)
    integer :: n
    type(strfun_chain_t), intent(in) :: sfchain
    n = sfchain%n_strfun
end function strfun_chain_get_n_strfun

```

<Strfun: public>+≡

```
public :: strfun_chain_get_n_parameters_tot
```

<Strfun: procedures>+≡

```

function strfun_chain_get_n_parameters_tot (sfchain) result (n)
    integer :: n
    type(strfun_chain_t), intent(in) :: sfchain
    n = sfchain%n_parameters_tot
end function strfun_chain_get_n_parameters_tot

```

Return any extra factor resulting from explicit mappings of the x parameters.

<Strfun: public>+≡

```
public :: strfun_chain_get_mapping_factor
```

<Strfun: procedures>+≡

```

function strfun_chain_get_mapping_factor (sfchain) result (f)
    real(default) :: f
    type(strfun_chain_t), intent(in) :: sfchain
    f = sfchain%mapping_factor
end function strfun_chain_get_mapping_factor

```

For pseudo-structure functions that actually are an external generator, the integration region must not be mapped and stay rigid. This function returns an array which tells, for each integration parameter, whether the corresponding integration dimension is rigid.

<Strfun: public>+≡

```
public :: strfun_chain_dimension_is_rigid
```

<Strfun: procedures>+≡

```

function strfun_chain_dimension_is_rigid (sfchain) result (rigid)
    logical, dimension(:), allocatable :: rigid
    type(strfun_chain_t), intent(in) :: sfchain

```

```

integer :: i, j, k
allocate (rigid (sfchain%n_parameters_tot))
k = 0
do i = 1, size (sfchain%n_parameters)
  do j = 1, sfchain%n_parameters(i)
    k = k + 1
    select case (sfchain%strfun(i)%type)
    case default
      rigid(k) = .false.
    end select
  end do
end do
end function strfun_chain_dimension_is_rigid

```

Return the indices of the colliding particles.

```

<Strfun: public>+≡
public :: strfun_chain_get_colliding_particles

<Strfun: procedures>+≡
function strfun_chain_get_colliding_particles (sfchain) result (index)
  integer, dimension(:), allocatable :: index
  type(strfun_chain_t), intent(in) :: sfchain
  allocate (index (size (sfchain%coll_index)))
  index = sfchain%coll_index
end function strfun_chain_get_colliding_particles

```

Return the quantum-numbers mask for the colliding particles. This is extracted from the last evaluator in the chain.

```

<Strfun: public>+≡
public :: strfun_chain_get_colliding_particles_mask

<Strfun: procedures>+≡
function strfun_chain_get_colliding_particles_mask (sfchain) result (mask)
  type(quantum_numbers_mask_t), dimension(:), allocatable :: mask
  type(strfun_chain_t), intent(in), target :: sfchain
  integer :: n_strfun
  type(quantum_numbers_mask_t), dimension(:), allocatable :: mask_eval
  allocate (mask (size (sfchain%coll_index)))
  n_strfun = sfchain%n_strfun
  if (n_strfun /= 0) then
    allocate (mask_eval (evaluator_get_n_tot (sfchain%eval(n_strfun))))
    mask_eval = evaluator_get_mask (sfchain%eval(n_strfun))
    mask = mask_eval(sfchain%coll_index)
  else
    mask = interaction_get_mask (beam_get_int_ptr (sfchain%beam))
  end if
end function strfun_chain_get_colliding_particles_mask

```

Return a pointer to the beam interaction.

```

<Strfun: public>+≡
public :: strfun_chain_get_beam_int_ptr

```

```

<Strfun: procedures>+≡
function strfun_chain_get_beam_int_ptr (sfchain) result (int)
  type(interaction_t), pointer :: int
  type(strfun_chain_t), intent(in), target :: sfchain
  int => beam_get_int_ptr (sfchain%beam)
end function strfun_chain_get_beam_int_ptr

```

Return a pointer to the last evaluator, which wraps up all structure functions.

```

<Strfun: public>+≡
  public :: strfun_chain_get_last_evaluator_ptr

<Strfun: procedures>+≡
function strfun_chain_get_last_evaluator_ptr (sfchain) result (eval)
  type(evaluator_t), pointer :: eval
  type(strfun_chain_t), intent(in), target :: sfchain
  if (sfchain%n_strfun /= 0) then
    eval => sfchain%eval(sfchain%n_strfun)
  else
    eval => null ()
  end if
end function strfun_chain_get_last_evaluator_ptr

```

Setting up structure functions

The index *i* is the overall structure function counter. *line* indicates the beam(s) for which the structure function applies, either 1 or 2, or 0 for both beams.

```

<Strfun: public>+≡
  public :: strfun_chain_set_strfun

<Strfun: interfaces>+≡
interface strfun_chain_set_strfun
  module procedure strfun_chain_set_isr
  module procedure strfun_chain_set_epa
  module procedure strfun_chain_set_lhapdf
end interface

<Strfun: procedures>+≡
subroutine strfun_chain_set_isr &
  (sfchain, i, line, isr_data, n_parameters)
  type(strfun_chain_t), intent(inout), target :: sfchain
  integer, intent(in) :: i, line, n_parameters
  type(isr_data_t), intent(in) :: isr_data
  call strfun_init (sfchain%strfun(i), isr_data)
  sfchain%n_parameters(i) = n_parameters
  call strfun_chain_link (sfchain, i, line, (/1/), (/3/))
end subroutine strfun_chain_set_isr

subroutine strfun_chain_set_epa &
  (sfchain, i, line, epa_data, n_parameters)
  type(strfun_chain_t), intent(inout), target :: sfchain
  integer, intent(in) :: i, line, n_parameters
  type(epa_data_t), intent(in) :: epa_data
  call strfun_init (sfchain%strfun(i), epa_data)

```

```

    sfchain%n_parameters(i) = n_parameters
    call strfun_chain_link (sfchain, i, line, (/1/), (/3/))
end subroutine strfun_chain_set_epa

subroutine strfun_chain_set_lhapdf &
    (sfchain, i, line, lhpdf_data, n_parameters)
    type(strfun_chain_t), intent(inout), target :: sfchain
    integer, intent(in) :: i, line, n_parameters
    type(lhapdf_data_t), intent(in) :: lhpdf_data
    call strfun_init (sfchain%strfun(i), lhpdf_data)
    sfchain%n_parameters(i) = n_parameters
    call strfun_chain_link (sfchain, i, line, (/1/), (/3/))
end subroutine strfun_chain_set_lhapdf

```

This procedure links a new structure function to the existing chain. *i* is the overall structure function counter. *line* indicates the beam(s) to which the structure function applies; 0 is for both beams. The last two arguments are the indices of the incoming and outgoing particle(s) within the current structure function. For a single-beam (double-beam) structure function, these arrays are of length 1 (2), respectively.

The connections of outgoing/incoming particles are recorded as links in the new structure-function entry `sfchain%strfun(i)`.

(*Strfun: procedures*) +=

```

subroutine strfun_chain_link (sfchain, i, line, in_index, out_index)
    type(strfun_chain_t), intent(inout), target :: sfchain
    integer, intent(in) :: i, line
    integer, dimension(:), intent(in) :: in_index, out_index
    select case (line)
    case (0)
        call link_single (1, in_index(1))
        call link_single (2, in_index(2))
        sfchain%last_strfun = i
        sfchain%out_index = out_index
    case default
        call link_single (line, in_index(1))
        sfchain%last_strfun(line) = i
        sfchain%out_index(line) = out_index(1)
    end select
contains
subroutine link_single (line, in_index)
    integer, intent(in) :: line, in_index
    integer :: j
    j = sfchain%last_strfun(line)
    select case (j)
    case (0)
        call interaction_set_source_link &
            (sfchain%strfun(i)%int, in_index, &
             sfchain%beam, sfchain%out_index(line))
    case default
        call interaction_set_source_link &
            (sfchain%strfun(i)%int, in_index, &
             sfchain%strfun(j)%int, sfchain%out_index(j))
    end select
end subroutine link_single

```

```

    end subroutine link_single
end subroutine strfun_chain_link

```

Setting up mappings

Set a particular mapping with a known type.

```

<Strfun: public>+≡
    public :: strfun_chain_set_mapping

<Strfun: procedures>+≡
    subroutine strfun_chain_set_mapping (sfchain, i, index, type, par)
        type(strfun_chain_t), intent(inout) :: sfchain
        integer, intent(in) :: i
        integer, dimension(:), intent(in) :: index
        integer, intent(in) :: type
        real(default), dimension(:), intent(in) :: par
        call strfun_mapping_init (sfchain%sf_mapping(i), index, type, par)
    end subroutine strfun_chain_set_mapping

```

Evaluators

```

<Strfun: public>+≡
    public :: strfun_chain_make_evaluators

<Strfun: procedures>+≡
    subroutine strfun_chain_make_evaluators (sfchain, ok)
        type(strfun_chain_t), intent(inout), target :: sfchain
        logical, intent(out), optional :: ok
        type(interaction_t), pointer :: beam_int, eval_int
        type(quantum_numbers_mask_t) :: qn_mask_conn
        type(quantum_numbers_mask_t), dimension(:), allocatable :: qn_mask_beam
        integer :: i, j
        sfchain%n_parameters_tot = sum (sfchain%n_parameters)
        beam_int => beam_get_int_ptr (sfchain%beam)
        if (.not. associated (beam_int)) call msg_bug &
            ("strfun_chain_make_evaluators: null beam pointer")
        allocate (qn_mask_beam (interaction_get_n_out (beam_int)))
        qn_mask_beam = interaction_get_mask (beam_int)
        call interaction_exchange_mask (beam_int)
        do i = 1, size (sfchain%strfun) - 1
            call interaction_exchange_mask (sfchain%strfun(i)%int)
        end do
        do i = size (sfchain%strfun), 1, -1
            call interaction_exchange_mask (sfchain%strfun(i)%int)
        end do
        if (any (qn_mask_beam .neqv. interaction_get_mask (beam_int))) then
            call beam_write (sfchain%beam)
            call msg_fatal (" Beam polarization/color/flavor incompatible with structure functions")
        end if
        eval_int => beam_int
        do i = 1, size (sfchain%strfun)
            qn_mask_conn = new_quantum_numbers_mask (.true., .false., .true.)

```

```

call evaluator_init_product (sfchain%eval(i), eval_int, &
    sfchain%strfun(i)%int, qn_mask_conn)
if (evaluator_is_empty (sfchain%eval(i))) then
    call msg_fatal ("Mismatch in beam and structure-function chain")
    if (present (ok)) ok = .false.
    return
end if
eval_int => evaluator_get_int_ptr (sfchain%eval(i))
do j = 1, size (sfchain%coll_index)
    sfchain%coll_index(i) = interaction_find_link (eval_int, &
        sfchain%strfun(sfchain%last_strfun(i))%int, &
        sfchain%out_index(i))
end do
if (any (sfchain%coll_index == 0)) &
    call msg_bug ("Structure functions: " &
        // "colliding particles can't be determined")
end do
if (present (ok)) ok = .true.
end subroutine strfun_chain_make_evaluators

```

<Strfun: public>+≡

```
public :: strfun_chain_set_kinematics
```

<Strfun: procedures>+≡

```

subroutine strfun_chain_set_kinematics (sfchain, r)
    type(strfun_chain_t), intent(inout) :: sfchain
    real(default), dimension(:), intent(in) :: r
    real(default), dimension(size(r)) :: x
    integer :: i, n, n1
    if (size (r) == sfchain%n_parameters_tot) then
        x = r
        sfchain%mapping_factor = 1
        do i = 1, size (sfchain%sf_mapping)
            call strfun_mapping_apply &
                (sfchain%sf_mapping(i), x, sfchain%mapping_factor)
        end do
        n = 0
        do i = 1, size (sfchain%strfun)
            call interaction_receive_momenta (sfchain%strfun(i)%int)
            n1 = sfchain%n_parameters(i)
            call strfun_set_kinematics (sfchain%strfun(i), x(n+1:n+n1))
            n = n + n1
        end do
        do i = 1, size (sfchain%strfun)
            call evaluator_receive_momenta (sfchain%eval(i))
        end do
    else
        call msg_bug ("Structure functions: mismatch in number of parameters")
    end if
end subroutine strfun_chain_set_kinematics

```

<Strfun: public>+≡

```
public :: strfun_chain_evaluate
```

<Strfun: procedures>+≡

```

subroutine strfun_chain_evaluate (sfchain, scale)
  type(strfun_chain_t), intent(inout) :: sfchain
  real(default), intent(in) :: scale
  integer :: i
  do i = size (sfchain%strfun), 1, -1
    call strfun_apply (sfchain%strfun(i), scale)
  end do
  do i = 1, size (sfchain%eval)
    call evaluator_evaluate (sfchain%eval(i))
  end do
end subroutine strfun_chain_evaluate

```

10.6.4 Test

```

<Strfun: public>+≡
  public :: strfun_test

<Strfun: procedures>+≡
  subroutine strfun_test ()
    use os_interface, only: os_data_t
    type(os_data_t) :: os_data
    type(model_t), pointer :: model
    print *, "*** Read model file"
    call syntax_model_file_init ()
    call model_list_read_model &
      (var_str("QCD"), var_str("test.mdl"), os_data, model)
    call syntax_model_file_final ()
    print *, "*****"
    call isr_test (model)
    print *, "*****"
    call epa_test (model)
    print *, "*****"
    call lhpdf_test (model)
  end subroutine strfun_test

  subroutine isr_test (model)
    use flavors
    use polarizations
    type(model_t), intent(in), target :: model
    type(flavor_t), dimension(2) :: flv
    type(polarization_t), dimension(2) :: pol
    type(beam_data_t), target :: beam_data
    type(isr_data_t), dimension(2) :: isr_data
    type(strfun_chain_t), target :: sfchain
    integer :: i
    print *, "*** ISR test"
    call flavor_init (flv, (/11, -11/), model)
    call polarization_init_unpolarized (pol(1), flv(1))
    call polarization_init_unpolarized (pol(2), flv(2))
    call beam_data_init_sqrts (beam_data, 500._default, flv, pol)
    do i = 1, 2
      call isr_data_init (isr_data(i), &
        model, flv(i), 0.06_default, 500._default, 0.511e-3_default)
    end do
  end subroutine isr_test

```

```

end do
call strfun_chain_init (sfchain, beam_data, 2, 0)
call strfun_chain_set_strfun (sfchain, 1, 1, isr_data(1), 1)
call strfun_chain_set_strfun (sfchain, 2, 2, isr_data(2), 3)
call strfun_chain_make_evaluators (sfchain)
call strfun_chain_set_kinematics &
    (sfchain, (/0.8_default, 0.4_default, 0.5_default, 0.2_default/))
call strfun_chain_evaluate (sfchain, 0._default)
call strfun_chain_write (sfchain)
call strfun_chain_final (sfchain)
end subroutine isr_test

subroutine epa_test (model)
    use flavors
    use polarizations
    type(model_t), intent(in), target :: model
    type(flavor_t), dimension(2) :: flv
    type(polarization_t), dimension(2) :: pol
    type(beam_data_t) :: beam_data
    type(epa_data_t) :: epa_data1
    type(epa_data_t) :: epa_data2
    type(strfun_chain_t), target :: sfchain
    print *, "*** EPA test"
    call flavor_init (flv, (/2, 1/), model)
    ! Prepare beams
    call polarization_init_circular (pol(1), flv(1), 0.3_default)
    call polarization_init_unpolarized (pol(2), flv(2))
    call beam_data_init_sqrt (beam_data, 1000._default, flv, pol)
    call strfun_chain_init (sfchain, beam_data, 2, 0)
    ! Initialize EPA for both
    call epa_data_init (epa_data1, model, &
        flv(1), 0.06_default, 1.e-6_default, 0._default, 500._default, &
        511.e-6_default)
    call epa_data_init (epa_data2, model, &
        flv(2), 0.06_default, 1.e-6_default, 1._default, 500._default)
    call strfun_chain_set_strfun (sfchain, 1, 1, epa_data1, 1)
    call strfun_chain_set_strfun (sfchain, 2, 2, epa_data2, 3)
!   call strfun_chain_write (sfchain); stop
    call strfun_chain_make_evaluators (sfchain)
    call strfun_chain_set_kinematics &
        (sfchain, (/0.8_default, 0.4_default, 0.5_default, 0.2_default/))
    call strfun_chain_evaluate (sfchain, 0._default)
    call strfun_chain_write (sfchain)
    ! Clean up
    call beam_data_final (beam_data)
    call polarization_final (pol)
    call strfun_chain_final (sfchain)
end subroutine epa_test

subroutine lhpdf_test (model)
    use flavors
    use polarizations
    type(model_t), intent(in), target :: model
    type(beam_data_t) :: beam_data

```

```

type(flavor_t), dimension(2) :: flv
type(polarization_t), dimension(2) :: pol
type(lhapdf_data_t), dimension(2) :: data
type(lhapdf_status_t) :: lhpdf_status
type(strfun_chain_t), target :: sfchain
real(default) :: scale
print *, "*** LHAPDF test"
call flavor_init (flv, (/ -PROTON, PHOTON /), model)
call polarization_init_unpolarized (pol(1), flv(1))
call polarization_init_unpolarized (pol(2), flv(2))
call beam_data_init_sqrts (beam_data, 2000._default, flv, pol)
call strfun_chain_init (sfchain, beam_data, 2, 0)
call lhpdf_data_init (data(1), lhpdf_status, model, flv(1), member=1)
call lhpdf_data_init (data(2), lhpdf_status, model, flv(2), &
    file=var_str("SASG.LHgrid"), photon_scheme=1)
call lhpdf_data_set_mask (data(2), &
    (/ .false., .false., .false., .true., .true., .true., &
    .false., &
    .true., .true., .true., .false., .false., .false. /))
!   call strfun_chain_write (sfchain); stop
call strfun_chain_set_strfun (sfchain, 1, 1, data(1), 1)
call strfun_chain_set_strfun (sfchain, 2, 2, data(2), 1)
!   call strfun_chain_write (sfchain); stop
call strfun_chain_make_evaluators (sfchain)
call strfun_chain_set_kinematics (sfchain, (/0.9_default, 0.4_default/))
scale = 1.e3_default
call strfun_chain_evaluate (sfchain, scale)
call strfun_chain_write (sfchain)
call strfun_chain_final (sfchain)
end subroutine lhpdf_test

```

Chapter 11

Partonic Events

This chapter deals with and combines the various components (interactions) of a partonic event: beams, spectra, scattering, decays.

Chapter 12

Phase space and hard matrix elements

These modules contain the internal representation and evaluation of phase space and the interface to (hard-)process evaluation.

mappings Generate invariant masses and decay angles from given random numbers (or the inverse operation). Each mapping pertains to a particular node in a phase-space tree. Different mappings account for uniform distributions, resonances, zero-mass behavior, and so on.

phs_trees Phase space parameterizations for scattering processes are defined recursively as if there was an initial particle decaying. This module sets up a representation in terms of abstract trees, where each node gets a unique binary number. Each tree is stored as an array of branches, where integers indicate the connections. This emulates pointers in a transparent way. Real pointers would also be possible, but seem to be less efficient for this particular case.

phs_forests The type defined by this module collects the decay trees corresponding to a given process and the applicable mappings. To set this up, a file is read which is either written by the user or by the **cascades** module functions. The module also contains the routines that evaluate phase space, i.e., generate momenta from random numbers and back.

cascades This module is a Feynman diagram generator with the particular purpose of finding the phase space parameterizations best suited for a given process. It uses a model file to set up the possible vertices, generates all possible diagrams, identifies resonances and singularities, and simplifies the list by merging equivalent diagrams and dropping irrelevant ones. This process can be controlled at several points by user-defined parameters. Note that it depends on the particular values of particle masses, so it cannot be done before reading the input file.

12.1 Mappings

Mappings are objects that encode the transformation of the interval $(0,1)$ to a physical variable m^2 or $\cos\theta$ (and back), as it is used in the phase space parameterization. The mapping objects contain fixed parameters, the associated methods implement the mapping and inverse mapping operations, including the computation of the Jacobian (phase space factor).

```
<mappings.f90>≡  
  <File header>  
  
  module mappings  
  
    <Use kinds>  
    use kinds, only: TC !NODEP!  
    <Use strings>  
    use constants, only: pi !NODEP!  
    <Use file utils>  
    use diagnostics !NODEP!  
    use models  
    use flavors  
  
    <Standard module head>  
  
    <Mappings: public>  
  
    <Mappings: parameters>  
  
    <Mappings: types>  
  
    <Mappings: interfaces>  
  
    contains  
  
    <Mappings: procedures>  
  
  end module mappings
```

12.1.1 Default parameters

This type holds the default parameters, needed for setting the scale in cases where no mass parameter is available. The contents are public.

```
<Mappings: public>≡  
  public :: mapping_defaults_t  
  
<Mappings: types>≡  
  type :: mapping_defaults_t  
    real(default) :: energy_scale = 10  
    real(default) :: invariant_mass_scale = 10  
    real(default) :: momentum_transfer_scale = 10  
  end type mapping_defaults_t
```

12.1.2 The Mapping type

Each mapping has a type (e.g., s-channel, infrared), a binary code (redundant, but useful for debugging), and a reference particle. The flavor code of this particle is stored for bookkeeping reasons, what matters are the mass and width of this particle. Furthermore, depending on the type, various mapping parameters can be set and used.

The parameters **a1** to **a3** (for m^2 mappings) and **b1** to **b3** (for $\cos\theta$ mappings) are values that are stored once to speed up the calculation, if **variable_limits** is false. The exact meaning of these parameters depends on the mapping type. The limits are fixed if there is a fixed c.m. energy.

```

<Mappings: public>+≡
    public :: mapping_t

<Mappings: types>+≡
    type :: mapping_t
    private
        integer :: type = NO_MAPPING
        integer(TC) :: bincode
        type(flavor_t) :: flv
        real(default) :: mass = 0
        real(default) :: width = 0
        logical :: a_unknown = .true.
        real(default) :: a1, a2, a3
        logical :: b_unknown = .true.
        real(default) :: b1, b2, b3
        logical :: variable_limits = .true.
    end type mapping_t

```

The valid mapping types:

```

<Mappings: parameters>≡
    <Mapping modes>

```

12.1.3 Screen output

Do not write empty mappings.

```

<Mappings: public>+≡
    public :: mapping_write

<Mappings: procedures>≡
    subroutine mapping_write (map, unit)
        type(mapping_t), intent(in) :: map
        integer, intent(in), optional :: unit
        integer :: u
        character(len=9) :: str
        u = output_unit (unit); if (u < 0) return
        select case(map%type)
            case(S_CHANNEL); str = "s_channel"
            case(COLLINEAR); str = "collinear"
            case(INFRARED); str = "infrared "
            case(RADIATION); str = "radiation"
            case(T_CHANNEL); str = "t_channel"
            case(U_CHANNEL); str = "u_channel"

```

```

end select
if (map%type /= NO_MAPPING) then
  write (u, '(1x,A,I4,A)') &
    "Branch #", map%bincode, ": " // &
    "Mapping (" // str // ") for particle " // &
    "' ' // char (flavor_get_name (map%flv)) // ' '"
end if
end subroutine mapping_write

```

12.1.4 Define a mapping

The initialization routine sets the mapping type and the particle (binary code and flavor code) for which the mapping applies (e.g., a Z resonance in branch #3). We only need the absolute value of the flavor code.

```

<Mappings: public>+≡
  public :: mapping_init

<Mappings: procedures>+≡
  subroutine mapping_init (mapping, bincode, type, f, model)
    type(mapping_t), intent(inout) :: mapping
    integer(TC), intent(in) :: bincode
    type(string_t), intent(in) :: type
    integer, intent(in) :: f
    type(model_t), intent(in), target :: model
    mapping%bincode = bincode
    select case (char (type))
    case ("s_channel"); mapping%type = S_CHANNEL
    case ("collinear"); mapping%type = COLLINEAR
    case ("infrared"); mapping%type = INFRARED
    case ("radiation"); mapping%type = RADIATION
    case ("t_channel"); mapping%type = T_CHANNEL
    case ("u_channel"); mapping%type = U_CHANNEL
    end select
    call flavor_init (mapping%flv, abs (f), model)
  end subroutine mapping_init

```

This sets the actual mass and width, using a parameter set. Since the auxiliary parameters will only be determined when the mapping is first called, they are marked as unknown.

```

<Mappings: public>+≡
  public :: mapping_set_parameters

<Mappings: procedures>+≡
  subroutine mapping_set_parameters (map, mapping_defaults, variable_limits)
    type(mapping_t), intent(inout) :: map
    type(mapping_defaults_t), intent(in) :: mapping_defaults
    logical, intent(in) :: variable_limits
    if (map%type /= NO_MAPPING) then
      map%mass = flavor_get_mass (map%flv)
      map%width = flavor_get_width (map%flv)
      map%variable_limits = variable_limits
      map%a_unknown = .true.
    end if
  end subroutine mapping_set_parameters

```

```

map%b_unknown = .true.
select case (map%type)
case (S_CHANNEL)
  if (map%mass <= 0) then
    call mapping_write (map)
    call msg_fatal &
      & (" S-channel resonance must have positive mass")
  else if (map%width <= 0) then
    call mapping_write (map)
    call msg_fatal &
      & (" S-channel resonance must have positive width")
  end if
case (RADIATION)
  map%width = max (map%width, mapping_defaults%energy_scale)
case (INFRARED, COLLINEAR)
  map%mass = max (map%mass, mapping_defaults%invariant_mass_scale)
case (T_CHANNEL, U_CHANNEL)
  map%mass = max (map%mass, mapping_defaults%momentum_transfer_scale)
end select
end if
end subroutine mapping_set_parameters

```

12.1.5 Compare mappings

Equality for single mappings and arrays

```

<Mappings: public>+≡
  public :: operator(==)

<Mappings: interfaces>≡
  interface operator(==)
    module procedure mapping_equal
  end interface

<Mappings: procedures>+≡
  function mapping_equal (m1, m2) result (equal)
    type(mapping_t), intent(in) :: m1, m2
    logical :: equal
    if (m1%type == m2%type) then
      select case (m1%type)
      case (NO_MAPPING)
        equal = .true.
      case (S_CHANNEL, RADIATION)
        equal = (m1%mass == m2%mass) .and. (m1%width == m2%width)
      case default
        equal = (m1%mass == m2%mass)
      end select
    else
      equal = .false.
    end if
  end function mapping_equal

```

12.1.6 Mappings of the invariant mass

Inserting an x value between 0 and 1, we want to compute the corresponding invariant mass $m^2(x)$ and the jacobian, aka phase space factor $f(x)$. We also need the reverse operation.

In general, the phase space factor f is defined by

$$\frac{1}{s} \int_{m_{\min}^2}^{m_{\max}^2} dm^2 g(m^2) = \int_0^1 dx \frac{1}{s} \frac{dm^2}{dx} g(m^2(x)) = \int_0^1 dx f(x) g(x), \quad (12.1)$$

where thus

$$f(x) = \frac{1}{s} \frac{dm^2}{dx}. \quad (12.2)$$

With this mapping, a function of the form

$$g(m^2) = c \frac{dx(m^2)}{dm^2} \quad (12.3)$$

is mapped to a constant:

$$\frac{1}{s} \int_{m_{\min}^2}^{m_{\max}^2} dm^2 g(m^2) = \int_0^1 dx f(x) g(m^2(x)) = \int_0^1 dx \frac{c}{s}. \quad (12.4)$$

Here is the mapping routine. Input are the available energy squared s , the limits for m^2 , and the x value. Output are the m^2 value and the phase space factor f .

```

<Mappings: public>+≡
  public :: mapping_compute_msq_from_x

<Mappings: procedures>+≡
  subroutine mapping_compute_msq_from_x (map, s, msq_min, msq_max, msq, f, x)
    type(mapping_t), intent(inout) :: map
    real(default), intent(in) :: s, msq_min, msq_max
    real(default), intent(out) :: msq, f
    real(default), intent(in) :: x
    real(default) :: z, msq0, msq1, tmp
    integer :: type
    type = map%type
    if (s == 0) &
      call msg_fatal (" Applying msq mapping for zero energy")
    select case(type)
    case (NO_MAPPING)
      <Constants for trivial msq mapping>
      <Apply trivial msq mapping>
    case (S_CHANNEL)
      <Constants for s-channel resonance mapping>
      <Apply s-channel resonance mapping>
    case (COLLINEAR, INFRARED, RADIATION)
      <Constants for s-channel pole mapping>
      <Apply s-channel pole mapping>
    case (T_CHANNEL, U_CHANNEL)
      <Constants for t-channel pole mapping>
      <Apply t-channel pole mapping>
    case default

```

```

        call msg_fatal ( " Attempt to apply undefined msq mapping")
    end select
end subroutine mapping_compute_msq_from_x

```

The inverse mapping

```

<Mappings: public>+≡
    public :: mapping_compute_x_from_msq
<Mappings: procedures>+≡
    subroutine mapping_compute_x_from_msq (map, s, msq_min, msq_max, msq, f, x)
        type(mapping_t), intent(inout) :: map
        real(default), intent(in) :: s, msq_min, msq_max
        real(default), intent(in) :: msq
        real(default), intent(out) :: f, x
        real(default) :: msq0, msq1, tmp
        integer :: type
        type = map%type
        if (s == 0) &
            call msg_fatal (" Applying inverse msq mapping for zero energy")
        <Modify mapping type if necessary>
        select case (type)
        case (NO_MAPPING)
            <Constants for trivial msq mapping>
            <Apply inverse trivial msq mapping>
        case (S_CHANNEL)
            <Constants for s-channel resonance mapping>
            <Apply inverse s-channel resonance mapping>
        case (COLLINEAR, INFRARED, RADIATION)
            <Constants for s-channel pole mapping>
            <Apply inverse s-channel pole mapping>
        case (T_CHANNEL, U_CHANNEL)
            <Constants for t-channel pole mapping>
            <Apply inverse t-channel pole mapping>
        case default
            call msg_fatal ( " Attempt to apply undefined msq mapping")
        end select
    end subroutine mapping_compute_x_from_msq

```

Trivial mapping

We simply map the boundaries of the interval (m_{\min}, m_{\max}) to $(0, 1)$:

$$m^2 = (1 - x)m_{\min}^2 + xm_{\max}^2; \quad (12.5)$$

the inverse is

$$x = \frac{m^2 - m_{\min}^2}{m_{\max}^2 - m_{\min}^2}. \quad (12.6)$$

Hence

$$f(x) = \frac{m_{\max}^2 - m_{\min}^2}{s}, \quad (12.7)$$

and we have, as required,

$$f(x) \frac{dx}{dm^2} = \frac{1}{s}. \quad (12.8)$$

We store the constant parameters the first time the mapping is called – or, if limits vary, recompute them each time.

```

⟨Constants for trivial msq mapping⟩≡
  if (map%variable_limits .or. map%a_unknown) then
    map%a1 = 0
    map%a2 = msq_max - msq_min
    map%a3 = map%a2 / s
    map%a_unknown = .false.
  end if

⟨Apply trivial msq mapping⟩≡
  msq = (1-x) * msq_min + x * msq_max
  f = map%a3

⟨Apply inverse trivial msq mapping⟩≡
  if (map%a2 /= 0) then
    x = (msq - msq_min) / map%a2
  else
    x = 0
  end if
  f = map%a3

```

Breit-Wigner mapping

A Breit-Wigner resonance with mass M and width Γ is flattened by the following mapping:

This mapping does not make much sense if the resonance mass is too low. If this is the case, revert to `NO_MAPPING`. There is a tricky point with this if the mass is too high: `msq_max` is not a constant if structure functions are around. However, switching the type depending on the overall energy does not change the integral, it is just another branching point.

$$m^2 = M(M + t\Gamma), \quad (12.9)$$

where

$$t = \tan \left[(1-x) \arctan \frac{m_{\min}^2 - M^2}{M\Gamma} + x \arctan \frac{m_{\max}^2 - M^2}{M\Gamma} \right]. \quad (12.10)$$

The inverse:

$$x = \frac{\arctan \frac{m^2 - M^2}{M\Gamma} - \arctan \frac{m_{\min}^2 - M^2}{M\Gamma}}{\arctan \frac{m_{\max}^2 - M^2}{M\Gamma} - \arctan \frac{m_{\min}^2 - M^2}{M\Gamma}} \quad (12.11)$$

The phase-space factor of this transformation is

$$f(x) = \frac{M\Gamma}{s} \left(\arctan \frac{m_{\max}^2 - M^2}{M\Gamma} - \arctan \frac{m_{\min}^2 - M^2}{M\Gamma} \right) (1 + t^2). \quad (12.12)$$

This maps any function proportional to

$$g(m^2) = \frac{M\Gamma}{(m^2 - M^2)^2 + M^2\Gamma^2} \quad (12.13)$$

to a constant times $1/s$.

```

⟨Constants for s-channel resonance mapping⟩≡

```

```

if (map%variable_limits .or. map%a_unknown) then
  msq0 = map%mass ** 2
  map%a1 = atan ((msq_min - msq0) / (map%mass * map%width))
  map%a2 = atan ((msq_max - msq0) / (map%mass * map%width))
  map%a3 = (map%a2 - map%a1) * (map%mass * map%width) / s
  map%a_unknown = .false.
end if

⟨Apply s-channel resonance mapping⟩≡
z = (1-x) * map%a1 + x * map%a2
if (-pi/2 < z .and. z < pi/2) then
  tmp = tan (z)
  msq = map%mass * (map%mass + map%width * tmp)
  f = map%a3 * (1 + tmp**2)
else
  msq = 0
  f = 0
end if

⟨Apply inverse s-channel resonance mapping⟩≡
tmp = (msq - msq0) / (map%mass * map%width)
x = (atan (tmp) - map%a1) / (map%a2 - map%a1)
f = map%a3 * (1 + tmp**2)

```

Resonance mapping does not make much sense if the resonance mass is outside the kinematical bounds. If this is the case, revert to NO_MAPPING. This is possible even if the kinematical bounds vary from event to event.

```

⟨Modify mapping type if necessary⟩≡
if (type == S_CHANNEL) then
  msq0 = map%mass**2
  if (msq0 < msq_min .or. msq0 > msq_max) type = NO_MAPPING
end if

```

Mapping for massless splittings

This mapping accounts for approximately scale-invariant behavior where $\ln M^2$ is evenly distributed.

$$m^2 = m_{\min}^2 + M^2 (\exp(xL) - 1) \quad (12.14)$$

where

$$L = \ln \left(\frac{m_{\max}^2 - m_{\min}^2}{M^2} + 1 \right). \quad (12.15)$$

The inverse:

$$x = \frac{1}{L} \ln \left(\frac{m^2 - m_{\min}^2}{M^2} + 1 \right) \quad (12.16)$$

The constant M is a characteristic scale. Above this scale ($m^2 - m_{\min}^2 \gg M^2$), this mapping behaves like $x \propto \ln m^2$, while below the scale it reverts to a linear mapping.

The phase-space factor is

$$f(x) = \frac{M^2}{s} \exp(xL) L. \quad (12.17)$$

A function proportional to

$$g(m^2) = \frac{1}{(m^2 - m_{\min}^2) + M^2} \quad (12.18)$$

is mapped to a constant, i.e., a simple pole near m_{\min} with a regulator mass M .

This type of mapping is useful for massless collinear and infrared singularities, where the scale is stored as the mass parameter. In the radiation case (IR radiation off massive particle), the heavy particle width is the characteristic scale.

```

⟨Constants for s-channel pole mapping⟩≡
  if (map%variable_limits .or. map%a_unknown) then
    if (type == RADIATION) then
      msq0 = map%width**2
    else
      msq0 = map%mass**2
    end if
    map%a1 = msq0
    map%a2 = log ((msq_max - msq_min) / msq0 + 1)
    map%a3 = map%a2 / s
    map%a_unknown = .false.
  end if

⟨Apply s-channel pole mapping⟩≡
  msq1 = map%a1 * exp (x * map%a2)
  msq = msq1 - map%a1 + msq_min
  f = map%a3 * msq1

⟨Apply inverse s-channel pole mapping⟩≡
  msq1 = msq - msq_min + map%a1
  x = log (msq1 / map%a1) / map%a2
  f = map%a3 * msq1

```

Mapping for t-channel poles

This is also approximately scale-invariant, and we use the same type of mapping as before. However, we map $1/x$ singularities at both ends of the interval; again, the mapping becomes linear when the distance is less than M^2 :

$$m^2 = \begin{cases} m_{\min}^2 + M^2 (\exp(xL) - 1) & \text{for } 0 < x < \frac{1}{2} \\ m_{\max}^2 - M^2 (\exp((1-x)L) - 1) & \text{for } \frac{1}{2} \leq x < 1 \end{cases} \quad (12.19)$$

where

$$L = 2 \ln \left(\frac{m_{\max}^2 - m_{\min}^2}{2M^2} + 1 \right). \quad (12.20)$$

The inverse:

$$x = \begin{cases} \frac{1}{L} \ln \left(\frac{m^2 - m_{\min}^2}{M^2} + 1 \right) & \text{for } m^2 < (m_{\max}^2 - m_{\min}^2)/2 \\ 1 - \frac{1}{L} \ln \left(\frac{m_{\max}^2 - m^2}{M^2} + 1 \right) & \text{for } m^2 \geq (m_{\max}^2 - m_{\min}^2)/2 \end{cases} \quad (12.21)$$

The phase-space factor is

$$f(x) = \begin{cases} \frac{M^2}{s} \exp(xL) L. & \text{for } 0 < x < \frac{1}{2} \\ \frac{M^2}{s} \exp((1-x)L) L. & \text{for } \frac{1}{2} \leq x < 1 \end{cases} \quad (12.22)$$

A (continuous) function proportional to

$$g(m^2) = \begin{cases} 1/(m^2 - m_{\min}^2) + M^2 & \text{for } m^2 < (m_{\max}^2 - m_{\min}^2)/2 \\ 1/((m_{\max}^2 - m^2) + M^2) & \text{for } m^2 \leq (m_{\max}^2 - m_{\min}^2)/2 \end{cases} \quad (12.23)$$

is mapped to a constant by this mapping, i.e., poles near both ends of the interval.

```

⟨Constants for t-channel pole mapping⟩≡
  if (map%variable_limits .or. map%a_unknown) then
    msq0 = map%mass**2
    map%a1 = msq0
    map%a2 = 2 * log ((msq_max - msq_min)/(2*msq0) + 1)
    map%a3 = map%a2 / s
    map%a_unknown = .false.
  end if

⟨Apply t-channel pole mapping⟩≡
  if (x < .5_default) then
    msq1 = map%a1 * exp (x * map%a2)
    msq = msq1 - map%a1 + msq_min
  else
    msq1 = map%a1 * exp ((1-x) * map%a2)
    msq = -(msq1 - map%a1) + msq_max
  end if
  f = map%a3 * msq1

⟨Apply inverse t-channel pole mapping⟩≡
  if (msq < (msq_max + msq_min)/2) then
    msq1 = msq - msq_min + map%a1
    x = log (msq1/map%a1) / map%a2
  else
    msq1 = msq_max - msq + map%a1
    x = 1 - log (msq1/map%a1) / map%a2
  end if
  f = map%a3 * msq1

```

12.1.7 Mappings of the polar angle

The other type of singularity, a simple pole just outside the integration region, can occur in the integration over $\cos \theta$. This applies to exchange of massless (or light) particles.

Double poles (Coulomb scattering) are also possible, but only in certain cases. These are also handled by the single-pole mapping.

The mapping is analogous to the previous m^2 pole mapping, but with a different normalization and notation of variables:

$$\frac{1}{2} \int_{-1}^1 d \cos \theta g(\theta) = \int_0^1 dx \frac{d \cos \theta}{dx} g(\theta(x)) = \int_0^1 dx f(x) g(x), \quad (12.24)$$

where thus

$$f(x) = \frac{1}{2} \frac{d \cos \theta}{dx}. \quad (12.25)$$

With this mapping, a function of the form

$$g(\theta) = c \frac{dx(\cos \theta)}{d \cos \theta} \quad (12.26)$$

is mapped to a constant:

$$\int_{-1}^1 d \cos \theta g(\theta) = \int_0^1 dx f(x) g(\theta(x)) = \int_0^1 dx c. \quad (12.27)$$

```

<Mappings: public>+≡
  public :: mapping_compute_ct_from_x

<Mappings: procedures>+≡
  subroutine mapping_compute_ct_from_x (map, s, ct, st, f, x)
    type(mapping_t), intent(inout) :: map
    real(default), intent(in) :: s
    real(default), intent(out) :: ct, st, f
    real(default), intent(in) :: x
    real(default) :: tmp, ct1
    select case (map%type)
    case (NO_MAPPING, S_CHANNEL, INFRARED, RADIATION)
      <Apply trivial ct mapping>
    case (T_CHANNEL, U_CHANNEL, COLLINEAR)
      <Constants for ct pole mapping>
      <Apply ct pole mapping>
    case default
      call msg_fatal (" Attempt to apply undefined ct mapping")
    end select
  end subroutine mapping_compute_ct_from_x

<Mappings: public>+≡
  public :: mapping_compute_x_from_ct

<Mappings: procedures>+≡
  subroutine mapping_compute_x_from_ct (map, s, ct, f, x)
    type(mapping_t), intent(inout) :: map
    real(default), intent(in) :: s
    real(default), intent(in) :: ct
    real(default), intent(out) :: f, x
    real(default) :: ct1
    select case (map%type)
    case (NO_MAPPING, S_CHANNEL, INFRARED, RADIATION)
      <Apply inverse trivial ct mapping>
    case (T_CHANNEL, U_CHANNEL, COLLINEAR)
      <Constants for ct pole mapping>
      <Apply inverse ct pole mapping>
    case default
      call msg_fatal (" Attempt to apply undefined inverse ct mapping")
    end select
  end subroutine mapping_compute_x_from_ct

```

Trivial mapping

This is just the mapping of the interval $(-1, 1)$ to $(0, 1)$:

$$\cos \theta = -1 + 2x \quad (12.28)$$

and

$$f(x) = 1 \quad (12.29)$$

with the inverse

$$x = \frac{1 + \cos \theta}{2} \quad (12.30)$$

```

<Apply trivial ct mapping>≡
    tmp = 2 * (1-x)
    ct = 1 - tmp
    st = sqrt (tmp * (2-tmp))
    f = 1

<Apply inverse trivial ct mapping>≡
    x = (ct + 1) / 2
    f = 1

```

Pole mapping

As above for m^2 , we simultaneously map poles at both ends of the $\cos \theta$ interval. The formulae are completely analogous:

$$\cos \theta = \begin{cases} \frac{M^2}{s} [\exp(xL) - 1] - 1 & \text{for } x < \frac{1}{2} \\ -\frac{M^2}{s} [\exp((1-x)L) - 1] + 1 & \text{for } x \geq \frac{1}{2} \end{cases} \quad (12.31)$$

where

$$L = 2 \ln \frac{M^2 + s}{M^2}. \quad (12.32)$$

Inverse:

$$x = \begin{cases} \frac{1}{2L} \ln \frac{1 + \cos \theta + M^2/s}{M^2/s} & \text{for } \cos \theta < 0 \\ 1 - \frac{1}{2L} \ln \frac{1 - \cos \theta + M^2/s}{M^2/s} & \text{for } \cos \theta \geq 0 \end{cases} \quad (12.33)$$

The phase-space factor:

$$f(x) = \begin{cases} \frac{M^2}{s} \exp(xL) L & \text{for } x < \frac{1}{2} \\ \frac{M^2}{s} \exp((1-x)L) L & \text{for } x \geq \frac{1}{2} \end{cases} \quad (12.34)$$

```

<Constants for ct pole mapping>≡
    if (map%variable_limits .or. map%b_unknown) then
        map%b1 = map%mass**2 / s
        map%b2 = log ((map%b1 + 1) / map%b1)
        map%b3 = 0
        map%b_unknown = .false.
    end if

```

```

<Apply ct pole mapping>≡
  if (x < .5_default) then
    ct1 = map%b1 * exp (2 * x * map%b2)
    ct = ct1 - map%b1 - 1
  else
    ct1 = map%b1 * exp (2 * (1-x) * map%b2)
    ct = -(ct1 - map%b1) + 1
  end if
  if (ct >= -1 .and. ct <= 1) then
    st = sqrt (1 - ct**2)
    f = ct1 * map%b2
  else
    ct = 1;  st = 0;  f = 0
  end if

<Apply inverse ct pole mapping>≡
  if (ct < 0) then
    ct1 = ct + map%b1 + 1
    x = log (ct1 / map%b1) / (2 * map%b2)
  else
    ct1 = -ct + map%b1 + 1
    x = 1 - log (ct1 / map%b1) / (2 * map%b2)
  end if
  f = ct1 * map%b2

```

12.2 Phase-space trees

The phase space evaluation is organized in terms of trees, where each branch corresponds to three integrations: m^2 , $\cos\theta$, and ϕ . The complete tree thus makes up a specific parameterization of the multidimensional phase-space integral. For the multi-channel integration, the phase-space tree is a single channel.

The trees imply mappings of formal Feynman tree graphs into arrays of integer numbers: Each branch, corresponding to a particular line in the graph, is assigned an integer code c (with kind value $\text{TC} = \text{tree code}$).

In this integer, each bit determines whether a particular external momentum flows through the line. The external branches therefore have codes 1, 2, 4, 8, ... An internal branch has those bits ORed corresponding to the momenta flowing through it. For example, a branch with momentum $p_1 + p_4$ has code $2^0 + 2^3 = 1 + 8 = 9$.

There is a two-fold ambiguity: Momentum conservation implies that the branch with code

$$c_0 = \sum_{i=1}^{n(\text{ext})} 2^{i-1} \quad (12.35)$$

i.e. the branch with momentum $p_1 + p_2 + \dots p_n$ has momentum zero, which is equivalent to tree code 0 by definition. Correspondingly,

$$c \quad \text{and} \quad c_0 - c = c \text{ XOR } c_0 \quad (12.36)$$

are equivalent. E.g., if there are five externals with codes $c = 1, 2, 4, 8, 16$, then $c = 9$ and $\bar{c} = 31 - 9 = 22$ are equivalent.

This ambiguity may be used to assign a direction to the line: If all momenta are understood as outgoing, $c = 9$ in the example above means $p_1 + p_4$, but $c = 22$ means $p_2 + p_3 + p_5 = -(p_1 + p_4)$.

Here we make use of the ambiguity in a slightly different way. First, the initial particles are singled out as those externals with the highest bits, the IN-bits. (Here: 8 and 16 for a $2 \rightarrow 3$ scattering process, 16 only for a $1 \rightarrow 4$ decay.) Then we invert those codes where all IN-bits are set. For a decay process this maps each tree of an equivalence class onto a unique representative (that one with the smallest integer codes). For a scattering process we proceed further:

The ambiguity remains in all branches where only one IN-bit is set, including the initial particles. If there are only externals with this property, we have an s -channel graph which we leave as it is. In all other cases, an internal with only one IN-bit is a t -channel line, which for phase space integration should be associated with one of the initial momenta as a reference axis. We take that one whose bit is set in the current tree code. (E.g., for branch $c = 9$ we use the initial particle $c = 8$ as reference axis, whereas for the same branch we would take $c = 16$ if it had been assigned $\bar{c} = 31 - 9 = 22$ as tree code.) Thus, different ways of coding the same t -channel graph imply different phase space parameterizations.

s -channel graphs have a unique parameterization. The same sets of parameterizations are used for t -channel graphs, except for the reference frames of their angular parts. We map each t -channel graph onto an s -channel graph as follows:

Working in ascending order, for each t -channel line (whose code has exactly one IN-bit set) the attached initial line is flipped upstream, while the outgoing

line is flipped downstream. (This works only if t -channel graphs are always parameterized beginning at their outer vertices, which we require as a restriction.) After all possible flips have been applied, we have an s -channel graph. We only have to remember the initial particle a vertex was originally attached to.

```

<phs_trees.f90>≡
  <File header>

  module phs_trees

    <Use kinds>
      use kinds, only: TC !NODEP!
    <Use strings>
      use constants, only: twopi, twopi2, twopi5 !NODEP!
    <Use file utils>
      use diagnostics !NODEP!
      use lorentz !NODEP!
      use permutations, only: permutation_t, permutation_size
      use permutations, only: permutation_init, permutation_find
      use permutations, only: tc_decay_level, tc_permute
      use models
      use flavors
      use mappings

    <Standard module head>

    <PHS trees: public>

    <PHS trees: types>

    contains

    <PHS trees: procedures>

  end module phs_trees

```

12.2.1 Particles

We define a particle type which contains only four-momentum and invariant mass squared, and a flag that tells whether the momentum is filled or not.

```

<PHS trees: public>≡
  public :: phs_prt_t

<PHS trees: types>≡
  type :: phs_prt_t
    private
    logical :: defined = .false.
    type(vector4_t) :: p
    real(default) :: p2
  end type phs_prt_t

```

Set contents:

```

<PHS trees: public>+≡
  public :: phs_prt_set_defined

```

```

public :: phs_prt_set_undefined
public :: phs_prt_set_momentum
public :: phs_prt_set_msq

<PHS trees: procedures>≡
elemental subroutine phs_prt_set_defined (prt)
  type(phs_prt_t), intent(inout) :: prt
  prt%defined = .true.
end subroutine phs_prt_set_defined

elemental subroutine phs_prt_set_undefined (prt)
  type(phs_prt_t), intent(inout) :: prt
  prt%defined = .false.
end subroutine phs_prt_set_undefined

elemental subroutine phs_prt_set_momentum (prt, p)
  type(phs_prt_t), intent(inout) :: prt
  type(vector4_t), intent(in) :: p
  prt%p = p
end subroutine phs_prt_set_momentum

elemental subroutine phs_prt_set_msq (prt, p2)
  type(phs_prt_t), intent(inout) :: prt
  real(default), intent(in) :: p2
  prt%p2 = p2
end subroutine phs_prt_set_msq

```

Access methods:

```

<PHS trees: public>+≡
public :: phs_prt_is_defined
public :: phs_prt_get_momentum
public :: phs_prt_get_msq

<PHS trees: procedures>+≡
elemental function phs_prt_is_defined (prt) result (defined)
  logical :: defined
  type(phs_prt_t), intent(in) :: prt
  defined = prt%defined
end function phs_prt_is_defined

elemental function phs_prt_get_momentum (prt) result (p)
  type(vector4_t) :: p
  type(phs_prt_t), intent(in) :: prt
  p = prt%p
end function phs_prt_get_momentum

elemental function phs_prt_get_msq (prt) result (p2)
  real(default) :: p2
  type(phs_prt_t), intent(in) :: prt
  p2 = prt%p2
end function phs_prt_get_msq

```

Addition of momenta (invariant mass square is computed).

```

<PHS trees: public>+≡

```

```

public :: phs_prt_combine
<PHS trees: procedures>+≡
elemental subroutine phs_prt_combine (prt, prt1, prt2)
  type(phs_prt_t), intent(inout) :: prt
  type(phs_prt_t), intent(in) :: prt1, prt2
  prt%defined = .true.
  prt%p = prt1%p + prt2%p
  prt%p2 = prt%p ** 2
end subroutine phs_prt_combine

```

Output

```

<PHS trees: public>+≡
public :: phs_prt_write
<PHS trees: procedures>+≡
subroutine phs_prt_write (prt, unit)
  type(phs_prt_t), intent(in) :: prt
  integer, intent(in), optional :: unit
  integer :: u
  u = output_unit (unit); if (u < 0) return
  if (prt%defined) then
    call vector4_write (prt%p, u)
    write (u, *) "M2 =", prt%p2
  else
    write (u, *) "[undefined]"
  end if
end subroutine phs_prt_write

```

12.2.2 The phase-space tree type

Definition

In the concrete implementation, each branch c may have two *daughters* c_1 and c_2 such that $c_1 + c_2 = c$, a *sibling* c_s and a *mother* c_m such that $c + c_s = c_m$, and a *friend* which is kept during flips, such that it can indicate a fixed reference frame. Absent entries are set $c = 0$.

First, declare the branch type. There is some need to have this public. Give initializations for all components, so no `init` routine is necessary. The branch has some information about the associated coordinates and about connections.

```

<PHS trees: types>+≡
type :: phs_branch_t
  private
  logical :: set = .false.
  logical :: inverted_decay = .false.
  logical :: inverted_axis = .false.
  integer(TC) :: mother = 0
  integer(TC) :: sibling = 0
  integer(TC) :: friend = 0
  integer(TC) :: origin = 0
  integer(TC), dimension(2) :: daughter = 0
  integer :: firstborn = 0

```

```

        logical :: has_children = .false.
        logical :: has_friend = .false.
    end type phs_branch_t

```

The tree type: No initialization, this is done by `phs_tree_init`. In addition to the branch array which

The branches are collected in an array which holds all possible branches, of which only a few are set. After flips have been applied, the branch $c_M = \sum_{i=1}^{n(\text{fin})} 2^{i-1}$ must be there, indicating the mother of all decay products. In addition, we should check for consistency at the beginning.

`n_branches` is the number of those actually set. `n externals` defines the number of significant bit, and `mask` is a code where all bits are set. Analogous: `n_in` and `mask_in` for the incoming particles.

The mapping array contains the mappings associated to the branches (corresponding indices). The array `mass_sum` contains the sum of the real masses of the external final-state particles associated to the branch. During phase-space evaluation, this determines the boundaries.

```

<PHS trees: public>+≡
    public :: phs_tree_t

<PHS trees: types>+≡
    type :: phs_tree_t
    private
        integer :: n_branches, n externals, n_in, n_msq, n_angles
        integer(TC) :: n_branches_tot, n_branches_out
        integer(TC) :: mask, mask_in, mask_out
        type(phs_branch_t), dimension(:), allocatable :: branch
        type(mapping_t), dimension(:), allocatable :: mapping
        real(default), dimension(:), allocatable :: mass_sum
    end type phs_tree_t

```

The maximum number of external particles that can be represented is related to the bit size of the integer that stores binary codes. With the default integer of 32 bit on common machines, this is more than enough space. If TC is actually the default integer kind, there is no need to keep it separate, but doing so marks this as a special type of integer. So, just state that the maximum number is 32:

```

<Limits: public parameters>+≡
    integer, parameter, public :: MAX_EXTERNAL = 32

```

Constructor and destructor

Allocate memory for a phase-space tree with given number of externals and incoming. The number of allocated branches can easily become large, but appears manageable for realistic cases, e.g., for `n_in=2` and `n_out=8` we get $2^{10} - 1 = 1023$.

```

<PHS trees: public>+≡
    public :: phs_tree_init
    public :: phs_tree_final

```

Here we set the masks for incoming and for all externals.

```

<PHS trees: procedures>+≡
elemental subroutine phs_tree_init (tree, n_in, n_out, n_masses, n_angles)
  type(phs_tree_t), intent(inout) :: tree
  integer, intent(in) :: n_in, n_out, n_masses, n_angles
  integer(TC) :: i
  tree%n_externals = n_in + n_out
  tree%n_branches_tot = 2**(n_in+n_out) - 1
  tree%n_branches_out = 2**n_out - 1
  tree%mask = 0
  do i = 0, n_in + n_out - 1
    tree%mask = ibset (tree%mask, i)
  end do
  tree%n_in = n_in
  tree%mask_in = 0
  do i = n_out, n_in + n_out - 1
    tree%mask_in = ibset (tree%mask_in, i)
  end do
  tree%mask_out = ieor (tree%mask, tree%mask_in)
  tree%n_msq = n_masses
  tree%n_angles = n_angles
  allocate (tree%branch (tree%n_branches_tot))
  tree%n_branches = 0
  allocate (tree%mapping (tree%n_branches_out))
  allocate (tree%mass_sum (tree%n_branches_out))
end subroutine phs_tree_init

elemental subroutine phs_tree_final (tree)
  type(phs_tree_t), intent(inout) :: tree
  deallocate (tree%branch)
  deallocate (tree%mapping)
  deallocate (tree%mass_sum)
end subroutine phs_tree_final

```

Screen output

Write only the branches that are set:

```

<PHS trees: public>+≡
public :: phs_tree_write

<PHS trees: procedures>+≡
subroutine phs_tree_write (tree, unit)
  type(phs_tree_t), intent(in) :: tree
  integer, intent(in), optional :: unit
  integer :: u
  integer(TC) :: k
  u = output_unit (unit); if (u < 0) return
  write (u,'(1X,A,I2,5X,A,I3)') &
    'External:', tree%n_externals, 'Mask:', tree%mask
  write (u,'(1X,A,I2,5X,A,I3)') &
    'Incoming:', tree%n_in, 'Mask:', tree%mask_in
  write (u,'(1X,A,I2,5X,A,I3)') &
    'Branches:', tree%n_branches

```

```

do k = size (tree%branch), 1, -1
  if (tree%branch(k)%set) &
    call phs_branch_write (tree%branch(k), unit=unit, kval=k)
end do
do k = 1, size (tree%mapping)
  call mapping_write (tree%mapping (k), unit)
end do
do k = 1, size (tree%mass_sum)
  if (tree%branch(k)%set) then
    write (u, *) k, "mass_sum =", tree%mass_sum(k)
  end if
end do
end subroutine phs_tree_write

subroutine phs_branch_write (b, unit, kval)
  type(phs_branch_t), intent(in) :: b
  integer, intent(in), optional :: unit
  integer(TC), intent(in), optional :: kval
  integer :: u
  integer(TC) :: k
  character(len=6) :: tmp
  character(len=1) :: firstborn(2), sign_decay, sign_axis
  integer :: i
  u = output_unit (unit); if (u < 0) return
  k = 0; if (present (kval)) k = kval
  if (b%origin /= 0) then
    write(tmp, '(A,I4,A)') '(', b%origin, ')'
  else
    tmp = ' '
  end if
  do i=1, 2
    if (b%firstborn == i) then
      firstborn(i) = "*"
    else
      firstborn(i) = " "
    end if
  end do
  if (b%inverted_decay) then
    sign_decay = "-"
  else
    sign_decay = "+"
  end if
  if (b%inverted_axis) then
    sign_axis = "-"
  else
    sign_axis = "+"
  end if
  if (b%has_children) then
    if (b%has_friend) then
      write(u, '(1X,A,I4,1x,A,2X,A,I4,A,I4,A,2X,A,3X,A,I4)') &
        & ' ', k, tmp, &
        & 'Daughters: ', &
        & b%daughter(1), firstborn(1), &
        & b%daughter(2), firstborn(2), sign_decay, &

```

```

        & 'Friend: ', b%friend
    else
        write(u, '(1X,A,I4,1x,A,2X,A,I4,A,I4,A,2X,A,2X,A)') &
            & '*', k, tmp, &
            & 'Daughters: ', &
            & b%daughter(1), firstborn(1), &
            & b%daughter(2), firstborn(2), sign_decay, &
            & '(axis '//sign_axis//')'
    end if
else
    write(u, '(2X,I4,3X,A,I4,I4)') k
end if
end subroutine phs_branch_write

```

12.2.3 PHS tree setup

Transformation into an array of branch codes and back

Assume that the tree/array has been created before with the appropriate length and is empty.

```

<PHS trees: public>+≡
    public :: phs_tree_from_array

<PHS trees: procedures>+≡
    subroutine phs_tree_from_array (tree, a)
        type(phs_tree_t), intent(inout) :: tree
        integer(TC), dimension(:), intent(in) :: a
        integer :: i
        integer(TC) :: k
        <Set branches from array a>
        <Set external branches if necessary>
        <Check number of branches>
        <Determine the connections>
        contains
        <Subroutine: set relatives>
    end subroutine phs_tree_from_array

```

First, set all branches specified by the user. If all IN-bits are set, we invert the branch code.

```

<Set branches from array a>≡
    do i=1, size(a)
        k = a(i)
        if (iand(k, tree%mask_in) == tree%mask_in) k = ieor(tree%mask, k)
        tree%branch(k)%set = .true.
        tree%n_branches = tree%n_branches+1
    end do

```

The external branches are understood, so set them now if not yet done. In all cases ensure that the representative with one bit set is used, except for decays where the in-particle is represented by all OUT-bits set instead.

```

<Set external branches if necessary>≡
    do i=0, tree%n externals-1

```

```

k = ibset(0,i)
if (iand(k, tree%mask_in) == tree%mask_in) k = ieor(tree%mask, k)
if (tree%branch(ieor(tree%mask, k))%set) then
  tree%branch(ieor(tree%mask, k))%set = .false.
  tree%branch(k)%set = .true.
else if (.not.tree%branch(k)%set) then
  tree%branch(k)%set = .true.
  tree%n_branches = tree%n_branches+1
end if
end do

```

Now the number of branches set can be checked. Here we assume that the tree is binary. For three externals there are three branches in total, and for each additional external branch we get another internal one.

```

<Check number of branches>≡
  if (tree%n_branches /= tree%n_externals*2-3) then
    call phs_tree_write (tree)
    call msg_bug &
      & (" Wrong number of branches set in phase space tree")
  end if

```

For all branches that are set, except for the externals, we try to find the daughter branches:

```

<Determine the connections>≡
  do k=1, size (tree%branch)
    if (tree%branch(k)%set .and. tc_decay_level (k) /= 1) then
      call branch_set_relatives(k)
    end if
  end do

```

To this end, we scan all codes less than the current code, whether we can find two branches which are set and which together give the current code. After that, the tree may still not be connected, but at least we know if a branch does not have daughters: This indicates some inconsistency.

The algorithm ensures that, at this stage, the first daughter has a smaller code value than the second one.

```

<Subroutine: set relatives>≡
  subroutine branch_set_relatives (k)
    integer(TC), intent(in) :: k
    integer(TC) :: m,n
    do m=1, k-1
      if(iand(k,m)==m) then
        n = ieor(k,m)
        if ( tree%branch(m)%set .and. tree%branch(n)%set ) then
          tree%branch(k)%daughter(1) = m; tree%branch(k)%daughter(2) = n
          tree%branch(m)%mother      = k; tree%branch(n)%mother      = k
          tree%branch(m)%sibling     = n; tree%branch(n)%sibling     = m
          tree%branch(k)%has_children = .true.
        end if
      end if
    end do
    call phs_tree_write (tree)
    call msg_bug &
      & (" Missing daughter branch(es) in phase space tree")
  end subroutine

```

```
end subroutine branch_set_relatives
```

The inverse: this is trivial, fortunately.

Flip t -channel into s -channel

Flipping the tree is done upwards, beginning from the decay products. First we select a t -channel branch k : one which is set, which does have an IN-bit, and which is not an external particle.

Next, we determine the adjacent in-particle (called the 'friend' f here, since it will provide the reference axis for the angular integration). In addition, we look for the 'mother' and 'sibling' of this particle. If the latter field is empty, we select the (unique) other out-particle which has no mother, calling the internal subroutine `find_orphan`.

The flip is done as follows: We assume that the first daughter d is an s -channel line, which is true if the daughters are sorted. This will stay the first daughter. The second one is a t -channel line; it is exchanged with the 'sibling' s . The new line which replaces the branch k is just the sum of s and d . In addition, we have to rearrange the relatives of s and d , as well of f .

Finally, we flip 'sibling' and 'friend' and set the new s -channel branch n which replaces the t -channel branch k . After this is complete, we are ready to execute another flip.

[Although the friend is not needed for the final flip, since it would be an initial particle anyway, we need to know whether we have t - or u -channel.]

```
<PHS trees: public>+≡
  public :: phs_tree_flip_t_to_s_channel

<PHS trees: procedures>+≡
  subroutine phs_tree_flip_t_to_s_channel (tree)
    type(phs_tree_t), intent(inout) :: tree
    integer(TC) :: k, f, m, n, d, s
    if (tree%n_in == 2) then
      FLIP: do k=3, tree%mask-1
        if (.not. tree%branch(k)%set) cycle FLIP
        f = iand(k,tree%mask_in)
        if (f==0 .or. f==k) cycle FLIP
        m = tree%branch(k)%mother
        s = tree%branch(k)%sibling
        if (s==0) call find_orphan(s)
        d = tree%branch(k)%daughter(1)
        n = ior(d,s)
        tree%branch(k)%set = .false.
        tree%branch(n)%set = .true.
        tree%branch(n)%origin = k
        tree%branch(n)%daughter(1) = d; tree%branch(d)%mother = n
        tree%branch(n)%daughter(2) = s; tree%branch(s)%mother = n
        tree%branch(n)%has_children = .true.
        tree%branch(d)%sibling = s; tree%branch(s)%sibling = d
        tree%branch(n)%sibling = f; tree%branch(f)%sibling = n
        tree%branch(n)%mother = m
        tree%branch(f)%mother = m
        if (m/=0) then
```

```

        tree%branch(m)%daughter(1) = n
        tree%branch(m)%daughter(2) = f
    end if
    tree%branch(n)%friend = f
    tree%branch(n)%has_friend = .true.
    tree%branch(n)%firstborn = 2
end do FLIP
end if
contains
    subroutine find_orphan(s)
        integer(TC) :: s
        do s=1, tree%mask_out
            if (tree%branch(s)%set .and. tree%branch(s)%mother==0) return
        end do
        call phs_tree_write (tree)
        call msg_bug (" Can't flip phase space tree to channel")
    end subroutine find_orphan
end subroutine phs_tree_flip_t_to_s_channel

```

After the tree has been flipped, one may need to determine what has become of a particular t -channel branch. This function gives the bincode of the flipped tree. If the original bincode does not contain IN-bits, we leave it as it is.

```

<PHS trees: procedures>+≡
function tc_flipped (tree, kt) result (ks)
    type(phs_tree_t), intent(in) :: tree
    integer(TC), intent(in) :: kt
    integer(TC) :: ks
    if (iand (kt, tree%mask_in) == 0) then
        ks = kt
    else
        ks = tree%branch(iand (kt, tree%mask_out))%mother
    end if
end function tc_flipped

```

Scan a tree and make sure that the first daughter has always a smaller code than the second one. Furthermore, delete any `friend` entry in the root branch – this branching has the incoming particle direction as axis anyway. Keep track of reordering by updating `inverted_axis`, `inverted_decay` and `firstborn`.

```

<PHS trees: public>+≡
    public :: phs_tree_canonicalize

<PHS trees: procedures>+≡
    subroutine phs_tree_canonicalize (tree)
        type(phs_tree_t), intent(inout) :: tree
        integer :: n_out
        integer(TC) :: k_out
        call branch_canonicalize (tree%branch(tree%mask_out))
        n_out = tree%n_externals - tree%n_in
        k_out = tree%mask_out
        if (tree%branch(k_out)%has_friend &
            & .and. tree%branch(k_out)%friend == ibset (0, n_out)) then
            tree%branch(k_out)%inverted_axis = .not.tree%branch(k_out)%inverted_axis
        end if
    end subroutine

```

```

tree%branch(k_out)%has_friend = .false.
tree%branch(k_out)%friend = 0
contains
recursive subroutine branch_canonicalize (b)
  type(phs_branch_t), intent(inout) :: b
  integer(TC) :: d1, d2
  if (b%has_children) then
    d1 = b%daughter(1)
    d2 = b%daughter(2)
    if (d1 > d2) then
      b%daughter(1) = d2
      b%daughter(2) = d1
      b%inverted_decay = .not.b%inverted_decay
      if (b%firstborn /= 0) b%firstborn = 3 - b%firstborn
    end if
    call branch_canonicalize (tree%branch(b%daughter(1)))
    call branch_canonicalize (tree%branch(b%daughter(2)))
  end if
end subroutine branch_canonicalize
end subroutine phs_tree_canonicalize

```

Mappings

Initialize a mapping for the current tree. This is done while reading from file, so the mapping parameters are read, but applied to the flipped tree. Thus, the size of the array of mappings is given by the number of outgoing particles only.

```

<PHS trees: public>+≡
  public :: phs_tree_init_mapping

<PHS trees: procedures>+≡
  subroutine phs_tree_init_mapping (tree, k, type, pdg, model)
    type(phs_tree_t), intent(inout) :: tree
    integer(TC), intent(in) :: k
    type(string_t), intent(in) :: type
    integer, intent(in) :: pdg
    type(model_t), intent(in), target :: model
    integer(TC) :: kk
    kk = tc_flipped (tree, k)
    call mapping_init (tree%mapping(kk), kk, type, pdg, model)
  end subroutine phs_tree_init_mapping

```

Set the physical parameters for the mapping, using a specific parameter set. Also set the mass sum array.

```

<PHS trees: public>+≡
  public :: phs_tree_set_mapping_parameters

<PHS trees: procedures>+≡
  subroutine phs_tree_set_mapping_parameters &
    (tree, mapping_defaults, variable_limits)
    type(phs_tree_t), intent(inout) :: tree
    type(mapping_defaults_t), intent(in) :: mapping_defaults
    logical, intent(in) :: variable_limits
    integer(TC) :: k

```

```

do k = 1, tree%n_branches_out
  call mapping_set_parameters &
    (tree%mapping(k), mapping_defaults, variable_limits)
end do
end subroutine phs_tree_set_mapping_parameters

```

Kinematics

Fill the mass sum array, starting from the external particles and working down to the tree root. For each bincode k we scan the bits in k ; if only one is set, we take the physical mass of the corresponding external particle; if more than one is set, we sum up the two masses (which we know have already been set).

```

<PHS trees: public>+≡
  public :: phs_tree_set_mass_sum

<PHS trees: procedures>+≡
  subroutine phs_tree_set_mass_sum (tree, flv)
    type(phs_tree_t), intent(inout) :: tree
    type(flavor_t), dimension(:), intent(in) :: flv
    integer(TC) :: k
    integer :: i
    tree%mass_sum = 0
    do k = 1, tree%n_branches_out
      do i = 0, size (flv) - 1
        if (btest(k,i)) then
          if (ibclr(k,i) == 0) then
            tree%mass_sum(k) = flavor_get_mass (flv(i+1))
          else
            tree%mass_sum(k) = &
              tree%mass_sum(ibclr(k,i)) + tree%mass_sum(ibset(0,i))
          end if
        end if
      end do
    end do
  end subroutine phs_tree_set_mass_sum

```

Structural comparison

This function allows to check whether one tree is the permutation of another one. The permutation is applied to the second tree in the argument list. We do not make up a temporary permuted tree, but compare the two trees directly. The branches are scanned recursively, where for each daughter we check the friend and the mapping as well. Once a discrepancy is found, the recursion is exited immediately.

```

<PHS trees: public>+≡
  public :: phs_tree_equivalent

<PHS trees: procedures>+≡
  function phs_tree_equivalent (t1, t2, perm) result (is_equal)
    type(phs_tree_t), intent(in) :: t1, t2

```

```

type(permutation_t), intent(in) :: perm
logical :: equal, is_equal
integer(TC) :: k1, k2, mask_in
k1 = t1%mask_out
k2 = t2%mask_out
mask_in = t1%mask_in
equal = .true.
call check (t1%branch(k1), t2%branch(k2), k1, k2)
is_equal = equal
contains
recursive subroutine check (b1, b2, k1, k2)
  type(phs_branch_t), intent(in) :: b1, b2
  integer(TC), intent(in) :: k1, k2
  integer(TC), dimension(2) :: d1, d2, pd2
  integer :: i
  if (.not.b1%has_friend .and. .not.b2%has_friend) then
    equal = .true.
  else if (b1%has_friend .and. b2%has_friend) then
    equal = (b1%friend == tc_permute (b2%friend, perm, mask_in))
  end if
  if (equal) then
    if (b1%has_children .and. b2%has_children) then
      d1 = b1%daughter
      d2 = b2%daughter
      do i=1, 2
        pd2(i) = tc_permute (d2(i), perm, mask_in)
      end do
      if (d1(1)==pd2(1) .and. d1(2)==pd2(2)) then
        equal = (b1%firstborn == b2%firstborn)
        if (equal) call check &
          & (t1%branch(d1(1)), t2%branch(d2(1)), d1(1), d2(1))
        if (equal) call check &
          & (t1%branch(d1(2)), t2%branch(d2(2)), d1(2), d2(2))
      else if (d1(1)==pd2(2) .and. d1(2)==pd2(1)) then
        equal = ( (b1%firstborn == 0 .and. b2%firstborn == 0) &
          & .or. (b1%firstborn == 3 - b2%firstborn) )
        if (equal) call check &
          & (t1%branch(d1(1)), t2%branch(d2(2)), d1(1), d2(2))
        if (equal) call check &
          & (t1%branch(d1(2)), t2%branch(d2(1)), d1(2), d2(1))
      else
        equal = .false.
      end if
    end if
  end if
  if (equal) then
    equal = (t1%mapping(k1) == t2%mapping(k2))
  end if
end subroutine check
end function phs_tree_equivalent

```

Scan two decay trees and determine the correspondence of mass variables, i.e., the permutation that transfers the ordered list of mass variables belonging to

the second tree into the first one. Mass variables are assigned beginning from branches and ending at the root.

<PHS trees: public>+≡

```
public :: phs_tree_find_msq_permutation
```

<PHS trees: procedures>+≡

```
subroutine phs_tree_find_msq_permutation (tree1, tree2, perm2, msq_perm)
  type(phs_tree_t), intent(in) :: tree1, tree2
  type(permutation_t), intent(in) :: perm2
  type(permutation_t), intent(out) :: msq_perm
  type(permutation_t) :: perm1
  integer(TC) :: mask_in, root
  integer(TC), dimension(:), allocatable :: index1, index2
  integer :: i
  allocate (index1 (tree1%n_msq), index2 (tree2%n_msq))
  call permutation_init (perm1, permutation_size (perm2))
  mask_in = tree1%mask_in
  root = tree1%mask_out
  i = 0
  call tree_scan (tree1, root, perm1, index1)
  i = 0
  call tree_scan (tree2, root, perm2, index2)
  call permutation_find (msq_perm, index1, index2)
contains
  recursive subroutine tree_scan (tree, k, perm, index)
    type(phs_tree_t), intent(in) :: tree
    integer(TC), intent(in) :: k
    type(permutation_t), intent(in) :: perm
    integer, dimension(:), intent(inout) :: index
    if (tree%branch(k)%has_children) then
      call tree_scan (tree, tree%branch(k)%daughter(1), perm, index)
      call tree_scan (tree, tree%branch(k)%daughter(2), perm, index)
      i = i + 1
      if (i <= size (index)) index(i) = tc_permute (k, perm, mask_in)
    end if
  end subroutine tree_scan
end subroutine phs_tree_find_msq_permutation
```

<PHS trees: public>+≡

```
public :: phs_tree_find_angle_permutation
```

<PHS trees: procedures>+≡

```
subroutine phs_tree_find_angle_permutation &
  (tree1, tree2, perm2, angle_perm, sig2)
  type(phs_tree_t), intent(in) :: tree1, tree2
  type(permutation_t), intent(in) :: perm2
  type(permutation_t), intent(out) :: angle_perm
  logical, dimension(:), allocatable, intent(out) :: sig2
  type(permutation_t) :: perm1
  integer(TC) :: mask_in, root
  integer(TC), dimension(:), allocatable :: index1, index2
  logical, dimension(:), allocatable :: sig1
  integer :: i
  allocate (index1 (tree1%n_angles), index2 (tree2%n_angles))
  allocate (sig1 (tree1%n_angles), sig2 (tree2%n_angles))
```

```

call permutation_init (perm1, permutation_size (perm2))
mask_in = tree1%mask_in
root = tree1%mask_out
i = 0
call tree_scan (tree1, root, perm1, index1, sig1)
i = 0
call tree_scan (tree2, root, perm2, index2, sig2)
call permutation_find (angle_perm, index1, index2)
contains
recursive subroutine tree_scan (tree, k, perm, index, sig)
  type(phs_tree_t), intent(in) :: tree
  integer(TC), intent(in) :: k
  type(permutation_t), intent(in) :: perm
  integer, dimension(:), intent(inout) :: index
  logical, dimension(:), intent(inout) :: sig
  integer(TC) :: k1, k2, kp
  logical :: s
  if (tree%branch(k)%has_children) then
    k1 = tree%branch(k)%daughter(1)
    k2 = tree%branch(k)%daughter(2)
    s = (tc_permute(k1, perm, mask_in) < tc_permute(k2, perm, mask_in))
    kp = tc_permute (k, perm, mask_in)
    i = i + 1
    index(i) = kp
    sig(i) = s
    i = i + 1
    index(i) = - kp
    sig(i) = s
    call tree_scan (tree, k1, perm, index, sig)
    call tree_scan (tree, k2, perm, index, sig)
  end if
end subroutine tree_scan
end subroutine phs_tree_find_angle_permutation

```

12.2.4 Phase-space evaluation

Determine momenta

This is done in two steps: First the masses are determined. This step may fail, in which case `ok` is set to false. If successful, we generate angles and the actual momenta. The array `decay_p` serves for transferring the individual three-momenta of the daughter particles in their mother rest frame from the mass generation to the momentum generation step.

```

<PHS trees: public>+≡
  public :: phs_tree_compute_momenta_from_x

<PHS trees: procedures>+≡
  subroutine phs_tree_compute_momenta_from_x &
    (tree, prt, factor, volume, sqrts, x, ok)
    type(phs_tree_t), intent(inout) :: tree
    type(phs_prt_t), dimension(:), intent(inout) :: prt
    real(default), intent(out) :: factor, volume
    real(default), intent(in) :: sqrts

```

```

real(default), dimension(:), intent(in) :: x
logical, intent(out) :: ok
real(default), dimension(tree%mask_out) :: decay_p
integer :: n1, n2
n1 = tree%n_msq
n2 = n1 + tree%n_angles
call phs_tree_set_msq &
    (tree, prt, factor, volume, decay_p, sqrts, x(1:n1), ok)
if (ok) call phs_tree_set_angles &
    (tree, prt, factor, decay_p, sqrts, x(n1+1:n2))
end subroutine phs_tree_compute_momenta_from_x

```

Mass generation is done recursively. The `ok` flag causes the filled tree to be discarded if set to `.false.`. This happens if a three-momentum turns out to be imaginary, indicating impossible kinematics. The index `ix` tells us how far we have used up the input array `x`.

(PHS trees: procedures)+≡

```

subroutine phs_tree_set_msq &
    (tree, prt, factor, volume, decay_p, sqrts, x, ok)
type(phs_tree_t), intent(inout) :: tree
type(phs_prt_t), dimension(:), intent(inout) :: prt
real(default), intent(out) :: factor, volume
real(default), dimension(:), intent(out) :: decay_p
real(default), intent(in) :: sqrts
real(default), dimension(:), intent(in) :: x
logical, intent(out) :: ok
integer :: ix
integer(TC) :: k
real(default) :: m_tot
ok = .true.
ix = 1
k = tree%mask_out
m_tot = tree%mass_sum(k)
decay_p(k) = 0.
if (m_tot < sqrts .or. k == 1) then
    if (tree%branch(k)%has_children) then
        call set_msq_x (tree%branch(k), k, factor, volume, .true.)
    else
        factor = 1
        volume = 1
    end if
else
    ok = .false.
end if
contains
recursive subroutine set_msq_x (b, k, factor, volume, initial)
type(phs_branch_t), intent(in) :: b
integer(TC), intent(in) :: k
real(default), intent(out) :: factor, volume
logical, intent(in) :: initial
real(default) :: msq, m, m_min, m_max, m1, m2, msq1, msq2, lda, rlda
integer(TC) :: k1, k2
real(default) :: f1, f2, v1, v2

```

```

k1 = b%daughter(1); k2 = b%daughter(2)
if (tree%branch(k1)%has_children) then
  call set_msq_x (tree%branch(k1), k1, f1, v1, .false.)
  if (.not.ok) return
else
  f1 = 1; v1 = 1
end if
if (tree%branch(k2)%has_children) then
  call set_msq_x (tree%branch(k2), k2, f2, v2, .false.)
  if (.not.ok) return
else
  f2 = 1; v2 = 1
end if
m_min = tree%mass_sum(k)
if (initial) then
  msq = sqrts**2
  m = sqrts
  m_max = sqrts
  factor = f1 * f2
  volume = v1 * v2 / (4 * twopi5)
else
  m_max = sqrts - m_tot + m_min
  call mapping_compute_msq_from_x &
    (tree%mapping(k), sqrts**2, m_min**2, m_max**2, msq, factor, &
    x(ix)); ix = ix + 1
  if (msq >= 0) then
    m = sqrt (msq)
    factor = f1 * f2 * factor
    volume = v1 * v2 * sqrts**2 / (4 * twopi2)
    call phs_prt_set_msq (prt(k), msq)
    call phs_prt_set_defined (prt(k))
  else
    ok = .false.
  end if
end if
if (ok) then
  msq1 = phs_prt_get_msq (prt(k1)); m1 = sqrt (msq1)
  msq2 = phs_prt_get_msq (prt(k2)); m2 = sqrt (msq2)
  lda = lambda (msq, msq1, msq2)
  if (lda > 0 .and. m > m1 + m2 .and. m <= m_max) then
    rlda = sqrt (lda)
    decay_p(k1) = rlda / (2*m)
    decay_p(k2) = - decay_p(k1)
    factor = rlda / msq * factor
  else
    ok = .false.
  end if
end if
end subroutine set_msq_x
end subroutine phs_tree_set_msq

```

The heart of phase space generation: Now we have the invariant masses, let us generate angles. At each branch, we take a Lorentz transformation and augment it by a boost to the current particle rest frame, and by rotations ϕ and

θ around the z and y axis, respectively. This transformation is passed down to the daughter particles, if present.

(*PHS trees: procedures*) \equiv

```

subroutine phs_tree_set_angles (tree, prt, factor, decay_p, sqrts, x)
  type(phs_tree_t), intent(inout) :: tree
  type(phs_prt_t), dimension(:), intent(inout) :: prt
  real(default), intent(inout) :: factor
  real(default), dimension(:), intent(in) :: decay_p
  real(default), intent(in) :: sqrts
  real(default), dimension(:), intent(in) :: x
  integer :: ix
  integer(TC) :: k
  ix = 1
  k = tree%mask_out
  call set_angles_x (tree%branch(k), k)
contains
recursive subroutine set_angles_x (b, k, L0)
  type(phs_branch_t), intent(in) :: b
  integer(TC), intent(in) :: k
  type(lorentz_transformation_t), intent(in), optional :: L0
  real(default) :: m, msq, ct, st, phi, f, E, p, bg
  type(lorentz_transformation_t) :: L, LL
  integer(TC) :: k1, k2
  type(vector3_t) :: axis
  p = decay_p(k)
  msq = phs_prt_get_msq (prt(k)); m = sqrt (msq)
  E = sqrt (msq + p**2)
  if (present (L0)) then
    call phs_prt_set_momentum (prt(k), L0 * vector4_moving (E,p,3))
  else
    call phs_prt_set_momentum (prt(k), vector4_moving (E,p,3))
  end if
  call phs_prt_set_defined (prt(k))
  if (b%has_children) then
    k1 = b%daughter(1)
    k2 = b%daughter(2)
    if (m > 0) then
      bg = p / m
    else
      bg = 0
    end if
    phi = x(ix) * twopi; ix = ix + 1
    call mapping_compute_ct_from_x &
      (tree%mapping(k), sqrts**2, ct, st, f, x(ix)); ix = ix + 1
    factor = factor * f
    if (.not. b%has_friend) then
!      L = boost (bg,3) * rotation (phi,3) * rotation (ct,st,2)
      L = LT_compose_r2_r3_b3 (ct, st, cos(phi), sin(phi), bg)
    else
      LL = boost (-bg,3); if (present (L0)) LL = LL * inverse(L0)
      axis = space_part ( &
        LL * phs_prt_get_momentum (prt(tree%branch(k)%friend)) )
      L = boost(bg,3) * rotation_to_2nd (vector3_canonical(3), axis) &
!        & * rotation(phi,3) * rotation(ct,st,2)

```

```

        * LT_compose_r2_r3_b3 (ct, st, cos(phi), sin(phi), 0._default)
    end if
    if (present (L0)) L = L0 * L
    call set_angles_x (tree%branch(k1), k1, L)
    call set_angles_x (tree%branch(k2), k2, L)
end if
end subroutine set_angles_x
end subroutine phs_tree_set_angles

```

Recover random numbers

For the other channels we want to compute the random numbers that would have generated the momenta that we already know.

```

<PHS trees: public>+≡
    public :: phs_tree_compute_x_from_momenta

<PHS trees: procedures>+≡
    subroutine phs_tree_compute_x_from_momenta (tree, prt, factor, sqrts, x)
        type(phs_tree_t), intent(inout) :: tree
        type(phs_prt_t), dimension(:), intent(in) :: prt
        real(default), intent(out) :: factor
        real(default), intent(in) :: sqrts
        real(default), dimension(:), intent(out) :: x
        real(default), dimension(tree%mask_out) :: decay_p
        integer :: n1, n2
        n1 = tree%n_msq
        n2 = n1 + tree%n_angles
        call phs_tree_get_msq &
            (tree, prt, factor, decay_p, sqrts, x(1:n1))
        call phs_tree_get_angles &
            (tree, prt, factor, decay_p, sqrts, x(n1+1:n2))
    end subroutine phs_tree_compute_x_from_momenta

```

The inverse operation follows exactly the same steps. The tree is *inout* because it contains mappings whose parameters can be reset when the mapping is applied.

```

<PHS trees: procedures>+≡
    subroutine phs_tree_get_msq (tree, prt, factor, decay_p, sqrts, x)
        type(phs_tree_t), intent(inout) :: tree
        type(phs_prt_t), dimension(:), intent(in) :: prt
        real(default), intent(out) :: factor
        real(default), dimension(:), intent(out) :: decay_p
        real(default), intent(in) :: sqrts
        real(default), dimension(:), intent(inout) :: x
        integer :: ix
        integer(TC) :: k
        real(default) :: m_tot
        ix = 1
        k = tree%mask_out
        m_tot = tree%mass_sum(k)
        decay_p(k) = 0.
        if (tree%branch(k)%has_children) then

```

```

        call get_msq_x (tree%branch(k), k, factor, .true.)
    else
        factor = 1
    end if
contains
recursive subroutine get_msq_x (b, k, factor, initial)
    type(phs_branch_t), intent(in) :: b
    integer(TC), intent(in) :: k
    real(default), intent(out) :: factor
    logical, intent(in) :: initial
    real(default) :: msq, m, m_min, m_max, msq1, msq2, lda, rlda
    integer(TC) :: k1, k2
    real(default) :: f1, f2
    k1 = b%daughter(1); k2 = b%daughter(2)
    if (tree%branch(k1)%has_children) then
        call get_msq_x (tree%branch(k1), k1, f1, .false.)
    else
        f1 = 1
    end if
    if (tree%branch(k2)%has_children) then
        call get_msq_x (tree%branch(k2), k2, f2, .false.)
    else
        f2 = 1
    end if
    m_min = tree%mass_sum(k)
    m_max = sqrts - m_tot + m_min
    msq = phs_prt_get_msq (prt(k)); m = sqrt (msq)
    if (initial) then
        factor = f1 * f2
    else
        call mapping_compute_x_from_msq &
            (tree%mapping(k), sqrts**2, m_min**2, m_max**2, msq, factor, &
            x(ix)); ix = ix + 1
        factor = f1 * f2 * factor
    end if
    msq1 = phs_prt_get_msq (prt(k1))
    msq2 = phs_prt_get_msq (prt(k2))
    lda = lambda (msq, msq1, msq2)
    if (lda > 0) then
        rlda = sqrt (lda)
        decay_p(k1) = rlda / (2 * m)
        decay_p(k2) = - decay_p(k1)
        factor = rlda / msq * factor
    else
        decay_p(k1) = 0
        decay_p(k2) = 0
        factor = 0
    end if
end subroutine get_msq_x
end subroutine phs_tree_get_msq

```

This subroutine is the most time-critical part of the whole program. Therefore, we do not exactly parallel the angle generation routine above but make sure that things get evaluated only if they are really needed, at the expense of

readability. Particularly important is to have as few multiplications of Lorentz transformations as possible.

(*PHS trees: procedures*) \equiv

```

subroutine phs_tree_get_angles (tree, prt, factor, decay_p, sqrts, x)
  type(phs_tree_t), intent(inout) :: tree
  type(phs_prt_t), dimension(:), intent(in) :: prt
  real(default), intent(inout) :: factor
  real(default), dimension(:), intent(in) :: decay_p
  real(default), intent(in) :: sqrts
  real(default), dimension(:), intent(out) :: x
  integer :: ix
  integer(TC) :: k
  ix = 1
  k = tree%mask_out
  if (tree%branch(k)%has_children) call get_angles_x (tree%branch(k), k)
contains
  recursive subroutine get_angles_x (b, k, ct0, st0, phi0, L0)
    type(phs_branch_t), intent(in) :: b
    integer(TC), intent(in) :: k
    real(default), intent(in), optional :: ct0, st0, phi0
    type(lorentz_transformation_t), intent(in), optional :: L0
    real(default) :: cp0, sp0, m, msq, ct, st, phi, bg, f
    type(lorentz_transformation_t) :: L, LL
    type(vector4_t) :: p1, pf
    type(vector3_t) :: n, axis
    integer(TC) :: k1, k2, kf
    logical :: has_friend, need_L
    k1 = b%daughter(1)
    k2 = b%daughter(2)
    kf = b%friend
    has_friend = b%has_friend
    if (present(L0)) then
      p1 = L0 * phs_prt_get_momentum (prt(k1))
      if (has_friend) pf = L0 * phs_prt_get_momentum (prt(kf))
    else
      p1 = phs_prt_get_momentum (prt(k1))
      if (has_friend) pf = phs_prt_get_momentum (prt(kf))
    end if
    if (present(phi0)) then
      cp0 = cos (phi0)
      sp0 = sin (phi0)
    end if
    msq = phs_prt_get_msq (prt(k)); m = sqrt (msq)
    if (m > 0) then
      bg = decay_p(k) / m
    else
      bg = 0
    end if
    if (has_friend) then
      if (present (phi0)) then
        axis = axis_from_p_r3_r2_b3 (pf, cp0, -sp0, ct0, -st0, -bg)
        LL = rotation_to_2nd (axis, vector3_canonical (3)) &
          * LT_compose_r3_r2_b3 (cp0, -sp0, ct0, -st0, -bg)
      else

```

```

        axis = axis_from_p_b3 (pf, -bg)
        LL = rotation_to_2nd (axis, vector3_canonical(3))
        if (bg /= 0) LL = LL * boost(-bg, 3)
    end if
    n = space_part (LL * p1)
else if (present (phi0)) then
    n = axis_from_p_r3_r2_b3 (p1, cp0, -sp0, ct0, -st0, -bg)
else
    n = axis_from_p_b3 (p1, -bg)
end if
phi = azimuthal_angle (n)
x(ix) = phi / twopi; ix = ix + 1
ct = polar_angle_ct (n)
st = sqrt (1 - ct**2)
call mapping_compute_x_from_ct (tree%mapping(k), sqrts**2, ct, f, &
    x(ix)); ix = ix + 1
factor = factor * f
if (tree%branch(k1)%has_children .or. tree%branch(k2)%has_children) then
    need_L = .true.
    if (has_friend) then
        if (present (L0)) then
            L = LL * L0
        else
            L = LL
        end if
    else if (present (L0)) then
        L = LT_compose_r3_r2_b3 (cp0, -sp0, ct0, -st0, -bg) * L0
    else if (present (phi0)) then
        L = LT_compose_r3_r2_b3 (cp0, -sp0, ct0, -st0, -bg)
    else if (bg /= 0) then
        L = boost(-bg, 3)
    else
        need_L = .false.
    end if
    if (need_L) then
        if (tree%branch(k1)%has_children) &
            call get_angles_x (tree%branch(k1), k1, ct, st, phi, L)
        if (tree%branch(k2)%has_children) &
            call get_angles_x (tree%branch(k2), k2, ct, st, phi, L)
    else
        if (tree%branch(k1)%has_children) &
            call get_angles_x (tree%branch(k1), k1, ct, st, phi)
        if (tree%branch(k2)%has_children) &
            call get_angles_x (tree%branch(k2), k2, ct, st, phi)
    end if
end if
end subroutine get_angles_x
end subroutine phs_tree_get_angles

```

Auxiliary stuff

This calculates all momenta that are not yet known by summing up daughter particle momenta. The external particles must be known. Only composite

particles not yet known are calculated.

<PHS trees: public>+≡

```
public :: phs_tree_combine_particles
```

<PHS trees: procedures>+≡

```
subroutine phs_tree_combine_particles (tree, prt)
  type(phs_tree_t), intent(in) :: tree
  type(phs_prt_t), dimension(:), intent(inout) :: prt
  call combine_particles_x (tree%mask_out)
contains
  recursive subroutine combine_particles_x (k)
    integer(TC), intent(in) :: k
    integer :: k1, k2
    if (tree%branch(k)%has_children) then
      k1 = tree%branch(k)%daughter(1); k2 = tree%branch(k)%daughter(2)
      call combine_particles_x (k1)
      call combine_particles_x (k2)
      if (.not. phs_prt_is_defined (prt(k))) then
        call phs_prt_combine (prt(k), prt(k1), prt(k2))
      end if
    end if
  end subroutine combine_particles_x
end subroutine phs_tree_combine_particles
```

12.3 The phase-space forest

Simply stated, a phase-space forest is a collection of phase-space trees. More precisely, a `phs_forest` object contains all parameterizations of phase space that WHIZARD will use for a single hard process, prepared in the form of `phs_tree` objects. This is suitable for evaluation by the VAMP integration package: each parameterization (tree) is a valid channel in the multi-channel adaptive integration, and each variable in a tree corresponds to an integration dimension, defined by an appropriate mapping of the $(0, 1)$ interval to the allowed range of the integration variable.

The trees are grouped in groves. The trees (integration channels) within a grove share a common weight, assuming that they are related by some approximate symmetry.

Trees/channels that are related by an exact symmetry are connected by an array of equivalences; each equivalence object holds the data that relate one channel to another.

The phase-space setup, i.e., the detailed structure of trees and forest, are read from a file. Therefore, this module also contains the syntax definition and the parser needed for interpreting this file.

```
(phs_forests.f90)≡  
  <File header>  
  
  module phs_forests  
  
    <Use kinds>  
    use kinds, only: TC !NODEP!  
    <Use strings>  
    <Use file utils>  
    use diagnostics !NODEP!  
    use lorentz !NODEP!  
    use vamp_equivalences !NODEP!  
    use permutations  
    use ifiles  
    use syntax_rules  
    use lexers  
    use parser  
    use models  
    use flavors  
    use interactions  
    use mappings  
    use phs_trees  
  
    <Standard module head>  
  
    <PHS forests: public>  
  
    <PHS forests: types>  
  
    <PHS forests: interfaces>  
  
    <PHS forests: variables>
```

```
contains

<PHS forests: procedures>

end module phs_forests
```

12.3.1 Phase-space setup parameters

This transparent container holds the parameters that the algorithm needs for phase-space setup, with reasonable defaults.

The threshold mass (for considering a particle as effectively massless) is specified separately for s- and t-channel. The default is to treat W and Z bosons as massive in the s-channel, but as massless in the t-channel. The b -quark is treated always massless, the t -quark always massive.

```
<PHS forests: public>≡
    public :: phs_parameters_t

<PHS forests: types>≡
    type :: phs_parameters_t
        real(default) :: sqrts = 0
        real(default) :: m_threshold_s = 50._default
        real(default) :: m_threshold_t = 100._default
        integer :: off_shell = 1
        integer :: t_channel = 2
    end type phs_parameters_t
```

Write phase-space parameters to file.

```
<PHS forests: public>+≡
    public :: phs_parameters_write

<PHS forests: procedures>≡
    subroutine phs_parameters_write (phs_par, unit)
        type(phs_parameters_t), intent(in) :: phs_par
        integer, intent(in), optional :: unit
        integer :: u
        u = output_unit (unit)
        write (u, *) "   sqrts           = ", phs_par%sqrts
        write (u, *) " m_threshold_s = ", phs_par%m_threshold_s
        write (u, *) " m_threshold_t = ", phs_par%m_threshold_t
        write (u, *) " off_shell = ", phs_par%off_shell
        write (u, *) " t_channel = ", phs_par%t_channel
    end subroutine phs_parameters_write
```

Read phase-space parameters from file.

```
<PHS forests: public>+≡
    public :: phs_parameters_read

<PHS forests: procedures>+≡
    subroutine phs_parameters_read (phs_par, unit)
        type(phs_parameters_t), intent(out) :: phs_par
        integer, intent(in) :: unit
        character(20) :: dummy
        character :: equals
```

```

    read (unit, *) dummy, equals, phs_par%sqrts
    read (unit, *) dummy, equals, phs_par%m_threshold_s
    read (unit, *) dummy, equals, phs_par%m_threshold_t
    read (unit, *) dummy, equals, phs_par%off_shell
    read (unit, *) dummy, equals, phs_par%t_channel
end subroutine phs_parameters_read

```

Comparison.

```

<PHS forests: interfaces>≡
  interface operator(==)
    module procedure phs_parameters_eq
  end interface
  interface operator(/=)
    module procedure phs_parameters_ne
  end interface

<PHS forests: procedures>+≡
  function phs_parameters_eq (phs_par1, phs_par2) result (equal)
    logical :: equal
    type(phs_parameters_t), intent(in) :: phs_par1, phs_par2
    equal = phs_par1%sqrts == phs_par2%sqrts &
      .and. phs_par1%m_threshold_s == phs_par2%m_threshold_s &
      .and. phs_par1%m_threshold_t == phs_par2%m_threshold_t &
      .and. phs_par1%off_shell == phs_par2%off_shell &
      .and. phs_par1%t_channel == phs_par2%t_channel
  end function phs_parameters_eq

  function phs_parameters_ne (phs_par1, phs_par2) result (ne)
    logical :: ne
    type(phs_parameters_t), intent(in) :: phs_par1, phs_par2
    ne = phs_par1%sqrts /= phs_par2%sqrts &
      .or. phs_par1%m_threshold_s /= phs_par2%m_threshold_s &
      .or. phs_par1%m_threshold_t /= phs_par2%m_threshold_t &
      .or. phs_par1%off_shell /= phs_par2%off_shell &
      .or. phs_par1%t_channel /= phs_par2%t_channel
  end function phs_parameters_ne

```

12.3.2 Equivalences

This type holds information about equivalences between phase-space trees. We make a linked list, where each node contains the two trees which are equivalent and the corresponding permutation of external particles. Two more arrays are to be filled: The permutation of mass variables and the permutation of angular variables, where the signature indicates a necessary exchange of daughter branches.

```

<PHS forests: types>+≡
  type :: equivalence_t
    private
    integer :: left, right
    type(permutation_t) :: perm
    type(permutation_t) :: msq_perm, angle_perm
    logical, dimension(:), allocatable :: angle_sig

```

```

    type(equivalence_t), pointer :: next => null ()
end type equivalence_t

```

```

<PHS forests: types>+≡
type :: equivalence_list_t
private
integer :: length = 0
type(equivalence_t), pointer :: first => null ()
type(equivalence_t), pointer :: last => null ()
end type equivalence_list_t

```

Append an equivalence to the list

```

<PHS forests: procedures>+≡
subroutine equivalence_list_add (eql, left, right, perm)
type(equivalence_list_t), intent(inout) :: eql
integer, intent(in) :: left, right
type(permutation_t), intent(in) :: perm
type(equivalence_t), pointer :: eq
allocate (eq)
eq%left = left
eq%right = right
eq%perm = perm
if (associated (eql%last)) then
    eql%last%next => eq
else
    eql%first => eq
end if
eql%last => eq
eql%length = eql%length + 1
end subroutine equivalence_list_add

```

Delete the list contents. Has to be pure because it is called from an elemental subroutine.

```

<PHS forests: procedures>+≡
pure subroutine equivalence_list_final (eql)
type(equivalence_list_t), intent(inout) :: eql
type(equivalence_t), pointer :: eq
do while (associated (eql%first))
    eq => eql%first
    eql%first => eql%first%next
    deallocate (eq)
end do
eql%last => null ()
eql%length = 0
end subroutine equivalence_list_final

```

Make a deep copy of the equivalence list. This allows for deep copies of groves and forests.

```

<PHS forests: interfaces>+≡
interface assignment(=)
module procedure equivalence_list_assign
end interface

```

```

(PHS forests: procedures)+≡
subroutine equivalence_list_assign (eql_out, eql_in)
  type(equivalence_list_t), intent(out) :: eql_out
  type(equivalence_list_t), intent(in) :: eql_in
  type(equivalence_t), pointer :: eq, eq_copy
  eq => eql_in%first
  do while (associated (eq))
    allocate (eq_copy)
    eq_copy = eq
    eq_copy%next => null ()
    if (associated (eql_out%first)) then
      eql_out%last%next => eq_copy
    else
      eql_out%first => eq_copy
    end if
    eql_out%last => eq_copy
    eq => eq%next
  end do
end subroutine equivalence_list_assign

```

The number of list entries

```

(PHS forests: procedures)+≡
elemental function equivalence_list_length (eql) result (length)
  integer :: length
  type(equivalence_list_t), intent(in) :: eql
  length = eql%length
end function equivalence_list_length

```

Recursively write the equivalences list

```

(PHS forests: procedures)+≡
subroutine equivalence_list_write (eql, unit)
  type(equivalence_list_t), intent(in) :: eql
  integer, intent(in), optional :: unit
  integer :: u
  u = output_unit (unit); if (u < 0) return
  if (associated (eql%first)) then
    call equivalence_write_rec (eql%first, u)
  else
    write (u, *) " [empty]"
  end if
contains
recursive subroutine equivalence_write_rec (eq, u)
  type(equivalence_t), intent(in) :: eq
  integer, intent(in) :: u
  integer :: i
  write (u, "(1x,A,1x,I5,1x,I5,5x,A)", advance="no") &
    "Equivalence:", eq%left, eq%right, "Final state permutation:"
  call permutation_write (eq%perm, u)
  write (u, "(1x,12x,1x,A,1x)", advance="no") &
    "      msq permutation:  "
  call permutation_write (eq%msq_perm, u)

```

```

write (u, "(1x,12x,1x,A,1x)", advance="no") &
    "    angle permutation:"
call permutation_write (eq%angle_perm, u)
write (u, "(1x,12x,1x,26x)", advance="no")
do i = 1, size (eq%angle_sig)
    if (eq%angle_sig(i)) then
        write (u, "(1x,A)", advance="no") "+"
    else
        write (u, "(1x,A)", advance="no") "-"
    end if
end do
write (u, *)
if (associated (eq%next)) call equivalence_write_rec (eq%next, u)
end subroutine equivalence_write_rec
end subroutine equivalence_list_write

```

12.3.3 Groves

A grove is a group of trees (phase-space channels) that share a common weight in the integration. Within a grove, channels can be declared equivalent, so they also share their integration grids (up to symmetries). The grove contains a list of equivalences. The `tree_count_offset` is the total number of trees of the preceding groves; when the trees are counted per forest (integration channels), the offset has to be added to all tree indices.

(PHS forests: types)+≡

```

type :: phs_grove_t
private
integer :: tree_count_offset
type(phs_tree_t), dimension(:), allocatable :: tree
type(equivalence_list_t) :: equivalence_list
end type phs_grove_t

```

Call `phs_tree_init` which is also elemental:

(PHS forests: procedures)+≡

```

elemental subroutine phs_grove_init &
    (grove, n_trees, n_in, n_out, n_masses, n_angles)
type(phs_grove_t), intent(inout) :: grove
integer, intent(in) :: n_trees, n_in, n_out, n_masses, n_angles
grove%tree_count_offset = 0
allocate (grove%tree (n_trees))
call phs_tree_init (grove%tree, n_in, n_out, n_masses, n_angles)
end subroutine phs_grove_init

```

The trees do not have pointer components, thus no call to `phs_tree_final`:

(PHS forests: procedures)+≡

```

elemental subroutine phs_grove_final (grove)
type(phs_grove_t), intent(inout) :: grove
deallocate (grove%tree)
call equivalence_list_final (grove%equivalence_list)
end subroutine phs_grove_final

```

Deep copy.

```

(PHS forests: interfaces)+≡
  interface assignment(=)
    module procedure phs_grove_assign0
    module procedure phs_grove_assign1
  end interface

(PHS forests: procedures)+≡
  subroutine phs_grove_assign0 (grove_out, grove_in)
    type(phs_grove_t), intent(out) :: grove_out
    type(phs_grove_t), intent(in) :: grove_in
    grove_out%tree_count_offset = grove_in%tree_count_offset
    if (allocated (grove_in%tree)) then
      allocate (grove_out%tree (size (grove_in%tree)))
      grove_out%tree = grove_in%tree
    end if
    grove_out%equivalence_list = grove_in%equivalence_list
  end subroutine phs_grove_assign0

  subroutine phs_grove_assign1 (grove_out, grove_in)
    type(phs_grove_t), dimension(:), intent(out) :: grove_out
    type(phs_grove_t), dimension(:), intent(in) :: grove_in
    integer :: i
    do i = 1, size (grove_in)
      call phs_grove_assign0 (grove_out(i), grove_in(i))
    end do
  end subroutine phs_grove_assign1

```

12.3.4 The forest type

This is a collection of trees and associated particles. In a given tree, each branch code corresponds to a particle in the `prt` array. Furthermore, we have an array of mass sums which is independent of the decay tree and of the particular event. The mappings directly correspond to the decay trees, and the decay groves collect the trees in classes. The permutation list consists of all permutations of outgoing particles that map the decay forest onto itself.

The particle codes `flv` (one for each external particle) are needed for determining masses and such. The trees and associated information are collected in the `grove` array, together with a lookup table that associates tree indices to groves. Finally, the `prt` array serves as workspace for phase-space evaluation.

```

(PHS forests: public)+≡
  public :: phs_forest_t

(PHS forests: types)+≡
  type :: phs_forest_t
    private
    integer :: n_in, n_out, n_tot
    integer :: n_masses, n_angles, n_dimensions
    integer :: n_trees, n_equivalences
    type(flavor_t), dimension(:), allocatable :: flv
    type(phs_grove_t), dimension(:), allocatable :: grove

```

```

        integer, dimension(:), allocatable :: grove_lookup
        type(phs_prt_t), dimension(:), allocatable :: prt_in
        type(phs_prt_t), dimension(:), allocatable :: prt_out
        type(phs_prt_t), dimension(:), allocatable :: prt
    end type phs_forest_t

```

The initialization merely allocates memory. We have to know how many trees there are in each grove, so we can initialize everything. The number of groves is the size of the `n_tree` array.

In the `grove_lookup` table we store the grove index that belongs to each absolute tree index. The difference between the absolute index and the relative (to the grove) index is stored, for each grove, as `tree_count_offset`.

The particle array is allocated according to the total number of branches each tree has, but not filled.

```

(PHS forests: public)+≡
    public :: phs_forest_init

(PHS forests: procedures)+≡
    subroutine phs_forest_init (forest, n_tree, n_in, n_out)
        type(phs_forest_t), intent(inout) :: forest
        integer, dimension(:), intent(in) :: n_tree
        integer, intent(in) :: n_in, n_out
        integer :: g, count
        forest%n_in = n_in
        forest%n_out = n_out
        forest%n_tot = n_in + n_out
        forest%n_masses = max (n_out - 2, 0)
        forest%n_angles = max (2*n_out - 2, 0)
        forest%n_dimensions = forest%n_masses + forest%n_angles
        forest%n_trees = sum (n_tree)
        forest%n_equivalences = 0
        allocate (forest%grove (size (n_tree)))
        call phs_grove_init &
            (forest%grove, n_tree, n_in, n_out, forest%n_masses, forest%n_angles)
        allocate (forest%grove_lookup (forest%n_trees))
        count = 0
        do g = 1, size (forest%grove)
            forest%grove(g)%tree_count_offset = count
            forest%grove_lookup (count+1:count+n_tree(g)) = g
            count = count + n_tree(g)
        end do
        allocate (forest%prt_in (n_in))
        allocate (forest%prt_out (n_out))
        allocate (forest%prt (2**forest%n_tot - 1))
    end subroutine phs_forest_init

```

The grove finalizer is called because it contains the equivalence list:

```

(PHS forests: public)+≡
    public :: phs_forest_final

(PHS forests: procedures)+≡
    subroutine phs_forest_final (forest)
        type(phs_forest_t), intent(inout) :: forest
        if (allocated (forest%grove)) then

```

```

        call phs_grove_final (forest%grove)
        deallocate (forest%grove)
    end if
    if (allocated (forest%grove_lookup)) deallocate (forest%grove_lookup)
    if (allocated (forest%prt)) deallocate (forest%prt)
end subroutine phs_forest_final

```

12.3.5 Screen output

Write the particles that are non-null, then the trees which point to them:

```

<PHS forests: public>+≡
    public :: phs_forest_write

<PHS forests: procedures>+≡
    subroutine phs_forest_write (forest, unit)
        type(phs_forest_t), intent(in) :: forest
        integer, intent(in), optional :: unit
        integer :: u
        integer :: i, g
        u = output_unit (unit); if (u < 0) return
        write (u, *) "Phase space forest:"
        write (u, *) "n_in  = ", forest%n_in
        write (u, *) "n_out = ", forest%n_out
        write (u, *) "n_tot = ", forest%n_tot
        write (u, *) "n_masses = ", forest%n_masses
        write (u, *) "n_angles = ", forest%n_angles
        write (u, *) "n_dim   = ", forest%n_dimensions
        write (u, *) "n_trees = ", forest%n_trees
        write (u, *) "n_equiv = ", forest%n_equivalences
        write (u, "(1x,A)", advance="no") "flavors  ="
        if (allocated (forest%flv)) then
            do i = 1, size (forest%flv)
                write (u, "(1x,I6)", advance="no") flavor_get_pdg (forest%flv(i))
            end do
            write (u, *)
        else
            write (u, *) "[empty]"
        end if
        write (u, *) "Groves and trees:"
        if (allocated (forest%grove)) then
            do g = 1, size (forest%grove)
                write (u, "(1x,A,1x,I4)") "Grove ", g
                call phs_grove_write (forest%grove(g), unit)
            end do
        else
            write (u, *) " [empty]"
        end if
        write (u, *) "Total number of equivalences: ", forest%n_equivalences
        write (u, *)
        write (u, *) "Incoming particles:"
        if (allocated (forest%prt_in)) then
            if (any (phs_prt_is_defined (forest%prt_in))) then
                do i = 1, size (forest%prt_in)

```

```

        if (phs_prt_is_defined (forest%prt_in(i))) then
            write (u, *) "Particle", i
            call phs_prt_write (forest%prt_in(i), u)
        end if
    end do
else
    write (u, "(3x,A)") "[all undefined]"
end if
else
    write (u, *) " [empty]"
end if
write (u, *)
write (u, *) "Outgoing particles:"
if (allocated (forest%prt_out)) then
    if (any (phs_prt_is_defined (forest%prt_out))) then
        do i = 1, size (forest%prt_out)
            if (phs_prt_is_defined (forest%prt_out(i))) then
                write (u, *) "Particle", i
                call phs_prt_write (forest%prt_out(i), u)
            end if
        end do
    else
        write (u, "(3x,A)") "[all undefined]"
    end if
else
    write (u, *) " [empty]"
end if
write (u, *)
write (u, *) "Tree particles:"
if (allocated (forest%prt)) then
    if (any (phs_prt_is_defined (forest%prt))) then
        do i = 1, size (forest%prt)
            if (phs_prt_is_defined (forest%prt(i))) then
                write (u, *) "Particle", i
                call phs_prt_write (forest%prt(i), u)
            end if
        end do
    else
        write (u, "(3x,A)") "[all undefined]"
    end if
else
    write (u, *) " [empty]"
end if
end subroutine phs_forest_write

subroutine phs_grove_write (grove, unit)
    type(phs_grove_t), intent(in) :: grove
    integer, intent(in), optional :: unit
    integer :: u
    integer :: t
    u = output_unit (unit); if (u < 0) return
    do t = 1, size (grove%tree)
        write (u, "(1x,A,1x,I4)") "Tree ", t
        call phs_tree_write (grove%tree(t), unit)
    end do
end subroutine phs_grove_write

```

```

end do
write (u, "(1x,A)") "Equivalence list:"
call equivalence_list_write (grove%equivalence_list, unit)
end subroutine phs_grove_write

```

Deep copy.

```

<PHS forests: public>+≡
public :: assignment(=)

<PHS forests: interfaces>+≡
interface assignment(=)
module procedure phs_forest_assign
end interface

<PHS forests: procedures>+≡
subroutine phs_forest_assign (forest_out, forest_in)
type(phs_forest_t), intent(out) :: forest_out
type(phs_forest_t), intent(in) :: forest_in
forest_out%n_in = forest_in%n_in
forest_out%n_out = forest_in%n_out
forest_out%n_tot = forest_in%n_tot
forest_out%n_masses = forest_in%n_masses
forest_out%n_angles = forest_in%n_angles
forest_out%n_dimensions = forest_in%n_dimensions
forest_out%n_trees = forest_in%n_trees
forest_out%n_equivalences = forest_in%n_equivalences
if (allocated (forest_in%flv)) then
allocate (forest_out%flv (size (forest_in%flv)))
forest_out%flv = forest_in%flv
end if
if (allocated (forest_in%grove)) then
allocate (forest_out%grove (size (forest_in%grove)))
forest_out%grove = forest_in%grove
end if
if (allocated (forest_in%grove_lookup)) then
allocate (forest_out%grove_lookup (size (forest_in%grove_lookup)))
forest_out%grove_lookup = forest_in%grove_lookup
end if
if (allocated (forest_in%prt_in)) then
allocate (forest_out%prt_in (size (forest_in%prt_in)))
forest_out%prt_in = forest_in%prt_in
end if
if (allocated (forest_in%prt_out)) then
allocate (forest_out%prt_out (size (forest_in%prt_out)))
forest_out%prt_out = forest_in%prt_out
end if
if (allocated (forest_in%prt)) then
allocate (forest_out%prt (size (forest_in%prt)))
forest_out%prt = forest_in%prt
end if
end subroutine phs_forest_assign

```

12.3.6 Accessing contents

Get the number of integration parameters

```
<PHS forests: public>+≡
    public :: phs_forest_get_n_parameters

<PHS forests: procedures>+≡
    function phs_forest_get_n_parameters (forest) result (n)
        integer :: n
        type(phs_forest_t), intent(in) :: forest
        n = forest%n_dimensions
    end function phs_forest_get_n_parameters
```

Get the number of integration channels

```
<PHS forests: public>+≡
    public :: phs_forest_get_n_channels

<PHS forests: procedures>+≡
    function phs_forest_get_n_channels (forest) result (n)
        integer :: n
        type(phs_forest_t), intent(in) :: forest
        n = forest%n_trees
    end function phs_forest_get_n_channels
```

Get the number of groves

```
<PHS forests: public>+≡
    public :: phs_forest_get_n_groves

<PHS forests: procedures>+≡
    function phs_forest_get_n_groves (forest) result (n)
        integer :: n
        type(phs_forest_t), intent(in) :: forest
        n = size (forest%grove)
    end function phs_forest_get_n_groves
```

Get the index bounds for a specific grove.

```
<PHS forests: public>+≡
    public :: phs_forest_get_grove_bounds

<PHS forests: procedures>+≡
    subroutine phs_forest_get_grove_bounds (forest, g, i0, i1, n)
        type(phs_forest_t), intent(in) :: forest
        integer, intent(in) :: g
        integer, intent(out) :: i0, i1, n
        n = size (forest%grove(g)%tree)
        i0 = forest%grove(g)%tree_count_offset + 1
        i1 = forest%grove(g)%tree_count_offset + n
    end subroutine phs_forest_get_grove_bounds
```

12.3.7 Read the phase space setup from file

The phase space setup is stored in a file. The file may be generated by the `cascades` module below, or by other means. This file has to be read and parsed to create the PHS forest as the internal phase-space representation.

Create lexer and syntax:

(*PHS forests: procedures*)+≡

```
subroutine define_phs_forest_syntax (ifile)
  type(ifile_t) :: ifile
  call ifile_append (ifile, "SEQ phase_space_list = process_phase_space*")
  call ifile_append (ifile, "SEQ process_phase_space = " &
    // "process_def process_header phase_space")
  call ifile_append (ifile, "SEQ process_def = process process_list")
  call ifile_append (ifile, "KEY process")
  call ifile_append (ifile, "LIS process_list = process_tag*")
  call ifile_append (ifile, "IDE process_tag")
  call ifile_append (ifile, "SEQ process_header = " &
    // "md5sum_process = md5sum " &
    // "md5sum_model = md5sum " &
    // "md5sum_parameters = md5sum " &
    // "sqrts = real " &
    // "m_threshold_s = real " &
    // "m_threshold_t = real " &
    // "off_shell = integer " &
    // "t_channel = integer ")
  call ifile_append (ifile, "KEY '='")
  call ifile_append (ifile, "KEY md5sum_process")
  call ifile_append (ifile, "KEY md5sum_model")
  call ifile_append (ifile, "KEY md5sum_parameters")
  call ifile_append (ifile, "KEY sqrts")
  call ifile_append (ifile, "KEY m_threshold_s")
  call ifile_append (ifile, "KEY m_threshold_t")
  call ifile_append (ifile, "KEY off_shell")
  call ifile_append (ifile, "KEY t_channel")
  call ifile_append (ifile, "QUO md5sum = '""' ... '""'")
  call ifile_append (ifile, "REA real")
  call ifile_append (ifile, "INT integer")
  call ifile_append (ifile, "SEQ phase_space = grove_def+")
  call ifile_append (ifile, "SEQ grove_def = grove tree_def+")
  call ifile_append (ifile, "KEY grove")
  call ifile_append (ifile, "SEQ tree_def = tree bincodes mapping*")
  call ifile_append (ifile, "KEY tree")
  call ifile_append (ifile, "SEQ bincodes = bincodes+")
  call ifile_append (ifile, "INT bincodes")
  call ifile_append (ifile, "SEQ mapping = map bincodes channel pdg")
  call ifile_append (ifile, "KEY map")
  call ifile_append (ifile, "ALT channel = s_channel | t_channel | u_channel | collinear | infrared")
  call ifile_append (ifile, "KEY s_channel")
  ! call ifile_append (ifile, "KEY t_channel")
  call ifile_append (ifile, "KEY u_channel")
  call ifile_append (ifile, "KEY collinear")
  call ifile_append (ifile, "KEY infrared")
  call ifile_append (ifile, "KEY radiation")
  call ifile_append (ifile, "INT pdg")
end subroutine
```

```
end subroutine define_phs_forest_syntax
```

The model-file syntax and lexer are fixed, therefore stored as module variables:

(PHS forests: variables)≡

```
type(syntax_t), target, save :: syntax_phs_forest
```

(PHS forests: public)+≡

```
public :: syntax_phs_forest_init
```

(PHS forests: procedures)+≡

```
subroutine syntax_phs_forest_init ()
  type(ifile_t) :: ifile
  call define_phs_forest_syntax (ifile)
  call syntax_init (syntax_phs_forest, ifile)
  call ifile_final (ifile)
end subroutine syntax_phs_forest_init
```

(PHS forests: procedures)+≡

```
subroutine lexer_init_phs_forest (lexer)
  type(lexer_t), intent(out) :: lexer
  call lexer_init (lexer, &
    comment_chars = "#!", &
    quote_chars = "'", &
    quote_match = "'", &
    single_chars = "", &
    special_class = (/ "=", /) , &
    keyword_list = syntax_get_keyword_list_ptr (syntax_phs_forest))
end subroutine lexer_init_phs_forest
```

(PHS forests: public)+≡

```
public :: syntax_phs_forest_final
```

(PHS forests: procedures)+≡

```
subroutine syntax_phs_forest_final ()
  call syntax_final (syntax_phs_forest)
end subroutine syntax_phs_forest_final
```

The concrete parser and interpreter. Generate an input stream for the external `unit`, read the parse tree (with given `syntax` and `lexer`) from this stream, and transfer the contents of the parse tree to the PHS forest.

We look for the matching `process` tag, count groves and trees for initializing the forest, and fill the trees.

If the optional parameters are set, compare the parameters stored in the file to those. Set `match` true if everything agrees.

(PHS forests: public)+≡

```
public :: phs_forest_read
```

(PHS forests: procedures)+≡

```
subroutine phs_forest_read &
  (forest, unit, process_id, n_in, n_out, model, found, &
    md5sum_process, md5sum_model, md5sum_parameters, phs_par, match)
  type(phs_forest_t), intent(out) :: forest
  integer, intent(in) :: unit
```

```

type(string_t), intent(in) :: process_id
integer, intent(in) :: n_in, n_out
type(model_t), intent(in), target :: model
logical, intent(out) :: found
character(32), intent(in), optional :: &
    md5sum_process, md5sum_model, md5sum_parameters
type(phs_parameters_t), intent(in), optional :: phs_par
logical, intent(out), optional :: match
type(stream_t) :: stream
type(lexer_t) :: lexer
type(parse_tree_t), target :: parse_tree
type(parse_node_t), pointer :: node_header, node_phs, node_grove
integer :: n_grove, g
integer, dimension(:), allocatable :: n_tree
integer :: t
call lexer_init_phs_forest (lexer)
call stream_init (stream, unit)
call parse_tree_init (parse_tree, syntax_phs_forest, lexer, stream)
call stream_final (stream)
call lexer_final (lexer)
!   call parse_tree_write (parse_tree)
node_header => parse_tree_get_process_ptr (parse_tree, process_id)
found = associated (node_header); if (.not. found) return
if (present (match)) then
    call phs_forest_check_input (node_header, &
        md5sum_process, md5sum_model, md5sum_parameters, phs_par, match)
    if (.not. match) return
end if
node_phs => parse_node_get_next_ptr (node_header)
n_grove = parse_node_get_n_sub (node_phs)
allocate (n_tree (n_grove))
do g = 1, n_grove
    node_grove => parse_node_get_sub_ptr (node_phs, g)
    n_tree(g) = parse_node_get_n_sub (node_grove) - 1
end do
call phs_forest_init (forest, n_tree, n_in, n_out)
do g = 1, n_grove
    node_grove => parse_node_get_sub_ptr (node_phs, g)
    do t = 1, n_tree(g)
        call phs_tree_set (forest%grove(g)%tree(t), &
            parse_node_get_sub_ptr (node_grove, t+1), model)
    end do
end do
call parse_tree_final (parse_tree)
end subroutine phs_forest_read

```

Check the input for consistency. If any MD5 sum or phase-space parameter disagrees, the phase-space file cannot be used. The MD5 sum checks are skipped if the stored MD5 sum is empty.

(PHS forests: procedures)+≡

```

subroutine phs_forest_check_input (pn_header, &
    md5sum_process, md5sum_model, md5sum_parameters, phs_par, match)
type(parse_node_t), intent(in), target :: pn_header

```

```

character(32), intent(in) :: &
    md5sum_process, md5sum_model, md5sum_parameters
type(phs_parameters_t), intent(in) :: phs_par
logical, intent(out) :: match
type(parse_node_t), pointer :: pn_md5sum, pn_rval, pn_ival
character(32) :: md5sum
type(phs_parameters_t) :: phs_par_old
pn_md5sum => parse_node_get_sub_ptr (pn_header, 3)
md5sum = parse_node_get_string (pn_md5sum)
if (md5sum /= "" .and. md5sum /= md5sum_process) then
    call msg_message ("Rebuilding phase space (process has changed)")
    match = .false.; return
end if
pn_md5sum => parse_node_get_next_ptr (pn_md5sum, 3)
md5sum = parse_node_get_string (pn_md5sum)
if (md5sum /= "" .and. md5sum /= md5sum_model) then
    call msg_message ("Rebuilding phase space (model has changed)")
    match = .false.; return
end if
pn_md5sum => parse_node_get_next_ptr (pn_md5sum, 3)
md5sum = parse_node_get_string (pn_md5sum)
if (md5sum /= "" .and. md5sum /= md5sum_parameters) then
    call msg_message &
        ("Rebuilding phase space (model parameters have changed)")
    match = .false.; return
end if
pn_rval => parse_node_get_next_ptr (pn_md5sum, 3)
phs_par_old%sqrts = parse_node_get_real (pn_rval)
pn_rval => parse_node_get_next_ptr (pn_rval, 3)
phs_par_old%m_threshold_s = parse_node_get_real (pn_rval)
pn_rval => parse_node_get_next_ptr (pn_rval, 3)
phs_par_old%m_threshold_t = parse_node_get_real (pn_rval)
pn_ival => parse_node_get_next_ptr (pn_rval, 3)
phs_par_old%off_shell = parse_node_get_integer (pn_ival)
pn_ival => parse_node_get_next_ptr (pn_ival, 3)
phs_par_old%t_channel = parse_node_get_integer (pn_ival)
if (phs_par_old /= phs_par) then
    call msg_message &
        ("Rebuilding phase space (phase-space parameters have changed)")
    match = .false.; return
end if
match = .true.
end subroutine phs_forest_check_input

```

Initialize a specific tree in the forest, using the contents of the 'tree' node. First, count the bincodes, allocate an array and read them in, and make the tree. Each *t*-channel tree is flipped to *s*-channel. Then, find mappings and initialize them.

(PHS forests: procedures)+≡

```

subroutine phs_tree_set (tree, node, model)
    type(phs_tree_t), intent(inout) :: tree
    type(parse_node_t), intent(in), target :: node
    type(model_t), intent(in), target :: model
    type(parse_node_t), pointer :: node_bincodes, node_mapping

```

```

integer :: n_bincodes
integer(TC), dimension(:), allocatable :: bincode
integer :: b, n_mappings, m
integer(TC) :: k
type(string_t) :: type
integer :: pdg
node_bincodes => parse_node_get_sub_ptr (node, 2)
n_bincodes = parse_node_get_n_sub (node_bincodes)
allocate (bincode (n_bincodes))
do b = 1, n_bincodes
    bincode(b) = parse_node_get_integer &
        (parse_node_get_sub_ptr (node_bincodes, b))
end do
call phs_tree_from_array (tree, bincode)
call phs_tree_flip_t_to_s_channel (tree)
call phs_tree_canonicalize (tree)
n_mappings = parse_node_get_n_sub (node) - 2
do m = 1, n_mappings
    node_mapping => parse_node_get_sub_ptr (node, m+2)
    k = parse_node_get_integer &
        (parse_node_get_sub_ptr (node_mapping, 2))
    type = parse_node_get_key &
        (parse_node_get_sub_ptr (node_mapping, 3))
    pdg = parse_node_get_integer &
        (parse_node_get_sub_ptr (node_mapping, 4))
    call phs_tree_init_mapping (tree, k, type, pdg, model)
end do
end subroutine phs_tree_set

```

12.3.8 Preparation

The trees that we read from file do not carry flavor information. This is set separately:

The flavor list must be unique for a unique set of masses; if a given particle can have different flavor, the mass must be degenerate, so we can choose one of the possible flavor combinations.

```

<PHS forests: public>+≡
    public :: phs_forest_set_flavors

<PHS forests: procedures>+≡
    subroutine phs_forest_set_flavors (forest, flv)
        type(phs_forest_t), intent(inout) :: forest
        type(flavor_t), dimension(:), intent(in) :: flv
        allocate (forest%flv (size (flv)))
        forest%flv = flv
    end subroutine phs_forest_set_flavors

```

Once the parameter set is fixed, the masses and the widths of the particles are known and the `mass_sum` arrays as well as the mapping parameters can be computed.

```

<PHS forests: public>+≡
    public :: phs_forest_set_parameters

```

```

<PHS forests: procedures>+=
  subroutine phs_forest_set_parameters &
    (forest, mapping_defaults, variable_limits)
    type(phs_forest_t), intent(inout) :: forest
    type(mapping_defaults_t), intent(in) :: mapping_defaults
    logical, intent(in) :: variable_limits
    integer :: g, t
    do g = 1, size (forest%grove)
      do t = 1, size (forest%grove(g)%tree)
        call phs_tree_set_mass_sum &
          (forest%grove(g)%tree(t), forest%flv(forest%n_in+1:))
        call phs_tree_set_mapping_parameters (forest%grove(g)%tree(t), &
          mapping_defaults, variable_limits)
      end do
    end do
  end subroutine phs_forest_set_parameters

```

12.3.9 Accessing the particle arrays

Set the incoming particles from the contents of an interaction.

```

<PHS forests: public>+=
  public :: phs_forest_set_prt_in

<PHS forests: procedures>+=
  subroutine phs_forest_set_prt_in (forest, int, lt_cm_to_lab)
    type(phs_forest_t), intent(inout) :: forest
    type(interaction_t), intent(in) :: int
    type(lorentz_transformation_t), intent(in), optional :: lt_cm_to_lab
    if (present (lt_cm_to_lab)) then
      call phs_prt_set_momentum (forest%prt_in, &
        inverse (lt_cm_to_lab) * &
        interaction_get_momenta (int, outgoing=.false.))
    else
      call phs_prt_set_momentum (forest%prt_in, &
        interaction_get_momenta (int, outgoing=.false.))
    end if
    call phs_prt_set_msq (forest%prt_in, &
      flavor_get_mass (forest%flv(:forest%n_in)) ** 2)
    call phs_prt_set_defined (forest%prt_in)
  end subroutine phs_forest_set_prt_in

```

Extract the outgoing particles and insert into an interaction.

```

<PHS forests: public>+=
  public :: phs_forest_get_prt_out

<PHS forests: procedures>+=
  subroutine phs_forest_get_prt_out (forest, int, lt_cm_to_lab)
    type(phs_forest_t), intent(in) :: forest
    type(interaction_t), intent(inout) :: int
    type(lorentz_transformation_t), intent(in), optional :: lt_cm_to_lab
    if (present (lt_cm_to_lab)) then
      call interaction_set_momenta (int, &
        lt_cm_to_lab * &

```

```

        phs_prt_get_momentum (forest%prt_out), outgoing=.true.)
    else
        call interaction_set_momenta (int, &
            phs_prt_get_momentum (forest%prt_out), outgoing=.true.)
    end if
end subroutine phs_forest_get_prt_out

```

12.3.10 Find equivalences among phase-space trees

Scan phase space for equivalences. We generate the complete set of unique permutations for the given list of outgoing particles, and use this for scanning equivalences within each grove. We scan all pairs of trees, using all permutations. This implies that trivial equivalences are included, and equivalences between different trees are recorded twice. This is intentional.

(PHS forests: procedures)+≡

```

subroutine phs_grove_set_equivalences (grove, perm_array)
    type(phs_grove_t), intent(inout) :: grove
    type(permutation_t), dimension(:), intent(in) :: perm_array
    type(equivalence_t), pointer :: eq
    integer :: t1, t2, i
    do t1 = 1, size (grove%tree)
        do t2 = 1, size (grove%tree)
            SCAN_PERM: do i = 1, size (perm_array)
                if (phs_tree_equivalent &
                    (grove%tree(t1), grove%tree(t2), perm_array(i))) then
                    call equivalence_list_add &
                        (grove%equivalence_list, t1, t2, perm_array(i))
                    eq => grove%equivalence_list%last
                    call phs_tree_find_msq_permutation &
                        (grove%tree(t1), grove%tree(t2), eq%perm, &
                            eq%msq_perm)
                    call phs_tree_find_angle_permutation &
                        (grove%tree(t1), grove%tree(t2), eq%perm, &
                            eq%angle_perm, eq%angle_sig)
                end if
            end do SCAN_PERM
        end do
    end do
end subroutine phs_grove_set_equivalences

```

(PHS forests: public)+≡

```

public :: phs_forest_set_equivalences

```

(PHS forests: procedures)+≡

```

subroutine phs_forest_set_equivalences (forest)
    type(phs_forest_t), intent(inout) :: forest
    type(permutation_t), dimension(:), allocatable :: perm_array
    integer :: i
    call permutation_array_make &
        (perm_array, flavor_get_pdg (forest%flv(forest%n_in+1:)))
    do i = 1, size (forest%grove)
        call phs_grove_set_equivalences (forest%grove(i), perm_array)
    end do
end subroutine phs_forest_set_equivalences

```

```

end do
forest%n_equivalences = sum (forest%grove%equivalence_list%length)
end subroutine phs_forest_set_equivalences

```

12.3.11 Interface for VAMP equivalences

Transform the equivalence lists into a `vamp_equivalence_list` object. The additional information that we need is: the number of extra integration dimensions (associated to structure functions), which ones of those correspond to external event generators (so that the binning must not be adapted), and whether there is any dependence on the first azimuthal angle (so its binning may be adapted or fixed).

```

<PHS forests: public>+≡
public :: phs_forest_setup_vamp_equivalences

<PHS forests: procedures>+≡
subroutine phs_forest_setup_vamp_equivalences &
  (forest, n_dim_extra, externally_generated, azimuthal_dependence, &
   vamp_eq)
  type(phs_forest_t), intent(in) :: forest
  integer, intent(in) :: n_dim_extra
  logical, dimension(n_dim_extra), intent(in) :: externally_generated
  logical, intent(in) :: azimuthal_dependence
  type(vamp_equivalences_t), intent(out) :: vamp_eq
  integer :: n_equivalences, n_channels, n_dim, n_masses, n_angles
  integer, dimension(forest%n_dimensions + n_dim_extra) :: perm, mode
  integer :: mode_azimuthal_angle
  type(equivalence_t), pointer :: eq
  integer :: i, j, g
  integer :: left, right
  n_equivalences = forest%n_equivalences
  n_channels = forest%n_trees
  n_dim = forest%n_dimensions
  n_masses = forest%n_masses
  n_angles = forest%n_angles
  call vamp_equivalences_init &
    (vamp_eq, n_equivalences, n_channels, n_dim + n_dim_extra)
  if (azimuthal_dependence) then
    mode_azimuthal_angle = VEQ_IDENTITY
  else
    mode_azimuthal_angle = VEQ_INVARIANT
  end if
  g = 0
  eq => null ()
  do i = 1, n_equivalences
    if (.not. associated (eq)) then
      g = g + 1
      eq => forest%grove(g)%equivalence_list%first
    end if
    do j = 1, n_masses
      perm(j) = permute (j, eq%msq_perm)
      mode(j) = VEQ_IDENTITY
    end do
  end do
end subroutine

```

```

end do
do j = 1, n_angles
  perm(n_masses+j) = n_masses + permute (j, eq%angle_perm)
  if (j == 1) then
    mode(n_masses+j) = mode_azimuthal_angle ! first azimuthal angle
  else if (mod(j,2) == 1) then
    mode(n_masses+j) = VEQ_SYMMETRIC ! other azimuthal angles
  else if (eq%angle_sig(j)) then
    mode(n_masses+j) = VEQ_IDENTITY ! polar angle +
  else
    mode(n_masses+j) = VEQ_INVERT ! polar angle -
  end if
end do
do j = 1, n_dim_extra
  perm(n_dim+j) = n_dim + j
  if (externally_generated(j)) then
    mode(n_dim+j) = VEQ_INVARIANT
  else
    mode(n_dim+j) = VEQ_IDENTITY
  end if
end do
left = eq%left + forest%grove(g)%tree_count_offset
right = eq%right + forest%grove(g)%tree_count_offset
call vamp_equivalence_set (vamp_eq, i, left, right, perm, mode)
eq => eq%next
end do
call vamp_equivalences_complete (vamp_eq)
end subroutine phs_forest_setup_vamp_equivalences

```

12.3.12 Phase-space evaluation

```

<PHS forests: public>+≡
  public :: phs_forest_evaluate_phase_space

<PHS forests: procedures>+≡
  subroutine phs_forest_evaluate_phase_space &
    (forest, channel, active, sqrts, x, factor, volume, ok)
    type(phs_forest_t), intent(inout) :: forest
    integer, intent(in) :: channel
    logical, dimension(:), intent(in) :: active
    real(default), intent(in) :: sqrts
    real(default), dimension(:,:), intent(inout) :: x
    real(default), dimension(:), intent(out) :: factor
    real(default), intent(out) :: volume
    logical, intent(out) :: ok
    integer :: g, t, ch
    integer(TC) :: k, k_root, k_in
    g = forest%grove_lookup (channel)
    t = channel - forest%grove(g)%tree_count_offset
    call phs_prt_set_undefined (forest%prt)
    call phs_prt_set_undefined (forest%prt_out)
    k_in = forest%n_tot
    forall (k = 1:forest%n_in)

```

```

        forest%prt(ibset(0,k_in-k)) = forest%prt_in(k)
    end forall
    do k = 1, forest%n_out
        call phs_prt_set_msq (forest%prt(ibset(0,k-1)), &
            flavor_get_mass (forest%flv(forest%n_in+k)) ** 2)
    end do
    k_root = 2**forest%n_out - 1
    select case (forest%n_in)
    case (1)
        forest%prt(k_root) = forest%prt_in(1)
    case (2)
        call phs_prt_combine &
            (forest%prt(k_root), forest%prt_in(1), forest%prt_in(2))
    end select
    call phs_tree_compute_momenta_from_x (forest%grove(g)%tree(t), &
        forest%prt, factor(channel), volume, sqrts, x(:,channel), ok)
    if (ok) then
        ch = 0
        do g = 1, size (forest%grove)
            do t = 1, size (forest%grove(g)%tree)
                ch = ch + 1
                if (ch == channel) cycle
                if (active(ch)) then
                    call phs_tree_combine_particles &
                        (forest%grove(g)%tree(t), forest%prt)
                    call phs_tree_compute_x_from_momenta &
                        (forest%grove(g)%tree(t), &
                            forest%prt, factor(ch), sqrts, x(:,ch))
                end if
            end do
        end do
        forall (k = 1:forest%n_out)
            forest%prt_out(k) = forest%prt(ibset(0,k-1))
        end forall
    end if
end subroutine phs_forest_evaluate_phase_space

```

12.3.13 Test of forest setup

Write a possible phase-space file for a $2 \rightarrow 3$ process and make the corresponding forest. Print the forest and the resulting VAMP equivalence array. Choose some in-particle momenta and a random-number array and evaluate out-particles and phase-space factors.

```

<PHS forests: public>+≡
    public :: phs_forest_test

<PHS forests: procedures>+≡
    subroutine phs_forest_test ()
        use os_interface, only: os_data_t
        type(os_data_t) :: os_data
        type(phs_forest_t) :: forest
        type(model_t), pointer :: model
        type(string_t) :: process_id
    end subroutine

```

```

type(flavor_t), dimension(5) :: flv
type(vamp_equivalences_t) :: vamp_eq
type(string_t) :: filename
type(interaction_t) :: int
integer :: unit
integer, parameter :: u = 20
integer, parameter :: n_dim_extra = 2
logical, dimension(2), parameter :: &
    externally_generated = (/ .true., .false. /)
logical, parameter :: azimuthal_dependence = .false.
type(mapping_defaults_t) :: mapping_defaults
logical :: found_process, ok
integer :: channel, ch
logical, dimension(4) :: active = .true.
real(default) :: sqrts = 1000
real(default), dimension(5,4) :: x
real(default), dimension(4) :: factor
real(default) :: volume
print *, "*** Read model file"
call syntax_model_file_init ()
call model_list_read_model &
    (var_str("QCD"), var_str("test.mdl"), os_data, model)
call syntax_model_file_final ()
print *
print *, "*** Create phase-space file 'test.phs'"
call flavor_init (flv, (/ 11, -11, 11, -11, 22 /), model)
open (file="test.phs", unit=u, action="write")
write (u, *) "process foo"
write (u, *) "  grove"
write (u, *) "    tree 3 7"
write (u, *) "      map 3 s_channel 23"
write (u, *) "    tree 5 7"
write (u, *) "    tree 6 7"
write (u, *) "  grove"
write (u, *) "    tree 9 11"
write (u, *) "      map 9 t_channel 22"
close (u)
print *
print *, "*** Read phase-space file 'test.phs'"
call syntax_phs_forest_init ()
process_id = "foo"
unit = free_unit ()
filename = "test.phs"
open (file=char(filename), unit=unit, action="read", status="old")
call phs_forest_read (forest, unit, process_id, 2, 3, model, found_process)
close (unit)
print *
print *, "*** Set parameters, flavors, equiv, momenta"
call phs_forest_set_flavors (forest, flv)
call phs_forest_set_parameters (forest, mapping_defaults, .false.)
call phs_forest_set_equivalences (forest)
call interaction_init (int, 2, 0, 3)
call interaction_set_momentum (int, &
    vector4_moving (500._default, 500._default, 3), 1)

```

```

call interaction_set_momentum (int, &
    vector4_moving (500._default,-500._default, 3), 2)
call phs_forest_set_prt_in (forest, int)
channel = 2
x = 0
x(:,channel) = (/ 0.3, 0.4, 0.1, 0.9, 0.6 /)
1 format (5(1x,G12.5))
print *, "Input values:"
print 1, x(:,channel)
print *
print *, "*** Evaluate phase space"
call phs_forest_evaluate_phase_space (forest, &
    channel, active, sqrts, x, factor, volume, ok)
call phs_forest_get_prt_out (forest, int)
print *, "Output values:"
do ch = 1, 4
    print 1, x(:,ch)
end do
call interaction_write (int)
print *, "factors:"
print 1, factor
print *, "volume:"
print 1, volume
call phs_forest_write (forest)
print *
print *, "*** Compute equivalences"
call phs_forest_setup_vamp_equivalences (forest, &
    n_dim_extra, externally_generated, azimuthal_dependence, &
    vamp_eq)
call vamp_equivalences_write (vamp_eq)
print *
print *, "*** Cleanup"
call vamp_equivalences_final (vamp_eq)
call phs_forest_final (forest)
call syntax_phs_forest_final ()
end subroutine phs_forest_test

```

12.4 Finding phase space parameterizations

If the phase space configuration is not found in the appropriate file, we should generate one.

The idea is to construct all Feynman diagrams subject to certain constraints which eliminate everything that is probably irrelevant for the integration. These Feynman diagrams (cascades) are grouped in groves by finding equivalence classes related by symmetry and ordered with respect to their importance (resonances). Finally, the result (or part of it) is written to file and used for the integration.

This module may eventually disappear and be replaced by CAML code. In particular, we need here a set of Feynman rules (vertices with particle codes, but not the factors). Thus, the module works for the Standard Model only.

Note that this module is stand-alone, it communicates to the main program only via the generated ASCII phase-space configuration file.

```

<cascades.f90>≡
  <File header>

  module cascades

    <Use kinds>
    use kinds, only: TC, i8, i32 !NODEP!
    <Use strings>
    use limits, only: CASCADE_SET_FILL_RATIO, MAX_WARN_RESONANCE !NODEP!
    <Use file utils>
    use diagnostics !NODEP!
    use hashes
    use pdg_arrays, only: UNDEFINED
    use models
    use flavors
    use phs_forests

    <Standard module head>

    <Cascades: public>

    <Cascades: parameters>

    <Cascades: types>

    <Cascades: interfaces>

    contains

    <Cascades: procedures>

  end module cascades

```

12.4.1 The mapping modes

The valid mapping modes, to be used below:

```

<Mapping modes>≡
  integer, parameter :: &
    & NO_MAPPING = 0, S_CHANNEL = 1, T_CHANNEL = 2, U_CHANNEL = -2, &
    & RADIATION = 3, COLLINEAR = 4, INFRARED = 5

  <Cascades: parameters>≡
    <Mapping modes>

```

12.4.2 The cascade type

A cascade is essentially the same as a decay tree (both definitions may be merged in a later version). It contains a linked tree of nodes, each of which representing an internal particle. In contrast to decay trees, each node has a definite particle code. These nodes need not be modified, therefore we can use pointers and do not have to copy them. Thus, physically each cascades has only a single node,

the mother particle. However, to be able to compare trees quickly, we store in addition an array of binary codes which is always sorted in ascending order. This is accompanied by a corresponding list of particle codes. The index is the location of the corresponding cascade in the cascade set, this may be used to access the daughters directly.

The real mass is the particle mass belonging to the particle code. The minimal mass is the sum of the real masses of all its daughters; this is the kinematical cutoff. The effective mass may be zero if the particle mass is below a certain threshold; it may be the real mass if the particle is resonant; or it may be some other value.

The logical `t_channel` is set if this a t -channel line, while `initial` is true only for an initial particle. Note that both initial particles are also `t_channel` by definition, and that they are distinguished by the direction of the tree: One of them decays and is the root of the tree, while the other one is one of the leaves.

The cascade is a list of nodes (particles) which are linked via the `daughter` entries. The node is the mother particle of the decay cascade. Much of the information in the nodes is repeated in arrays, to be accessible more easily. The arrays will be kept sorted by binary codes.

The counter `n_t_channel` is non-negative once an initial particle is included in the tree: then, it counts the number of t -channel lines.

The `multiplicity` is the number of branchings to follow until all daughters are on-shell. A resonant or non-decaying particle has multiplicity one. Merging nodes, the multiplicities add unless the mother is a resonance. An initial or final node has multiplicity zero.

The arrays correspond to the subnode tree `tree` of the current cascade. PDG codes are stored only for those positions which are resonant, with the exception of the last entry, i.e., the current node. Other positions, in particular external legs, are assigned undefined PDG code.

A cascade is uniquely identified by its tree, the tree of PDG codes, and the tree of mappings. The tree of resonances is kept only to mask the PDG tree as described above.

```

<Cascades: types>≡
  type :: cascade_t
    private
      ! counters
      integer :: index = 0
      integer :: grove = 0
      ! status
      logical :: active = .false.
      logical :: complete = .false.
      logical :: incoming = .false.
      ! this node
      integer(TC) :: bincode = 0
      type(flavor_t) :: flv
      integer :: pdg = UNDEFINED
      logical :: is_vector = .false.
      real(default) :: m_min = 0
      real(default) :: m_rea = 0
      real(default) :: m_eff = 0
      integer :: mapping = NO_MAPPING

```

```

logical :: on_shell = .false.
logical :: resonant = .false.
logical :: log_enhanced = .false.
logical :: t_channel = .false.
! global tree properties
integer :: multiplicity = 0
integer :: internal = 0
integer :: n_resonances = 0
integer :: n_log_enhanced = 0
integer :: n_t_channel = -1
! the sub-node tree
integer :: depth = 0
integer(TC), dimension(:), allocatable :: tree
integer, dimension(:), allocatable :: tree_pdg
integer, dimension(:), allocatable :: tree_mapping
logical, dimension(:), allocatable :: tree_resonant
! branch connections
logical :: has_children = .false.
type(cascade_t), pointer :: daughter1 => null ()
type(cascade_t), pointer :: daughter2 => null ()
type(cascade_t), pointer :: mother => null ()
! next in list
type(cascade_t), pointer :: next => null ()
end type cascade_t

```

<Cascades: procedures>≡

```

subroutine cascade_init (cascade, depth)
  type(cascade_t), intent(out) :: cascade
  integer, intent(in) :: depth
  integer, save :: index = 0
  index = cascade_index ()
  cascade%index = index
  cascade%depth = depth
  cascade%active = .true.
  allocate (cascade%tree (depth))
  allocate (cascade%tree_pdg (depth))
  allocate (cascade%tree_mapping (depth))
  allocate (cascade%tree_resonant (depth))
end subroutine cascade_init

```

Keep and increment a global index

<Cascades: procedures>+≡

```

function cascade_index (seed) result (index)
  integer :: index
  integer, intent(in), optional :: seed
  integer, save :: i = 0
  if (present (seed)) i = seed
  i = i + 1
  index = i
end function cascade_index

```

We need three versions of writing cascades. This goes to the phase-space file:

<Cascades: procedures>+≡

```

subroutine cascade_write_file_format (cascade, unit)
  type(cascade_t), intent(in) :: cascade
  integer, intent(in), optional :: unit
  integer :: u, i
1  format(3x,A,1x,40(1x,I4))
2  format(3x,A,1x,I3,1x,A,1x,I7)
  u = output_unit (unit); if (u < 0) return
  write (u, 1) "tree", reduced (cascade%tree)
  do i = 1, cascade%depth
    select case (cascade%tree_mapping(i))
    case (NO_MAPPING)
    case (S_CHANNEL)
      write(u,2) 'map', &
        cascade%tree(i), 's_channel', abs (cascade%tree_pdg(i))
    case (T_CHANNEL)
      write(u,2) 'map', &
        cascade%tree(i), 't_channel', abs (cascade%tree_pdg(i))
    case (U_CHANNEL)
      write(u,2) 'map', &
        cascade%tree(i), 'u_channel', abs (cascade%tree_pdg(i))
    case (RADIATION)
      write(u,2) 'map', &
        cascade%tree(i), 'radiation', abs (cascade%tree_pdg(i))
    case (COLLINEAR)
      write(u,2) 'map', &
        cascade%tree(i), 'collinear', abs (cascade%tree_pdg(i))
    case (INFRARED)
      write(u,2) 'map', &
        cascade%tree(i), 'infrared', abs (cascade%tree_pdg(i))
    case default
      call msg_bug (" Impossible mapping mode encountered")
    end select
  end do
contains
  function reduced (array)
    integer(TC), dimension(:), intent(in) :: array
    integer(TC), dimension(max((size(array)-3)/2, 1)) :: reduced
    integer :: i, j
    j = 1
    do i=1, size(array)
      if (decay_level(array(i)) > 1) then
        reduced(j) = array(i)
        j = j+1
      end if
    end do
  end function reduced
  function decay_level (k) result (l)
    integer(TC), intent(in) :: k
    integer :: l
    integer :: i
    l = 0
    do i = 0, bit_size(k) - 1
      if (btest(k,i)) l = l + 1
    end do
  end function

```

```

end function decay_level
subroutine start_comment (u)
  integer, intent(in) :: u
  write(u, '(1x,A)', advance='no') '!'
end subroutine start_comment
end subroutine cascade_write_file_format

```

This creates metapost source for graphical display:

(Cascades: procedures)+≡

```

subroutine cascade_write_graph_format (cascade, count, unit)
  type(cascade_t), intent(in) :: cascade
  integer, intent(in) :: count
  integer, intent(in), optional :: unit
  integer :: u
  integer(TC) :: mask
  type(string_t) :: left_str, right_str
  u = output_unit (unit); if (u < 0) return
  mask = 2**((cascade%depth+3)/2) - 1
  left_str = ""
  right_str = ""
  write (u, '(A)') "\begin{minipage}{105pt}"
  write (u, '(A)') "\vspace{30pt}"
  write (u, '(A)') "\begin{center}"
  write (u, '(A)') "\begin{fmfgraph*}(55,55)"
  call graph_write (cascade, mask)
  write (u, '(A)') "\fmfleft{" // char (extract (left_str, 2)) // "}"
  write (u, '(A)') "\fmfright{" // char (extract (right_str, 2)) // "}"
  write (u, '(A)') "\end{fmfgraph*}\\"
  write (u, '(A,I5,A)') "\fbox{$", count, "$}"
  write (u, '(A)') "\end{center}"
  write (u, '(A)') "\end{minipage}"
  write (u, '(A)') "%"

```

contains

```

recursive subroutine graph_write (cascade, mask, reverse)
  type(cascade_t), intent(in) :: cascade
  integer(TC), intent(in) :: mask
  logical, intent(in), optional :: reverse
  logical :: rev
  rev = .false.; if (present(reverse)) rev = reverse
  if (cascade%has_children) then
    if (.not.rev) then
      call vertex_write (cascade, cascade%daughter1, mask)
      call vertex_write (cascade, cascade%daughter2, mask)
    else
      call vertex_write (cascade, cascade%daughter2, mask, .true.)
      call vertex_write (cascade, cascade%daughter1, mask, .true.)
    end if
    if (cascade%complete) then
      call vertex_write (cascade, cascade%mother, mask, .true.)
      write (u, '(A,I3,A)') &
        "\fmfv{d.shape=square}{v", cascade%bincode, "}"
    end if
  else
    if (cascade%incoming) then

```

```

        call external_write (cascade%bincode, &
            flavor_get_tex_name (flavor_anti (cascade%flv)), left_str)
    else
        call external_write (cascade%bincode, &
            flavor_get_tex_name (cascade%flv), right_str)
    end if
end if
end if
end subroutine graph_write
recursive subroutine vertex_write (cascade, daughter, mask, reverse)
    type(cascade_t), intent(in) :: cascade, daughter
    integer(TC), intent(in) :: mask
    logical, intent(in), optional :: reverse
    call graph_write (daughter, mask, reverse)
    if (daughter%has_children) then
        call line_write (cascade%bincode, daughter%bincode, cascade%flv, &
            mapping=daughter%mapping)
    else
        call line_write (cascade%bincode, daughter%bincode, cascade%flv)
    end if
end subroutine vertex_write
subroutine line_write (i1, i2, flv, mapping)
    integer(TC), intent(in) :: i1, i2
    type(flavor_t), intent(in) :: flv
    integer, intent(in), optional :: mapping
    integer :: k1, k2
    type(string_t) :: prt_type
    select case (flavor_get_spin_type (flv))
    case (SCALAR);      prt_type = "plain"
    case (SPINOR);      prt_type = "fermion"
    case (VECTOR);      prt_type = "boson"
    case (VECTORSPINOR); prt_type = "fermion"
    case (TENSOR);      prt_type = "dbl_wiggly"
    case default;       prt_type = "dashes"
    end select
    if (flavor_is_antiparticle (flv)) then
        k1 = i2; k2 = i1
    else
        k1 = i1; k2 = i2
    end if
    if (present (mapping)) then
        select case (mapping)
        case (S_CHANNEL)
            write (u, '(A,I3,A,I3,A)') "\fmf{" // char (prt_type) // &
                & ",f=blue,lab=\sm\blue$" // &
                & char (flavor_get_tex_name (flv)) // "$}" // &
                & "{v", k1, ",v", k2, "}"
        case (T_CHANNEL, U_CHANNEL)
            write (u, '(A,I3,A,I3,A)') "\fmf{" // char (prt_type) // &
                & ",f=cyan,lab=\sm\cyan$" // &
                & char (flavor_get_tex_name (flv)) // "$}" // &
                & "{v", k1, ",v", k2, "}"
        case (RADIATION)
            write (u, '(A,I3,A,I3,A)') "\fmf{" // char (prt_type) // &
                & ",f=green,lab=\sm\green$" // &

```

```

        & char (flavor_get_tex_name (flv)) // "$}" // &
        & "{v", k1, ",v", k2, "}"
    case (COLLINEAR)
        write (u, '(A,I3,A,I3,A)') "\fmf{" // char (prt_type) // &
        & ",f=magenta,lab=\sm\magenta$" // &
        & char (flavor_get_tex_name (flv)) // "$}" // &
        & "{v", k1, ",v", k2, "}"
    case (INFRARED)
        write (u, '(A,I3,A,I3,A)') "\fmf{" // char (prt_type) // &
        & ",f=red,lab=\sm\red$" // &
        & char (flavor_get_tex_name (flv)) // "$}" // &
        & "{v", k1, ",v", k2, "}"
    case default
        write (u, '(A,I3,A,I3,A)') "\fmf{" // char (prt_type) // &
        & ",f=black}" // &
        & "{v", k1, ",v", k2, "}"
    end select
else
    write (u, '(A,I3,A,I3,A)') "\fmf{" // char (prt_type) // &
    & "}" // &
    & "{v", k1, ",v", k2, "}"
end if
end subroutine line_write
subroutine external_write (bincode, name, ext_str)
    integer(TC), intent(in) :: bincode
    type(string_t), intent(in) :: name
    type(string_t), intent(inout) :: ext_str
    character(len=5) :: str
    write (str, '(A2,I3)') ",v", bincode
    ext_str = ext_str // str
    write (u, '(A,I3,A,I3,A)') "\fmflabel{\sm$" &
    // char (name) &
    // "\",(" , bincode, ")" &
    // "$}{v", bincode, "}"
end subroutine external_write
end subroutine cascade_write_graph_format

```

This is for screen/debugging output:

(Cascades: procedures)+≡

```

subroutine cascade_write (cascade, unit)
    type(cascade_t), intent(in) :: cascade
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write (u, *) 'Cascade #', cascade%index
    write (u, *) ' Grove:      #', cascade%grove
    write (u, *) ' act/cmp/inc: ', &
        cascade%active, cascade%complete, cascade%incoming
    write (u, *) ' Bincode:      ', cascade%bincode
    write (u, "(1x,A)", advance="no") ' Flavor:      '
    call flavor_write (cascade%flv, unit)
    write (u, *) ' Active flavor:', cascade%pdg
    write (u, *) ' Is vector:    ', cascade%is_vector
    write (u, *) ' Mass (m/r/e): ', &

```

```

        cascade%m_min, cascade%m_rea, cascade%m_eff
write (u, *) ' Mapping:      ', cascade%mapping
write (u, *) ' res/log/tch: ', &
        cascade%resonant, cascade%log_enhanced, cascade%t_channel
write (u, *) ' Multiplicity: ', cascade%multiplicity
write (u, *) ' n internal:   ', cascade%internal
write (u, *) ' n res/log/tch:', &
        cascade%n_resonances, cascade%n_log_enhanced, cascade%n_t_channel
write (u, *) ' Depth:      ', cascade%depth
write (u, *) ' Tree:       ', cascade%tree
write (u, *) ' Tree(PDG):   ', cascade%tree_pdg
write (u, *) ' Tree(mapping):', cascade%tree_mapping
write (u, *) ' Tree(res):    ', cascade%tree_resonant
if (cascade%has_children) then
    write (u, *) ' Daughter1/2: ', &
        cascade%daughter1%index, cascade%daughter2%index
end if
if (associated (cascade%mother)) then
    write (u, *) ' Mother:      ', cascade%mother%index
end if
end subroutine cascade_write

```

12.4.3 Creating new cascades

This initializes a single-particle cascade (external, final state). The PDG entry in the tree is set undefined because the cascade is not resonant. However, the flavor entry is set, so the cascade flavor is identified nevertheless.

(*Cascades: procedures*)+≡

```

subroutine cascade_init_outgoing (cascade, flv, pos, m_thr)
    type(cascade_t), intent(out) :: cascade
    type(flavor_t), intent(in) :: flv
    integer, intent(in) :: pos
    real(default), intent(in) :: m_thr
    call cascade_init (cascade, 1)
    cascade%bincode = ibset (0_TC, pos-1)
    cascade%flv = flv
    cascade%pdg = 0
    cascade%is_vector = flavor_get_spin_type (flv) == VECTOR
    cascade%m_min = flavor_get_mass (flv)
    cascade%m_rea = cascade%m_min
    if (cascade%m_rea >= m_thr) then
        cascade%m_eff = cascade%m_rea
    end if
    cascade%on_shell = .true.
    cascade%multiplicity = 1
    cascade%tree(1) = cascade%bincode
    cascade%tree_pdg(1) = cascade%pdg
    cascade%tree_mapping(1) = NO_MAPPING
    cascade%tree_resonant(1) = .false.
end subroutine cascade_init_outgoing

```

The same for an incoming line:

```

<Cascades: procedures>+=
  subroutine cascade_init_incoming (cascade, flv, pos, m_thr)
    type(cascade_t), intent(out) :: cascade
    type(flavor_t), intent(in) :: flv
    integer, intent(in) :: pos
    real(default), intent(in) :: m_thr
    call cascade_init (cascade, 1)
    cascade%incoming = .true.
    cascade%bincode = ibset (O_TC, pos-1)
    cascade%flv = flavor_anti (flv)
    cascade%pdg = 0
    cascade%is_vector = flavor_get_spin_type (flv) == VECTOR
    cascade%m_min = flavor_get_mass (flv)
    cascade%m_rea = cascade%m_min
    if (cascade%m_rea >= m_thr) then
      cascade%m_eff = cascade%m_rea
    end if
    cascade%on_shell = .true.
    cascade%n_t_channel = 0
    cascade%tree(1) = cascade%bincode
    cascade%tree_pdg(1) = cascade%pdg
    cascade%tree_mapping(1) = NO_MAPPING
    cascade%tree_resonant(1) = .false.
  end subroutine cascade_init_incoming

```

12.4.4 Tools

This function returns true if the two cascades share no common external particle. This is a requirement for joining them.

```

<Cascades: interfaces>≡
  interface operator(.disjunct.)
    module procedure cascade_disjunct
  end interface

<Cascades: procedures>+=
  function cascade_disjunct (cascade1, cascade2) result (flag)
    logical :: flag
    type(cascade_t), intent(in) :: cascade1, cascade2
    flag = iand (cascade1%bincode, cascade2%bincode) == 0
  end function cascade_disjunct

```

12.4.5 Hash entries for cascades

We will set up a hash array which contains keys of and pointers to cascades. We hold a list of cascade (pointers) within each bucket. This is not for collision resolution, but for keeping similar, but unequal cascades together.

```

<Cascades: types>+=
  type :: cascade_p

```

```

        type(cascade_t), pointer :: cascade => null ()
        type(cascade_p), pointer :: next => null ()
    end type cascade_p

```

Here is the bucket or hash entry type:

```

<Cascades: types>+≡
type :: hash_entry_t
    integer(i32) :: hashval = 0
    integer(i8), dimension(:), allocatable :: key
    type(cascade_p), pointer :: first => null ()
    type(cascade_p), pointer :: last => null ()
end type hash_entry_t

```

Finalize: just deallocate the list; the contents are just pointers.

```

<Cascades: procedures>+≡
subroutine hash_entry_final (hash_entry)
    type(hash_entry_t), intent(inout) :: hash_entry
    type(cascade_p), pointer :: current
    do while (associated (hash_entry%first))
        current => hash_entry%first
        hash_entry%first => current%next
        deallocate (current)
    end do
end subroutine hash_entry_final

```

Output: concise format for debugging, just list cascade indices.

```

<Cascades: procedures>+≡
subroutine hash_entry_write (hash_entry, unit)
    type(hash_entry_t), intent(in) :: hash_entry
    integer, intent(in), optional :: unit
    type(cascade_p), pointer :: current
    integer :: u, i
    u = output_unit (unit); if (u < 0) return
    write (u, "(1x,A)", advance="no") "Entry:"
    do i = 1, size (hash_entry%key)
        write (u, "(1x,I3)", advance="no") hash_entry%key(i)
    end do
    write (u, "(1x,A)", advance="no") "->"
    current => hash_entry%first
    do while (associated (current))
        write (u, "(1x,I7)", advance="no") current%cascade%index
        current => current%next
    end do
    write (u, *)
end subroutine hash_entry_write

```

This function adds a cascade pointer to the bucket. If ok is present, check first if it is already there and return failure if yes.

```

<Cascades: procedures>+≡
subroutine hash_entry_add_cascade_ptr (hash_entry, cascade, ok)
    type(hash_entry_t), intent(inout) :: hash_entry
    type(cascade_t), intent(in), target :: cascade

```

```

logical, intent(out), optional :: ok
type(cascade_p), pointer :: current
if (present(ok)) then
    ok = .not. hash_entry_contains (hash_entry, cascade)
    if (.not. ok) return
end if
allocate (current)
current%cascade => cascade
if (associated (hash_entry%last)) then
    hash_entry%last%next => current
else
    hash_entry%first => current
end if
hash_entry%last => current
end subroutine hash_entry_add_cascade_ptr

```

This function checks whether a cascade is already in the bucket. For incomplete cascades, we look for an exact match. It should suffice to verify the tree, the PDG codes, and the mapping modes. This is the information that is written to the phase space file.

For complete cascades, we ignore the PDG code at positions with mappings infrared, collinear, or t/u-channel. Thus a cascade which is distinguished only by PDG code at such places, is flagged existent. If the convention is followed that light particles come before heavier ones (in the model definition), this ensures that the lightest particle is kept in the appropriate place, corresponding to the strongest peak.

For external cascades (incoming/outgoing) we take the PDG code into account even though it is zeroed in the PDG-code tree.

(Cascades: procedures) +=

```

function hash_entry_contains (hash_entry, cascade) result (flag)
    logical :: flag
    type(hash_entry_t), intent(in), target :: hash_entry
    type(cascade_t), intent(in) :: cascade
    type(cascade_p), pointer :: current
    integer, dimension(:), allocatable :: tree_pdg
    flag = .false.
    allocate (tree_pdg (size (cascade%tree_pdg)))
    if (cascade%has_children) then
        if (cascade%complete) then
            where (cascade%tree_mapping == INFRARED .or. &
                 cascade%tree_mapping == COLLINEAR .or. &
                 cascade%tree_mapping == T_CHANNEL .or. &
                 cascade%tree_mapping == U_CHANNEL)
                tree_pdg = 0
            elsewhere
                tree_pdg = cascade%tree_pdg
            end where
        else
            tree_pdg = cascade%tree_pdg
        end if
    else
        tree_pdg = flavor_get_pdg (cascade%flv)
    end if
end function

```

```

current => hash_entry%first
do while (associated (current))
  if (current%cascade%depth == cascade%depth) then
    if (all (current%cascade%tree == cascade%tree)) then
      if (all (current%cascade%tree_mapping == cascade%tree_mapping)) &
        then
          if (all (current%cascade%tree_pdg .match. tree_pdg)) then
            flag = .true.; return
          end if
        end if
      end if
    end if
  end if
  current => current%next
end do
end function hash_entry_contains

```

This function returns a pointer to the list entry of a cascade that is similar to the input, i.e. tree and PDG codes match but the mappings may be distributed differently.

```

<Cascades: procedures>+=
function hash_entry_get_similar_p (hash_entry, cascade) result (current)
  type(cascade_p), pointer :: current
  type(hash_entry_t), intent(in), target :: hash_entry
  type(cascade_t), intent(in) :: cascade
  current => hash_entry%first
  do while (associated (current))
    if (current%cascade%depth == cascade%depth) then
      if (all (current%cascade%tree == cascade%tree)) then
        if (all (current%cascade%tree_pdg &
          .match. cascade%tree_pdg)) return
        end if
      end if
    end if
    current => current%next
  end do
end function hash_entry_get_similar_p

```

For PDG codes, we specify that the undefined code matches any code. This is already defined for flavor objects, but here we need it for the codes themselves.

```

<Cascades: interfaces>+=
interface operator(.match.)
  module procedure pdg_match
end interface

<Cascades: procedures>+=
elemental function pdg_match (pdg1, pdg2) result (flag)
  logical :: flag
  integer(TC), intent(in) :: pdg1, pdg2
  select case (pdg1)
  case (0)
    flag = .true.
  case default
    select case (pdg2)
    case (0)

```

```

        flag = .true.
      case default
        flag = pdg1 == pdg2
      end select
    end select
  end function pdg_match

```

12.4.6 The cascade set

The cascade set will later be transformed into the decay forest. It is set up as a linked list. In addition to the usual `first` and `last` pointers, there is a `first_t` pointer which points to the first t-channel cascade (after all s-channel cascades), and a `first_k` pointer which points to the first final cascade (with a keystone).

As an auxiliary device, the object contains a hash array with associated parameters where an additional pointer is stored for each cascade. The keys are made from the relevant cascade data. This hash is used for fast detection (and thus avoidance) of double entries in the cascade list.

```

<Cascades: public>≡
  public :: cascade_set_t

<Cascades: types>+≡
  type :: cascade_set_t
    private
    type(model_t), pointer :: model
    integer :: n_in, n_out, n_tot
    integer :: depth_out, depth_tot
    real(default) :: sqrts = 0
    real(default) :: m_threshold_s = 0
    real(default) :: m_threshold_t = 0
    integer :: off_shell = 0
    integer :: t_channel = 0
    integer :: n_groves = 0
    ! The cascade list
    type(cascade_t), pointer :: first => null ()
    type(cascade_t), pointer :: last => null ()
    type(cascade_t), pointer :: first_t => null ()
    type(cascade_t), pointer :: first_k => null ()
    ! The hashtable
    integer :: n_entries = 0
    real :: fill_ratio = 0
    integer :: n_entries_max = 0
    integer(i32) :: mask = 0
    type(hash_entry_t), dimension(:), allocatable :: entry
  end type cascade_set_t

```

Return true if there are cascades which are active and complete, so the phase space file would be nonempty.

```

<Cascades: public>+≡
  public :: cascade_set_is_valid

```

```

<Cascades: procedures>+=
function cascade_set_is_valid (cascade_set) result (flag)
  logical :: flag
  type(cascade_set_t), intent(in) :: cascade_set
  type(cascade_t), pointer :: cascade
  flag = .false.
  cascade => cascade_set%first_k
  do while (associated (cascade))
    if (cascade%active .and. cascade%complete) then
      flag = .true.
      return
    end if
    cascade => cascade%next
  end do
end function cascade_set_is_valid

```

The initializer sets up the hash table with some initial size guessed by looking at the number of external particles. We choose 256 for 3 external particles and a factor of 4 for each additional particle, limited at $2^{30}=1\text{G}$.

```

<Limits: public parameters>+=
real, parameter, public :: CASCADE_SET_FILL_RATIO = 0.1

<Cascades: procedures>+=
subroutine cascade_set_init (cascade_set, model, n_in, n_out, phs_par)
  type(cascade_set_t), intent(out) :: cascade_set
  type(model_t), intent(in), target :: model
  integer, intent(in) :: n_in, n_out
  type(phs_parameters_t), intent(in) :: phs_par
  integer :: size_guess
  cascade_set%model => model
  cascade_set%n_in = n_in
  cascade_set%n_out = n_out
  cascade_set%n_tot = n_in + n_out
  select case (n_in)
    case (1); cascade_set%depth_out = 2 * n_out - 3
    case (2); cascade_set%depth_out = 2 * n_out - 1
  end select
  cascade_set%depth_tot = 2 * cascade_set%n_tot - 3
  cascade_set%sqrts = phs_par%sqrts
  cascade_set%m_threshold_s = phs_par%m_threshold_s
  cascade_set%m_threshold_t = phs_par%m_threshold_t
  cascade_set%off_shell = phs_par%off_shell
  cascade_set%t_channel = phs_par%t_channel
  cascade_set%fill_ratio = CASCADE_SET_FILL_RATIO
  size_guess = ishft (256, min (2 * (cascade_set%n_tot - 3), 22))
  cascade_set%n_entries_max = size_guess * cascade_set%fill_ratio
  cascade_set%mask = size_guess - 1
  allocate (cascade_set%entry (0:cascade_set%mask))
end subroutine cascade_set_init

```

The finalizer has to delete both the hash and the list. We assume that the hash only contains pointers, so it is simply deallocated, while the list entries are physically deleted.

```

<Cascades: public>+=
  public :: cascade_set_final

<Cascades: procedures>+=
  subroutine cascade_set_final (cascade_set)
    type(cascade_set_t), intent(inout), target :: cascade_set
    type(cascade_t), pointer :: current
    deallocate (cascade_set%entry)
    do while (associated (cascade_set%first))
      current => cascade_set%first
      cascade_set%first => cascade_set%first%next
      deallocate (current)
    end do
  end subroutine cascade_set_final

```

Three output routines: phase-space file, graph source code, and screen output.

This version generates the phase space file. It deals only with complete cascades.

```

<Cascades: public>+=
  public :: cascade_set_write_file_format

<Cascades: procedures>+=
  subroutine cascade_set_write_file_format (cascade_set, unit)
    type(cascade_set_t), intent(in), target :: cascade_set
    integer, intent(in), optional :: unit
    type(cascade_t), pointer :: cascade
    integer :: u, grove, count
    logical :: first_in_grove
    u = output_unit (unit); if (u < 0) return
    count = 0
    do grove = 1, cascade_set%n_groves
      first_in_grove = .true.
      cascade => cascade_set%first_k
      do while (associated (cascade))
        if (cascade%active .and. cascade%complete) then
          if (cascade%grove == grove) then
            if (first_in_grove) then
              first_in_grove = .false.
              write (u, *)
              write (u, "(1x,'!',1x,A,I2,A)", advance='no') &
                'Multiplicity =', cascade%multiplicity, ","
              select case (cascade%n_resonances)
                case (0)
                  write (u, '(1x,A)', advance='no') 'no resonances, '
                case (1)
                  write (u, '(1x,A)', advance='no') ' 1 resonance, '
                case default
                  write (u, '(1x,I2,1x,A)', advance='no') &
                    cascade%n_resonances, 'resonances, '
              end select
              write (u, '(1x,I2,1x,A)', advance='no') &
                cascade%n_log_enhanced, 'logs, '
              select case (cascade%n_t_channel)
                case (0); write (u, '(1x,A)') 's-channel graph'

```

```

        case (1); write (u, '(1x,A)') ' 1 t-channel line'
        case default
            write(u,'(1x,I2,1x,A)') &
                cascade%n_t_channel, 't-channel lines'
        end select
        write (u, '(1x,A,I3)') 'grove #', grove
    end if
    count = count + 1
    write (u, "(1x,'!',1x,A,1x)", advance="no") "Channel #"
    write (u, *) count
    call cascade_write_file_format (cascade, u)
end if
end if
cascade => cascade%next
end do
end do
end subroutine cascade_set_write_file_format

```

This is the graph output format., the driver-file

```

(Cascades: procedures)+≡
subroutine cascade_set_write_graph_format (cascade_set, filename, unit)
    type(cascade_set_t), intent(in), target :: cascade_set
    type(string_t), intent(in) :: filename
    integer, intent(in), optional :: unit
    type(cascade_t), pointer :: cascade
    integer :: u, grove, count, pgcount
    logical :: first_in_grove
    u = output_unit (unit); if (u < 0) return
    write (u, '(A)') "\documentclass[10pt]{article}"
    write (u, '(A)') "\usepackage{feynmp}"
    write (u, '(A)') "\usepackage{color}"
    write (u, *)
    write (u, '(A)') "\textwidth 18.5cm"
    write (u, '(A)') "\evensidemargin -1.5cm"
    write (u, '(A)') "\oddsidemargin -1.5cm"
    write (u, *)
    write (u, '(A)') "\newcommand{\blue}{\color{blue}}"
    write (u, '(A)') "\newcommand{\green}{\color{green}}"
    write (u, '(A)') "\newcommand{\red}{\color{red}}"
    write (u, '(A)') "\newcommand{\magenta}{\color{magenta}}"
    write (u, '(A)') "\newcommand{\cyan}{\color{cyan}}"
    write (u, '(A)') "\newcommand{\sm}{\footnotesize}"
    write (u, '(A)') "\setlength{\parindent}{0pt}"
    write (u, '(A)') "\setlength{\parsep}{20pt}"
    write (u, *)
    write (u, '(A)') "\begin{document}"
    write (u, '(A)') "\begin{fmffile}{ // char (filename) // }"
    write (u, '(A)') "\fmfcmd{color magenta; magenta = red + blue;}"
    write (u, '(A)') "\fmfcmd{color cyan; cyan = green + blue;}"
    write (u, '(A)') "\begin{fmfshrink}{0.5}"
    write (u, '(A)') "\begin{flushleft}"
    write (u, *)
    write (u, '(A)') "\noindent" // &

```

```

& "\textbf{\large\texttt{WHIZARD} phase space channels}" // &
& "\hfill\today"
write (u, *)
write (u, '(A)') "\vspace{10pt}"
! call write_process_tex_form (u, process_id, code, n_in, n_out)
write (u, *)
write (u, '(A)') "\textbf{Color code:}" " // &
& "{\blue resonance,}" " // &
& "{\cyan t-channel,}" " // &
& "{\green radiation,}" " // &
& "{\red infrared,}" " // &
& "{\magenta collinear,}" " // &
& "external/off-shell"
write (u, *)
write (u, '(A)') "\vspace{-20pt}"
count = 0
pgcount = 0
do grove = 1, cascade_set%n_groves
  first_in_grove = .true.
  cascade => cascade_set%first
  do while (associated (cascade))
    if (cascade%active .and. cascade%complete) then
      if (cascade%grove == grove) then
        if (first_in_grove) then
          first_in_grove = .false.
          write (u, *)
          write (u, '(A)') "\vspace{20pt}"
          write (u, '(A)') "\begin{tabular}{l}"
          write (u, '(A,I5,A)') &
            & "\fbox{\bf Grove \boldmath$, grove, "$} \\[10pt]"
          write (u, '(A,I1,A)') "Multiplicity: ", &
            cascade%multiplicity, "\\"
          write (u, '(A,I1,A)') "Resonances: ", &
            cascade%n_resonances, "\\"
          write (u, '(A,I1,A)') "Log-enhanced: ", &
            cascade%n_log_enhanced, "\\"
          write (u, '(A,I1,A)') "t-channel: ", &
            cascade%n_t_channel, ""
          write (u, '(A)') "\end{tabular}"
        end if
        count = count + 1
        call cascade_write_graph_format (cascade, count, unit)
        if (pgcount >= 250) then
          write (u, '(A)') "\clearpage"
          pgcount = 0
        end if
      end if
    end if
    cascade => cascade%next
  end do
end do
write (u, '(A)') "\end{flushleft}"
write (u, '(A)') "\end{fmfshrink}"
write (u, '(A)') "\end{fmffile}"

```

```

        write (u, '(A)') "\end{document}"
    end subroutine cascade_set_write_graph_format

```

This is for screen output and debugging:

```

<Cascades: public>+=
    public :: cascade_set_write

<Cascades: procedures>+=
    subroutine cascade_set_write (cascade_set, unit, active_only, complete_only)
        type(cascade_set_t), intent(in), target :: cascade_set
        integer, intent(in), optional :: unit
        logical, intent(in), optional :: active_only, complete_only
        logical :: active, complete
        type(cascade_t), pointer :: cascade
        integer :: u, i
        u = output_unit (unit); if (u < 0) return
        active = .true.; if (present (active_only)) active = active_only
        complete = .false.; if (present (complete_only)) complete = complete_only
        write (u, *) "Cascade set:"
        write (u, "(3x,A)", advance="no") "Model:"
        if (associated (cascade_set%model)) then
            write (u, "(1x,A)") char (model_get_name (cascade_set%model))
        else
            write (u, "(1x,A)") "[none]"
        end if
        write (u, "(3x,A)", advance="no") "n_in/out/tot ="
        write (u, *) cascade_set%n_in, cascade_set%n_out, cascade_set%n_tot
        write (u, "(3x,A)", advance="no") "depth_out/tot ="
        write (u, *) cascade_set%depth_out, cascade_set%depth_tot
        write (u, "(3x,A)", advance="no") "mass thr(s/t) ="
        write (u, *) cascade_set%m_threshold_s, cascade_set%m_threshold_t
        write (u, "(3x,A)", advance="no") "off shell ="
        write (u, *) cascade_set%off_shell
        write (u, "(3x,A)", advance="no") "n_groves ="
        write (u, *) cascade_set%n_groves
        write (u, *)
        write (u, *) "Cascade list:"
        if (associated (cascade_set%first)) then
            cascade => cascade_set%first
            do while (associated (cascade))
                if (active .and. .not. cascade%active) cycle
                if (complete .and. .not. cascade%complete) cycle
                call cascade_write (cascade, unit)
                cascade => cascade%next
            end do
        else
            write (u, *) "[empty]"
        end if
        write (u, *) "Hash array"
        write (u, "(3x,A)", advance="no") "n_entries ="
        write (u, *) cascade_set%n_entries
        write (u, "(3x,A)", advance="no") "fill_ratio ="
        write (u, *) cascade_set%fill_ratio
        write (u, "(3x,A)", advance="no") "n_entries_max ="

```

```

write (u, *) cascade_set%n_entries_max
write (u, "(3x,A)", advance="no") "mask      ="
write (u, *) cascade_set%mask
do i = 0, ubound (cascade_set%entry, 1)
  if (allocated (cascade_set%entry(i)%key)) then
    write (u, *) i
    call hash_entry_write (cascade_set%entry(i), u)
  end if
end do
end subroutine cascade_set_write

```

12.4.7 Adding cascades

Add a cascade to the set. We first try to insert it in the hash array. If successful, add it to the list. Failure indicates that it is already present, and we drop it.

The hash key is built solely from the tree array, so neither particle codes nor resonances count, just topology.

Technically, hash and list receive only pointers, so the cascade can be considered as being in either of both. We treat it as part of the list.

```

<Cascades: procedures>+≡
subroutine cascade_set_add (cascade_set, cascade, ok)
  type(cascade_set_t), intent(inout), target :: cascade_set
  type(cascade_t), intent(in), target :: cascade
  logical, intent(out) :: ok
  integer(i8), dimension(1) :: mold
  call cascade_set_hash_insert &
    (cascade_set, transfer (cascade%tree, mold), cascade, ok)
  if (ok) call cascade_set_list_add (cascade_set, cascade)
end subroutine cascade_set_add

```

Add a new cascade to the list:

```

<Cascades: procedures>+≡
subroutine cascade_set_list_add (cascade_set, cascade)
  type(cascade_set_t), intent(inout) :: cascade_set
  type(cascade_t), intent(in), target :: cascade
  if (associated (cascade_set%last)) then
    cascade_set%last%next => cascade
  else
    cascade_set%first => cascade
  end if
  cascade_set%last => cascade
end subroutine cascade_set_list_add

```

Add a cascade entry to the hash array:

```

<Cascades: procedures>+≡
subroutine cascade_set_hash_insert (cascade_set, key, cascade, ok)
  type(cascade_set_t), intent(inout), target :: cascade_set
  integer(i8), dimension(:), intent(in) :: key
  type(cascade_t), intent(in), target :: cascade
  logical, intent(out) :: ok
  integer(i32) :: h

```

```

    if (cascade_set%n_entries >= cascade_set%n_entries_max) &
        call cascade_set_hash_expand (cascade_set)
    h = hash (key)
    call cascade_set_hash_insert_rec (cascade_set, h, h, key, cascade, ok)
end subroutine cascade_set_hash_insert

```

Double the hashtable size when necessary:

```

<Cascades: procedures>+=
subroutine cascade_set_hash_expand (cascade_set)
    type(cascade_set_t), intent(inout), target :: cascade_set
    type(hash_entry_t), dimension(:), allocatable, target :: table_tmp
    type(cascade_p), pointer :: current
    integer :: i, s
    allocate (table_tmp (0:cascade_set%mask))
    table_tmp = cascade_set%entry
    deallocate (cascade_set%entry)
    s = 2 * size (table_tmp)
    cascade_set%n_entries = 0
    cascade_set%n_entries_max = s * cascade_set%fill_ratio
    cascade_set%mask = s - 1
    allocate (cascade_set%entry (0:cascade_set%mask))
    do i = 0, ubound (table_tmp, 1)
        current => table_tmp(i)%first
        do while (associated (current))
            call cascade_set_hash_insert_rec &
                (cascade_set, table_tmp(i)%hashval, table_tmp(i)%hashval, &
                    table_tmp(i)%key, current%cascade)
            current => current%next
        end do
    end do
end subroutine cascade_set_hash_expand

```

Insert the cascade at the bucket determined by the hash value. If the bucket is filled, check first for a collision (unequal keys). In that case, choose the following bucket and repeat. Otherwise, add the cascade to the bucket.

If the bucket is empty, record the hash value, allocate and store the key, and then add the cascade to the bucket.

If ok is present, before insertion we check whether the cascade is already stored, and return failure if yes.

```

<Cascades: procedures>+=
recursive subroutine cascade_set_hash_insert_rec &
    (cascade_set, h, hashval, key, cascade, ok)
    type(cascade_set_t), intent(inout) :: cascade_set
    integer(i32), intent(in) :: h, hashval
    integer(i8), dimension(:), intent(in) :: key
    type(cascade_t), intent(in), target :: cascade
    logical, intent(out), optional :: ok
    integer(i32) :: i
    i = iand (h, cascade_set%mask)
    if (allocated (cascade_set%entry(i)%key)) then
        if (size (cascade_set%entry(i)%key) /= size (key)) then
            call cascade_set_hash_insert_rec &

```

```

        (cascade_set, h + 1, hashval, key, cascade, ok)
    else if (any (cascade_set%entry(i)%key /= key)) then
        call cascade_set_hash_insert_rec &
            (cascade_set, h + 1, hashval, key, cascade, ok)
    else
        call hash_entry_add_cascade_ptr (cascade_set%entry(i), cascade, ok)
    end if
else
    cascade_set%entry(i)%hashval = hashval
    allocate (cascade_set%entry(i)%key (size (key)))
    cascade_set%entry(i)%key = key
    call hash_entry_add_cascade_ptr (cascade_set%entry(i), cascade, ok)
    cascade_set%n_entries = cascade_set%n_entries + 1
end if
end subroutine cascade_set_hash_insert_rec

```

12.4.8 External particles

We want to initialize the cascade set with the outgoing particles. In case of multiple processes, initial cascades are prepared for all of them. The hash array check ensures that no particle appears more than once at the same place.

```

<Cascades: procedures>+≡
subroutine cascade_set_add_outgoing (cascade_set, flv)
    type(cascade_set_t), intent(inout), target :: cascade_set
    type(flavor_t), dimension(:, :), intent(in) :: flv
    integer :: pos, prc, n_out, n_prc
    type(cascade_t), pointer :: cascade
    logical :: ok
    n_out = size (flv, dim=1)
    n_prc = size (flv, dim=2)
    do prc = 1, n_prc
        do pos = 1, n_out
            allocate (cascade)
            call cascade_init_outgoing &
                (cascade, flv(pos, prc), pos, cascade_set%m_threshold_s)
            call cascade_set_add (cascade_set, cascade, ok)
            if (.not. ok) then
                deallocate (cascade)
            end if
        end do
    end do
end subroutine cascade_set_add_outgoing

```

The incoming particles are added one at a time. Nevertheless, we may have several processes which are looped over. At the first opportunity, we set the pointer `first_t` in the cascade set which should point to the first t-channel cascade.

Return the indices of the first and last cascade generated.

```

<Cascades: procedures>+≡
subroutine cascade_set_add_incoming (cascade_set, n1, n2, pos, flv)
    type(cascade_set_t), intent(inout), target :: cascade_set

```

```

integer, intent(out) :: n1, n2
integer, intent(in) :: pos
type(flavor_t), dimension(:), intent(in) :: flv
integer :: prc, n_prc
type(cascade_t), pointer :: cascade
logical :: ok
n1 = 0
n2 = 0
n_prc = size (flv)
do prc = 1, n_prc
  allocate (cascade)
  call cascade_init_incoming &
    (cascade, flv(prc), pos, cascade_set%m_threshold_t)
  call cascade_set_add (cascade_set, cascade, ok)
  if (ok) then
    if (n1 == 0) n1 = cascade%index
    n2 = cascade%index
    if (.not. associated (cascade_set%first_t)) then
      cascade_set%first_t => cascade
    end if
  else
    deallocate (cascade)
  end if
end do
end subroutine cascade_set_add_incoming

```

12.4.9 Cascade combination I: flavor assignment

We have two disjunct cascades, now use the vertex table to determine the possible flavors of the combination cascade. For each possibility, try to generate a new cascade. The total cascade depth has to be one less than the limit, because this is reached by setting the keystone.

(Cascades: procedures) +=

```

subroutine cascade_match_pair (cascade_set, cascade1, cascade2, s_channel)
  type(cascade_set_t), intent(inout), target :: cascade_set
  type(cascade_t), intent(in), target :: cascade1, cascade2
  logical, intent(in) :: s_channel
  integer, dimension(:), allocatable :: pdg3
  integer :: i, depth_max
  type(flavor_t) :: flv
  if (s_channel) then
    depth_max = cascade_set%depth_out
  else
    depth_max = cascade_set%depth_tot
  end if
  if (cascade1%depth + cascade2%depth < depth_max) then
    call model_match_vertex (cascade_set%model, &
      flavor_get_pdg (cascade1%flv), &
      flavor_get_pdg (cascade2%flv), &
      pdg3)
    do i = 1, size (pdg3)
      call flavor_init (flv, pdg3(i), cascade_set%model)
    end do
  end if
end subroutine cascade_match_pair

```

```

        if (s_channel) then
            call cascade_combine_s (cascade_set, cascade1, cascade2, flv)
        else
            call cascade_combine_t (cascade_set, cascade1, cascade2, flv)
        end if
    end do
    deallocate (pdg3)
end if
end subroutine cascade_match_pair

```

The triplet version takes a third cascade, and we check whether this triplet has a matching vertex in the database. If yes, we make a keystone cascade.

```

<Cascades: procedures>+=
subroutine cascade_match_triplet &
    (cascade_set, cascade1, cascade2, cascade3, s_channel)
    type(cascade_set_t), intent(inout), target :: cascade_set
    type(cascade_t), intent(in), target :: cascade1, cascade2, cascade3
    logical, intent(in) :: s_channel
    integer :: depth_max
    depth_max = cascade_set%depth_tot
    if (cascade1%depth + cascade2%depth + cascade3%depth == depth_max) then
        if (model_check_vertex (cascade_set%model, &
            flavor_get_pdg (cascade1%flv), &
            flavor_get_pdg (cascade2%flv), &
            flavor_get_pdg (cascade3%flv))) then
            call cascade_combine_keystone &
                (cascade_set, cascade1, cascade2, cascade3, s_channel)
        end if
    end if
end subroutine cascade_match_triplet

```

12.4.10 Cascade combination II: kinematics setup and check

Having three matching flavors, we start constructing the combination cascade. We look at the mass hierarchies and determine whether the cascade is to be kept. In passing we set mapping modes, resonance properties and such.

If successful, the cascade is finalized. For a resonant cascade, we prepare in addition a copy without the resonance.

```

<Cascades: procedures>+=
subroutine cascade_combine_s (cascade_set, cascade1, cascade2, flv)
    type(cascade_set_t), intent(inout), target :: cascade_set
    type(cascade_t), intent(in), target :: cascade1, cascade2
    type(flavor_t), intent(in) :: flv
    type(cascade_t), pointer :: cascade3, cascade4
    logical :: keep
    keep = .false.
    allocate (cascade3)
    call cascade_init (cascade3, cascade1%depth + cascade2%depth + 1)
    cascade3%brcode = ior (cascade1%brcode, cascade2%brcode)
    cascade3%flv = flavor_anti (flv)
    cascade3%pdg = flavor_get_pdg (cascade3%flv)

```

```

cascade3%is_vector = flavor_get_spin_type (flv) == VECTOR
cascade3%m_min = cascade1%m_min + cascade2%m_min
cascade3%m_rea = flavor_get_mass (flv)
if (cascade3%m_rea > cascade_set%m_threshold_s) then
    cascade3%m_eff = cascade3%m_rea
end if
! Potentially resonant cases [sqrts = m_rea for on-shell decay]
if (cascade3%m_rea > cascade3%m_min &
    .and. cascade3%m_rea <= cascade_set%sqrts) then
    if (flavor_get_width (flv) /= 0) then
        if (cascade1%on_shell .or. cascade2%on_shell) then
            keep = .true.
            cascade3%mapping = S_CHANNEL
            cascade3%resonant = .true.
        end if
    else
        call warn_decay (flv)
    end if
! Collinear and IR singular cases
else if (cascade3%m_rea < cascade_set%sqrts) then
    ! Massless splitting
    if (cascade1%m_eff == 0 .and. cascade2%m_eff == 0 &
        .and. cascade3%depth <= 3) then
        keep = .true.
        cascade3%log_enhanced = .true.
        if (cascade3%is_vector) then
            if (cascade1%is_vector .and. cascade2%is_vector) then
                cascade3%mapping = COLLINEAR    ! three-vector-vertex
            else
                cascade3%mapping = INFRARED      ! vector splitting into matter
            end if
        else
            if (cascade1%is_vector .or. cascade2%is_vector) then
                cascade3%mapping = COLLINEAR    ! vector radiation off matter
            else
                cascade3%mapping = INFRARED      ! scalar radiation/splitting
            end if
        end if
        ! IR radiation off massive particle
    else if (cascade3%m_eff > 0 .and. cascade1%m_eff > 0 &
        .and. cascade2%m_eff == 0 &
        .and. (cascade1%on_shell .or. cascade1%mapping == RADIATION) &
        .and. abs (cascade3%m_eff - cascade1%m_eff) &
            < cascade_set%m_threshold_s) &
        then
        keep = .true.
        cascade3%log_enhanced = .true.
        cascade3%mapping = RADIATION
    else if (cascade3%m_eff > 0 .and. cascade2%m_eff > 0 &
        .and. cascade1%m_eff == 0 &
        .and. (cascade2%on_shell .or. cascade2%mapping == RADIATION) &
        .and. abs (cascade3%m_eff - cascade2%m_eff) &
            < cascade_set%m_threshold_s) &
        then

```

```

        keep = .true.
        cascade3%log_enhanced = .true.
        cascade3%mapping = RADIATION
    end if
end if
! Non-singular cases, including failed resonances
if (.not. keep) then
    ! Two on-shell particles from a virtual mother
    if (cascade1%on_shell .or. cascade2%on_shell) then
        keep = .true.
        cascade3%m_eff = max (cascade3%m_min, &
                               cascade1%m_eff + cascade2%m_eff)
        if (cascade3%m_eff < cascade_set%m_threshold_s) then
            cascade3%m_eff = 0
        end if
    end if
end if
! Complete and register the cascade (two in case of resonance)
if (keep) then
    cascade3%on_shell = cascade3%resonant .or. cascade3%log_enhanced
    if (cascade3%resonant) then
        cascade3%pdg = flavor_get_pdg (cascade3%flv)
        allocate (cascade4)
        cascade4 = cascade3
        cascade4%index = cascade_index ()
        call cascade_fusion (cascade_set, cascade1, cascade2, cascade3)
        cascade4%pdg = UNDEFINED
        cascade4%mapping = NO_MAPPING
        cascade4%resonant = .false.
        cascade4%on_shell = .false.
        call cascade_fusion (cascade_set, cascade1, cascade2, cascade4)
    else
        call cascade_fusion (cascade_set, cascade1, cascade2, cascade3)
    end if
else
    deallocate (cascade3)
end if
contains
subroutine warn_decay (flv)
    type(flavor_t), intent(in) :: flv
    integer :: i
    integer, dimension(MAX_WARN_RESONANCE), save :: warned_code = 0
    LOOP_WARNED: do i = 1, MAX_WARN_RESONANCE
        if (warned_code(i) == 0) then
            warned_code(i) = flavor_get_pdg (flv)
            write (msg_buffer, "(A)") &
                & " Intermediate decay of zero-width particle " &
                & // char (flavor_get_name (flv)) &
                & // " may be possible."
            call msg_warning
            exit LOOP_WARNED
        else if (warned_code(i) == flavor_get_pdg (flv)) then
            exit LOOP_WARNED
        end if
    end do
end subroutine warn_decay

```

```

        end do LOOP_WARNED
    end subroutine warn_decay
end subroutine cascade_combine_s

```

(Limits: public parameters)+≡

```
integer, parameter, public :: MAX_WARN_RESONANCE = 50
```

This is the t-channel version. `cascade1` is t-channel and contains the seed, `cascade2` is s-channel. We check for kinematically allowed beam decay (which is a fatal error), or massless splitting / soft radiation. The cascade is kept in all remaining cases and submitted for registration.

(Cascades: procedures)+≡

```

subroutine cascade_combine_t (cascade_set, cascade1, cascade2, flv)
    type(cascade_set_t), intent(inout), target :: cascade_set
    type(cascade_t), intent(in), target :: cascade1, cascade2
    type(flavor_t), intent(in) :: flv
    type(cascade_t), pointer :: cascade3
    allocate (cascade3)
    call cascade_init (cascade3, cascade1%depth + cascade2%depth + 1)
    cascade3%bincode = ior (cascade1%bincode, cascade2%bincode)
    cascade3%flv = flavor_anti (flv)
    cascade3%pdg = flavor_get_pdg (cascade3%flv)
    cascade3%is_vector = flavor_get_spin_type (flv) == VECTOR
    if (cascade1%incoming) then
        cascade3%m_min = cascade2%m_min
    else
        cascade3%m_min = cascade1%m_min + cascade2%m_min
    end if
    cascade3%m_rea = flavor_get_mass (flv)
    if (cascade3%m_rea > cascade_set%m_threshold_t) then
        cascade3%m_eff = max (cascade3%m_rea, cascade2%m_eff)
    else if (cascade2%m_eff > cascade_set%m_threshold_t) then
        cascade3%m_eff = cascade2%m_eff
    else
        cascade3%m_eff = 0
    end if
    ! Allowed decay of beam particle
    if (cascade1%incoming &
        .and. cascade1%m_rea > cascade2%m_rea + cascade3%m_rea) then
        call beam_decay ()
    ! Massless splitting
    else if (cascade1%m_eff == 0 &
        .and. cascade2%m_eff < cascade_set%m_threshold_t &
        .and. cascade3%m_eff == 0) then
        cascade3%mapping = U_CHANNEL
        cascade3%log_enhanced = .true.
    ! IR radiation off massive particle
    else if (cascade1%m_eff /= 0 .and. cascade2%m_eff == 0 &
        .and. cascade3%m_eff /= 0 &
        .and. (cascade1%on_shell .or. cascade1%mapping == RADIATION) &
        .and. abs (cascade1%m_eff - cascade3%m_eff) &
        < cascade_set%m_threshold_t) &
        then
        cascade3%pdg = flavor_get_pdg (flv)
    end if
end subroutine

```

```

        cascade3%log_enhanced = .true.
        cascade3%mapping = RADIATION
    end if
    cascade3%t_channel = .true.
    call cascade_fusion (cascade_set, cascade1, cascade2, cascade3)
contains
    subroutine beam_decay ()
        write (msg_buffer, "(1x,A,1x,'->',1x,A,1x,A)") &
            char (flavor_get_name (cascade1%flv)), &
            char (flavor_get_name (cascade3%flv)), &
            char (flavor_get_name (cascade2%flv))
        call msg_message
        write (msg_buffer, "(1x,'mass(',A,')' =',1x,E17.10)") &
            char (flavor_get_name (cascade1%flv)), cascade1%m_rea
        call msg_message
        write (msg_buffer, "(1x,'mass(',A,')' =',1x,E17.10)") &
            char (flavor_get_name (cascade3%flv)), cascade3%m_rea
        call msg_message
        write (msg_buffer, "(1x,'mass(',A,')' =',1x,E17.10)") &
            char (flavor_get_name (cascade2%flv)), cascade2%m_rea
        call msg_message
        call msg_fatal (" Phase space: Initial beam particle can decay")
    end subroutine beam_decay
end subroutine cascade_combine_t

```

Here we complete a decay cascade. The third input is the single-particle cascade for the initial particle. There is no resonance or mapping assignment. The only condition for keeping the cascade is the mass sum of the final state, which must be less than the available energy.

Two modifications are necessary for scattering cascades: a pure s-channel diagram (cascade1 is the incoming particle) do not have a logarithmic mapping at top-level. And in a t-channel diagram, the last line exchanged is mapped t-channel, not u-channel. In both cases we register a new cascade with the modified mapping.

```

<Cascades: procedures>+≡
    subroutine cascade_combine_keystone &
        (cascade_set, cascade1, cascade2, cascade3, s_channel)
        type(cascade_set_t), intent(inout), target :: cascade_set
        type(cascade_t), intent(in), target :: cascade1, cascade2, cascade3
        logical, intent(in) :: s_channel
        type(cascade_t), pointer :: cascade4, cascade0
        logical :: keep, ok
        keep = .false.
        allocate (cascade4)
        call cascade_init &
            (cascade4, cascade1%depth + cascade2%depth + cascade3%depth)
        cascade4%complete = .true.
!       cascade4%bincode = ior (ior (cascade1%bincode, cascade2%bincode), &
!           cascade3%bincode)
        if (s_channel) then
            cascade4%bincode = ior (cascade1%bincode, cascade2%bincode)
        else
            cascade4%bincode = cascade3%bincode
        end if
    end subroutine

```

```

end if
cascade4%flv = cascade3%flv
cascade4%pdg = cascade3%pdg
cascade4%is_vector = cascade3%is_vector
cascade4%m_min = cascade1%m_min + cascade2%m_min
cascade4%m_rea = cascade3%m_rea
cascade4%m_eff = cascade3%m_rea
if (cascade4%m_min < cascade_set%sqrts) then
    keep = .true.
end if
if (keep) then
    if (cascade1%incoming .and. cascade2%log_enhanced) then
        allocate (cascade0)
        cascade0 = cascade2
        cascade0%next => null ()
        cascade0%index = cascade_index ()
        cascade0%mapping = NO_MAPPING
        cascade0%log_enhanced = .false.
        cascade0%n_log_enhanced = cascade0%n_log_enhanced - 1
        cascade0%tree_mapping(cascade0%depth) = NO_MAPPING
        call cascade_keystone &
            (cascade_set, cascade1, cascade0, cascade3, cascade4, ok)
        if (ok) call cascade_set_add (cascade_set, cascade0, ok)
    else if (cascade1%t_channel .and. cascade1%mapping == U_CHANNEL) then
        allocate (cascade0)
        cascade0 = cascade1
        cascade0%next => null ()
        cascade0%index = cascade_index ()
        cascade0%mapping = T_CHANNEL
        cascade0%tree_mapping(cascade0%depth) = T_CHANNEL
        call cascade_keystone &
            (cascade_set, cascade0, cascade2, cascade3, cascade4, ok)
        if (ok) call cascade_set_add (cascade_set, cascade0, ok)
    else
        call cascade_keystone &
            (cascade_set, cascade1, cascade2, cascade3, cascade4, ok)
    end if
else
    deallocate (cascade4)
end if
end subroutine cascade_combine_keystone

```

12.4.11 Cascade combination III: node connections and tree fusion

Here we assign global tree properties. If the allowed number of off-shell lines is exceeded, discard the new cascade. Otherwise, assign the trees, sort them, and assign connections. Finally, append the cascade to the list. This may fail (because in the hash array there is already an equivalent cascade). On failure, discard the cascade.

(Cascades: procedures)+≡

```

subroutine cascade_fusion (cascade_set, cascade1, cascade2, cascade3)

```

```

type(cascade_set_t), intent(inout), target :: cascade_set
type(cascade_t), intent(in), target :: cascade1, cascade2
type(cascade_t), pointer :: cascade3
integer :: i1, i2, i3, i4
logical :: ok
cascade3%internal = (cascade3%depth - 3) / 2
if (cascade3%resonant) then
    cascade3%multiplicity = 1
    cascade3%n_resonances = &
        cascade1%n_resonances + cascade2%n_resonances + 1
else
    cascade3%multiplicity = cascade1%multiplicity + cascade2%multiplicity
    cascade3%n_resonances = cascade1%n_resonances + cascade2%n_resonances
end if
if (cascade3%log_enhanced) then
    cascade3%n_log_enhanced = &
        cascade1%n_log_enhanced + cascade2%n_log_enhanced + 1
else
    cascade3%n_log_enhanced = &
        cascade1%n_log_enhanced + cascade2%n_log_enhanced
end if
if (cascade3%t_channel) then
    cascade3%n_t_channel = cascade1%n_t_channel + 1
end if
if (cascade3%internal - cascade3%n_resonances - cascade3%n_log_enhanced &
    > cascade_set%off_shell) then
    deallocate (cascade3)
else if (cascade3%n_t_channel > cascade_set%t_channel) then
    deallocate (cascade3)
else
    i1 = cascade1%depth
    i2 = i1 + 1
    i3 = i1 + cascade2%depth
    i4 = cascade3%depth
    cascade3%tree(:i1) = cascade1%tree
    where (cascade1%tree_mapping /= NO_MAPPING)
        cascade3%tree_pdg(:i1) = cascade1%tree_pdg
    elsewhere
        cascade3%tree_pdg(:i1) = UNDEFINED
    end where
    cascade3%tree_mapping(:i1) = cascade1%tree_mapping
    cascade3%tree_resonant(:i1) = cascade1%tree_resonant
    cascade3%tree(i2:i3) = cascade2%tree
    where (cascade2%tree_mapping /= NO_MAPPING)
        cascade3%tree_pdg(i2:i3) = cascade2%tree_pdg
    elsewhere
        cascade3%tree_pdg(i2:i3) = UNDEFINED
    end where
    cascade3%tree_mapping(i2:i3) = cascade2%tree_mapping
    cascade3%tree_resonant(i2:i3) = cascade2%tree_resonant
    cascade3%tree(i4) = cascade3%bincode
    cascade3%tree_pdg(i4) = cascade3%pdg
    cascade3%tree_mapping(i4) = cascade3%mapping
    cascade3%tree_resonant(i4) = cascade3%resonant

```

```

        call tree_sort (cascade3%tree, &
            cascade3%tree_pdg, cascade3%tree_mapping, cascade3%tree_resonant)
        cascade3%has_children = .true.
        cascade3%daughter1 => cascade1
        cascade3%daughter2 => cascade2
        call cascade_set_add (cascade_set, cascade3, ok)
        if (.not. ok) deallocate (cascade3)
    end if
end subroutine cascade_fusion

```

Here we combine a cascade pair with an incoming particle, i.e., we set a keystone. Otherwise, this is similar. On the first opportunity, we set the **first_k** pointer in the cascade set.

(*Cascades: procedures*) +=

```

subroutine cascade_keystone &
    (cascade_set, cascade1, cascade2, cascade3, cascade4, ok)
    type(cascade_set_t), intent(inout), target :: cascade_set
    type(cascade_t), intent(in), target :: cascade1, cascade2, cascade3
    type(cascade_t), pointer :: cascade4
    logical, intent(out) :: ok
    integer :: i1, i2, i3, i4
    cascade4%internal = (cascade4%depth - 3) / 2
    cascade4%multiplicity = cascade1%multiplicity + cascade2%multiplicity
    cascade4%n_resonances = cascade1%n_resonances + cascade2%n_resonances
    cascade4%n_log_enhanced = &
        cascade1%n_log_enhanced + cascade2%n_log_enhanced
    cascade4%n_t_channel = cascade1%n_t_channel + cascade2%n_t_channel + 1
    if (cascade4%internal - cascade4%n_resonances - cascade4%n_log_enhanced &
        > cascade_set%off_shell) then
        deallocate (cascade4)
        ok = .false.
    else if (cascade4%n_t_channel > cascade_set%t_channel) then
        deallocate (cascade4)
        ok = .false.
    else
        i1 = cascade1%depth
        i2 = i1 + 1
        i3 = i1 + cascade2%depth
        i4 = cascade4%depth
        cascade4%tree(:i1) = cascade1%tree
        where (cascade1%tree_mapping /= NO_MAPPING)
            cascade4%tree_pdg(:i1) = cascade1%tree_pdg
        elsewhere
            cascade4%tree_pdg(:i1) = UNDEFINED
        end where
        cascade4%tree_mapping(:i1) = cascade1%tree_mapping
        cascade4%tree_resonant(:i1) = cascade1%tree_resonant
        cascade4%tree(i2:i3) = cascade2%tree
        where (cascade2%tree_mapping /= NO_MAPPING)
            cascade4%tree_pdg(i2:i3) = cascade2%tree_pdg
        elsewhere
            cascade4%tree_pdg(i2:i3) = UNDEFINED
        end where
    end if
end subroutine cascade_keystone

```

```

        cascade4%tree_mapping(i2:i3) = cascade2%tree_mapping
        cascade4%tree_resonant(i2:i3) = cascade2%tree_resonant
!      cascade4%tree(i4) = cascade3%bincode
        cascade4%tree(i4) = cascade4%bincode
        cascade4%tree_pdg(i4) = UNDEFINED
        cascade4%tree_mapping(i4) = NO_MAPPING
        cascade4%tree_resonant(i4) = .false.
        call tree_sort (cascade4%tree, &
            cascade4%tree_pdg, cascade4%tree_mapping, cascade4%tree_resonant)
        cascade4%has_children = .true.
        cascade4%daughter1 => cascade1
        cascade4%daughter2 => cascade2
        cascade4%mother => cascade3
        call cascade_set_add (cascade_set, cascade4, ok)
        if (ok) then
            if (.not. associated (cascade_set%first_k)) then
                cascade_set%first_k => cascade4
            end if
        else
            deallocate (cascade4)
        end if
    end if
end subroutine cascade_keystone

```

Sort a tree (array of binary codes) and particle code array simultaneously, by ascending binary codes. A convenient method is to use the `maxloc` function iteratively, to find and remove the largest entry in the tree array one by one.

(Cascades: procedures)+≡

```

subroutine tree_sort (tree, pdg, mapping, resonant)
    integer(TC), dimension(:), intent(inout) :: tree
    integer, dimension(:), intent(inout) :: pdg, mapping
    logical, dimension(:), intent(inout) :: resonant
    integer(TC), dimension(size(tree)) :: tree_tmp
    integer, dimension(size(pdg)) :: pdg_tmp, mapping_tmp
    logical, dimension(size(resonant)) :: resonant_tmp
    integer, dimension(1) :: pos
    integer :: i
    tree_tmp = tree
    pdg_tmp = pdg
    mapping_tmp = mapping
    resonant_tmp = resonant
    do i = size(tree), 1, -1
        pos = maxloc (tree_tmp)
        tree(i) = tree_tmp (pos(1))
        pdg(i) = pdg_tmp (pos(1))
        mapping(i) = mapping_tmp (pos(1))
        resonant(i) = resonant_tmp (pos(1))
        tree_tmp(pos(1)) = 0
    end do
end subroutine tree_sort

```

12.4.12 Cascade set generation

We use a nested scan to combine all cascades with all other cascades.

```
(Cascades: procedures) +=  
  subroutine cascade_set_generate_s (cascade_set)  
    type(cascade_set_t), intent(inout), target :: cascade_set  
    type(cascade_t), pointer :: cascade1, cascade2  
    cascade1 => cascade_set%first  
    LOOP1: do while (associated (cascade1))  
      cascade2 => cascade_set%first  
      LOOP2: do while (associated (cascade2))  
        if (cascade2%index >= cascade1%index) exit LOOP2  
        if (cascade1 .disjunct. cascade2) then  
          call cascade_match_pair (cascade_set, cascade1, cascade2, .true.)  
        end if  
        cascade2 => cascade2%next  
      end do LOOP2  
      cascade1 => cascade1%next  
    end do LOOP1  
  end subroutine cascade_set_generate_s
```

The t-channel cascades are directed and have a seed (one of the incoming particles) and a target (the other one). We loop over all possible seeds and targets. Inside this, we loop over all t-channel cascades (*cascade1*) and s-channel cascades (*cascade2*) and try to combine them.

```
(Cascades: procedures) +=  
  subroutine cascade_set_generate_t (cascade_set, pos_seed, pos_target)  
    type(cascade_set_t), intent(inout), target :: cascade_set  
    integer, intent(in) :: pos_seed, pos_target  
    type(cascade_t), pointer :: cascade_seed, cascade_target  
    type(cascade_t), pointer :: cascade1, cascade2  
    integer(TC) :: bc_seed, bc_target  
    bc_seed = ibset (0_TC, pos_seed-1)  
    bc_target = ibset (0_TC, pos_target-1)  
    cascade_seed => cascade_set%first_t  
    LOOP_SEED: do while (associated (cascade_seed))  
      if (cascade_seed%bincode == bc_seed) then  
        cascade_target => cascade_set%first_t  
        LOOP_TARGET: do while (associated (cascade_target))  
          if (cascade_target%bincode == bc_target) then  
            cascade1 => cascade_set%first_t  
            LOOP_T: do while (associated (cascade1))  
              if ((cascade1 .disjunct. cascade_target) &  
                  .and. .not. (cascade1 .disjunct. cascade_seed)) then  
                cascade2 => cascade_set%first  
                LOOP_S: do while (associated (cascade2))  
                  if ((cascade2 .disjunct. cascade_target) &  
                      .and. (cascade2 .disjunct. cascade1)) then  
                    call cascade_match_pair &  
                      (cascade_set, cascade1, cascade2, .false.)  
                  end if  
                  cascade2 => cascade2%next  
                end do LOOP_S  
              end if  
            end do LOOP_T  
          end if  
        end do LOOP_TARGET  
      end if  
      cascade_seed => cascade_seed%next  
    end do LOOP_SEED
```

```

        end if
        cascade1 => cascade1%next
    end do LOOP_T
    end if
    cascade_target => cascade_target%next
end do LOOP_TARGET
end if
cascade_seed => cascade_seed%next
end do LOOP_SEED
end subroutine cascade_set_generate_t

```

This part completes the phase space for decay processes. It is similar to s-channel cascade generation, but combines two cascade with the particular cascade of the incoming particle. This particular cascade is expected to be pointed at by `first_t`.

(Cascades: procedures)+≡

```

subroutine cascade_set_generate_decay (cascade_set)
    type(cascade_set_t), intent(inout), target :: cascade_set
    type(cascade_t), pointer :: cascade1, cascade2
    type(cascade_t), pointer :: cascade_in
    cascade_in => cascade_set%first_t
    cascade1 => cascade_set%first
    do while (associated (cascade1))
        if (cascade1 .disjunct. cascade_in) then
            cascade2 => cascade1%next
            do while (associated (cascade2))
                if ((cascade2 .disjunct. cascade1) &
                    .and. (cascade2 .disjunct. cascade_in)) then
                    call cascade_match_triplet (cascade_set, &
                        cascade1, cascade2, cascade_in, .true.)
                end if
                cascade2 => cascade2%next
            end do
        end if
        cascade1 => cascade1%next
    end do
end subroutine cascade_set_generate_decay

```

This part completes the phase space for scattering processes. We combine a t-channel cascade (containing the seed) with a s-channel cascade and the target.

(Cascades: procedures)+≡

```

subroutine cascade_set_generate_scattering &
    (cascade_set, ns1, ns2, nt1, nt2, pos_seed, pos_target)
    type(cascade_set_t), intent(inout), target :: cascade_set
    integer, intent(in) :: pos_seed, pos_target
    integer, intent(in) :: ns1, ns2, nt1, nt2
    type(cascade_t), pointer :: cascade_seed, cascade_target
    type(cascade_t), pointer :: cascade1, cascade2
    integer(TC) :: bc_seed, bc_target
    bc_seed = ibset (0_TC, pos_seed-1)
    bc_target = ibset (0_TC, pos_target-1)
    cascade_seed => cascade_set%first_t
    LOOP_SEED: do while (associated (cascade_seed))

```

```

if (cascade_seed%index < ns1) then
  cascade_seed => cascade_seed%next
  cycle LOOP_SEED
else if (cascade_seed%index > ns2) then
  exit LOOP_SEED
else if (cascade_seed%bincode == bc_seed) then
  cascade_target => cascade_set%first_t
  LOOP_TARGET: do while (associated (cascade_target))
    if (cascade_target%index < nt1) then
      cascade_target => cascade_target%next
      cycle LOOP_TARGET
    else if (cascade_target%index > nt2) then
      exit LOOP_TARGET
    else if (cascade_target%bincode == bc_target) then
      cascade1 => cascade_set%first_t
      LOOP_T: do while (associated (cascade1))
        if ((cascade1 .disjunct. cascade_target) &
            .and. .not. (cascade1 .disjunct. cascade_seed)) then
          cascade2 => cascade_set%first
          LOOP_S: do while (associated (cascade2))
            if ((cascade2 .disjunct. cascade_target) &
                .and. (cascade2 .disjunct. cascade1)) then
              call cascade_match_triplet (cascade_set, &
                                          cascade1, cascade2, cascade_target, .false.)
            end if
            cascade2 => cascade2%next
          end do LOOP_S
        end if
        cascade1 => cascade1%next
      end do LOOP_T
    end if
    cascade_target => cascade_target%next
  end do LOOP_TARGET
end if
cascade_seed => cascade_seed%next
end do LOOP_SEED
end subroutine cascade_set_generate_scattering

```

12.4.13 Groves

After all cascades are recorded, we group the complete cascades in groves. A grove consists of cascades with identical multiplicity, number of resonances, log-enhanced, and t-channel lines.

(Cascades: procedures)+≡

```

subroutine cascade_set_assign_groves (cascade_set)
  type(cascade_set_t), intent(inout), target :: cascade_set
  type(cascade_t), pointer :: cascade1, cascade2
  integer :: multiplicity, n_resonances, n_log_enhanced, n_t_channel
  integer :: grove
  grove = 0
  cascade1 => cascade_set%first_k
  do while (associated (cascade1))

```

```

if (cascade1%active .and. cascade1%complete &
    .and. cascade1%grove == 0) then
    grove = grove + 1
    cascade1%grove = grove
    multiplicity = cascade1%multiplicity
    n_resonances = cascade1%n_resonances
    n_log_enhanced = cascade1%n_log_enhanced
    n_t_channel = cascade1%n_t_channel
    cascade2 => cascade1%next
    do while (associated (cascade2))
        if (cascade2%grove == 0) then
            if (cascade2%multiplicity == multiplicity &
                .and. cascade2%n_resonances == n_resonances &
                .and. cascade2%n_log_enhanced == n_log_enhanced &
                .and. cascade2%n_t_channel == n_t_channel) then
                cascade2%grove = grove
            end if
        end if
        cascade2 => cascade2%next
    end do
end if
cascade1 => cascade1%next
end do
cascade_set%n_groves = grove
end subroutine cascade_set_assign_groves

```

12.4.14 Generate the phase space file

Generate a complete phase space configuration. First, all s-channel graphs that can be built up from the outgoing particles. Then we distinguish (1) decay, where we complete the s-channel graphs by connecting to the input line, and (2) scattering, where we now generate t-channel graphs by introducing an incoming particle, and complete this by connecting to the other incoming particle.

```

<Cascades: public>+≡
    public :: cascade_set_generate

<Cascades: procedures>+≡
    subroutine cascade_set_generate &
        (cascade_set, model, n_in, n_out, flv, phs_par)
        type(cascade_set_t), intent(out) :: cascade_set
        type(model_t), intent(in), target :: model
        integer, intent(in) :: n_in, n_out
        type(flavor_t), dimension(:,:), intent(in) :: flv
        type(phs_parameters_t), intent(in) :: phs_par
        integer :: n11, n12, n21, n22
        if (phase_space_vanishes (phs_par%sqrts, n_in, flv)) return
        call cascade_set_init (cascade_set, model, n_in, n_out, phs_par)
        call cascade_set_add_outgoing (cascade_set, flv(n_in+1,:))
        call cascade_set_generate_s (cascade_set)
        select case (n_in)
        case(1)
            call cascade_set_add_incoming &
                (cascade_set, n11, n12, n_out + 1, flv(1,:))

```

```

        call cascade_set_generate_decay (cascade_set)
case(2)
    call cascade_set_add_incoming &
        (cascade_set, n11, n12, n_out + 1, flv(1,:))
    call cascade_set_add_incoming &
        (cascade_set, n21, n22, n_out + 2, flv(2,:))
    call cascade_set_generate_t (cascade_set, n_out + 1, n_out + 2)
    call cascade_set_generate_t (cascade_set, n_out + 2, n_out + 1)
    call cascade_set_generate_scattering &
        (cascade_set, n11, n12, n21, n22, n_out + 1, n_out + 2)
    call cascade_set_generate_scattering &
        (cascade_set, n21, n22, n11, n12, n_out + 2, n_out + 1)
end select
call cascade_set_assign_groves (cascade_set)
end subroutine cascade_set_generate

```

Sanity check: Before anything else is done, check if there could possibly be any phase space.

```

<Cascades: procedures>+=
function phase_space_vanishes (sqrts, n_in, flv) result (flag)
    logical :: flag
    real(default), intent(in) :: sqrts
    integer, intent(in) :: n_in
    type(flavor_t), dimension(:,:), intent(in) :: flv
    real(default), dimension(:,:), allocatable :: mass
    real(default), dimension(:), allocatable :: mass_in, mass_out
    integer :: n_prt, n_flv
    flag = .false.
    if (sqrts <= 0) then
        call msg_error ("Phase space vanishes (sqrts must be positive)")
        flag = .true.; return
    end if
    n_prt = size (flv, 1)
    n_flv = size (flv, 2)
    allocate (mass (n_prt, n_flv), mass_in (n_flv), mass_out (n_flv))
    mass = flavor_get_mass (flv)
    mass_in = sum (mass(:,n_in,:), 1)
    mass_out = sum (mass(n_in+1:,:), 1)
    if (any (mass_in > sqrts)) then
        call msg_error ("Mass sum of incoming particles " &
            // "is more than available energy")
        flag = .true.; return
    end if
    if (any (mass_out > sqrts)) then
        call msg_error ("Mass sum of outgoing particles " &
            // "is more than available energy")
        flag = .true.; return
    end if
end function phase_space_vanishes

```

12.4.15 Test

```
<Cascades: public>+≡
  public :: cascade_test

<Cascades: procedures>+≡
  subroutine cascade_test
    use os_interface, only: os_data_t
    type(os_data_t) :: os_data
    type(model_t), pointer :: model
    type(flavor_t), dimension(5,2) :: flv
    type(cascade_set_t) :: cascade_set
    type(string_t) :: name, filename
    type(phs_parameters_t) :: phs_par
    name = "QCD"
    filename = "test.mdl"
    call syntax_model_file_init ()
    call model_list_read_model (name, filename, os_data, model)
    call model_write (model, verbose=.true.)
    call flavor_init (flv(1,1), 2, model)
    call flavor_init (flv(2,1),-2, model)
    call flavor_init (flv(3,1), 1, model)
    call flavor_init (flv(4,1),-1, model)
    call flavor_init (flv(5,1),21, model)
    call flavor_init (flv(1,2), 2, model)
    call flavor_init (flv(2,2),-2, model)
    call flavor_init (flv(3,2), 2, model)
    call flavor_init (flv(4,2),-2, model)
    call flavor_init (flv(5,2),21, model)
    phs_par%sqrts = 1000._default
    phs_par%off_shell = 2
    call cascade_set_generate (cascade_set, model, 2, 3, flv, phs_par)
    call cascade_set_write (cascade_set)
    call cascade_set_write_file_format (cascade_set)
    call cascade_set_final (cascade_set)
    call model_list_final ()
  end subroutine cascade_test
```

Chapter 13

Integration and event generation

With all necessary ingredients set up in the previous modules, the modules in this chapter do the high-level work of interfacing the process library, integrating and generating events.

process_libraries Create a process library, compile it, and load it, providing procedure pointers that the following modules can use.

hard_interactions Set up hard matrix element data appropriate for a given process and evaluate matrix elements in various ways (traced over all quantum numbers for integration, exclusive in some quantum numbers for analysis, expanded in color-flow patterns for showering).

processes Collect phase space, hard interactions, structure functions, cuts and whatever is needed to compute total partonic cross sections and partial decay widths.

events In the simulation step, generate individual events, concatenate decays, etc.

13.0.16 Process library interface

The process library is generated dynamically, and it does not provide a module. To access it, we define explicit interfaces that have to be included in the calling modules. These interfaces must be accessed both at compile time and at run-time, therefore we define a separate module that can be installed independent of the rest.

```
<prclib_interfaces.f90>≡  
  <File header>
```

```
module prclib_interfaces  
  
  use iso_c_binding !NODEP!  
  use kinds !NODEP!
```

⟨Standard module head⟩

⟨Prclib interfaces: public⟩

⟨Prclib interfaces: interfaces⟩

end module prclib_interfaces

Return the number of processes contained in the library.

⟨Prclib interfaces: public⟩≡

public :: prc_get_n_processes

⟨Prclib interfaces: interfaces⟩≡

abstract interface

function prc_get_n_processes () result (n) bind(C)

import

integer(c_int) :: n

end function prc_get_n_processes

end interface

Return the C pointer to a string, and its length.

⟨Prclib interfaces: public⟩+≡

public :: prc_get_stringptr

⟨Prclib interfaces: interfaces⟩+≡

abstract interface

subroutine prc_get_stringptr (i, cptr, len) bind(C)

import

integer(c_int), intent(in) :: i

type(c_ptr), intent(out) :: cptr

integer(c_int), intent(out) :: len

end subroutine prc_get_stringptr

end interface

Return an integer.

⟨Prclib interfaces: public⟩+≡

public :: prc_get_int

⟨Prclib interfaces: interfaces⟩+≡

abstract interface

function prc_get_int (pid) result (n) bind(C)

import

integer(c_int), intent(in) :: pid

integer(c_int) :: n

end function prc_get_int

end interface

Return a two-dimensional integer array

⟨Prclib interfaces: public⟩+≡

public :: prc_set_int_tab1

⟨Prclib interfaces: interfaces⟩+≡

abstract interface

subroutine prc_set_int_tab1 (pid, cptr, shape) bind(C)

import

integer(c_int), intent(in) :: pid

type(c_ptr), intent(in) :: cptr

```

        integer(c_int), dimension(2), intent(in) :: shape
    end subroutine prc_set_int_tab1
end interface

```

Return a three-dimensional integer and a two-dimensional logical array.

<Prclib interfaces: public>+≡

```

    public :: prc_set_int_tab2

```

<Prclib interfaces: interfaces>+≡

```

    abstract interface
        subroutine prc_set_int_tab2 (pid, cptr, shape, lcptr, lshape) bind(C)
            import
            integer(c_int), intent(in) :: pid
            type(c_ptr), intent(in) :: cptr
            integer(c_int), dimension(3), intent(in) :: shape
            type(c_ptr), intent(in) :: lcptr
            integer(c_int), dimension(2), intent(in) :: lshape
        end subroutine prc_set_int_tab2
    end interface

```

These procedure signatures correspond to the process-specific API. The actual procedures are assigned by the pointer-assignment functions with signatures below.

Do overall process initialization if necessary.

<Prclib interfaces: public>+≡

```

    public :: prc_init

```

<Prclib interfaces: interfaces>+≡

```

    abstract interface
        subroutine prc_init (par) bind(C)
            import
            real(c_default_float), dimension(*), intent(in) :: par
        end subroutine prc_init
    end interface

```

Do overall process finalization if necessary.

<Prclib interfaces: public>+≡

```

    public :: prc_final

```

<Prclib interfaces: interfaces>+≡

```

    abstract interface
        subroutine prc_final () bind(C)
        end subroutine prc_final
    end interface

```

Update the α_s value used for the matrix element computation.

<Prclib interfaces: public>+≡

```

    public :: prc_update_alpha_s

```

<Prclib interfaces: interfaces>+≡

```

    interface
        subroutine prc_update_alpha_s (alpha_s) bind(C)
            import
            real(c_default_float), intent(in) :: alpha_s
        end subroutine prc_update_alpha_s
    end interface

```

Reset the counters for individual helicities. momenta.

```
<Prclib interfaces: public>+≡
  public :: prc_reset_helicity_selection

<Prclib interfaces: interfaces>+≡
  abstract interface
    subroutine prc_reset_helicity_selection (threshold, cutoff) bind(C)
      import
      real(c_default_float), intent(in) :: threshold
      integer(c_int), intent(in) :: cutoff
    end subroutine prc_reset_helicity_selection
  end interface
```

Request the calculation of a new event, given a set of particle momenta.

```
<Prclib interfaces: public>+≡
  public :: prc_new_event

<Prclib interfaces: interfaces>+≡
  abstract interface
    subroutine prc_new_event (p) bind(C)
      import
      real(c_default_float), dimension(0:3,*), intent(in) :: p
    end subroutine prc_new_event
  end interface
```

Return true if the selected combination of flavor, helicity and color is allowed.

```
<Prclib interfaces: public>+≡
  public :: prc_is_allowed

<Prclib interfaces: interfaces>+≡
  abstract interface
    function prc_is_allowed (flv, hel, col) result (is_allowed) bind(C)
      import
      logical(c_bool) :: is_allowed
      integer(c_int), intent(in) :: flv, hel, col
    end function prc_is_allowed
  end interface
```

Assuming that the event has been computed, return a particular amplitude.

```
<Prclib interfaces: public>+≡
  public :: prc_get_amplitude

<Prclib interfaces: interfaces>+≡
  abstract interface
    function prc_get_amplitude (flv, hel, col) result (amp) bind(C)
      import
      complex(c_default_complex) :: amp
      integer(c_int), intent(in) :: flv, hel, col
    end function prc_get_amplitude
  end interface
```

Function that returns the pointer to a procedure:

```
<Prclib interfaces: public>+≡
  public :: prc_get_fptr
```

```

<Prclib interfaces: interfaces>+≡
  abstract interface
    subroutine prc_get_fptr (pid, fptr) bind(C)
      import
        integer(c_int), intent(in) :: pid
        type(c_funptr), intent(out) :: fptr
    end subroutine prc_get_fptr
  end interface

```

13.1 Process library access

This module interfaces the OS to create, build, and use process libraries.

```

<process_libraries.f90>≡
<File header>

  module process_libraries

    use iso_c_binding !NODEP!
    use kinds !NODEP!
    <Use strings>
    <Use file utils>
    use diagnostics !NODEP!
    use md5
    use os_interface
    use variables
    use models
    use flavors
    use prclib_interfaces

    <Standard module head>

    <Process libraries: public>

    <Process libraries: parameters>

    <Process libraries: types>

    <Process libraries: interfaces>

    <Process libraries: variables>

    contains

    <Process libraries: procedures>

  end module process_libraries

```

13.1.1 Status codes

```

<Process libraries: parameters>≡
  integer, parameter :: STAT_UNKNOWN = 0
  integer, parameter :: STAT_CONFIGURED = 1

```

```

integer, parameter :: STAT_CODE_GENERATED = 2
integer, parameter :: STAT_COMPILED = 3
integer, parameter :: STAT_LOADED = 4
integer, parameter :: STAT_INTEGRATED = 5

```

13.1.2 Process configuration data

Process configuration data.

```

<Process libraries: public>≡
  public :: process_configuration_t

<Process libraries: types>≡
  type :: process_configuration_t
    private
    integer :: status = STAT_UNKNOWN
    type(string_t) :: id
    type(model_t), pointer :: model => null ()
    integer :: n_in = 0
    integer :: n_out = 0
    integer :: n_tot = 0
    type(string_t), dimension(:), allocatable :: prt_in, prt_out
    type(string_t) :: restrictions
    character(32) :: md5sum = ""
    logical :: result_is_known = .false.
    integer :: n_calls = 0
    real(default) :: integral = 0
    real(default) :: error = 0
    real(default) :: accuracy = 0
    real(default) :: chi2 = 0
    real(default) :: efficiency = 0
    type(process_configuration_t), pointer :: next => null ()
  end type process_configuration_t

```

Initialize a process configuration. The configuration is `intent(inout)` such that any `next` pointer is kept if an existing configuration is overwritten. Otherwise, all contents are reset.

```

<Process libraries: procedures>≡
  subroutine process_configuration_init &
    (prc_conf, prc_id, model, prt_in, prt_out, status, restrictions)
    type(process_configuration_t), intent(inout) :: prc_conf
    type(string_t), intent(in) :: prc_id
    type(model_t), intent(in), target :: model
    type(string_t), dimension(:), intent(in) :: prt_in, prt_out
    integer, intent(in), optional :: status
    type(string_t), intent(in), optional :: restrictions
    prc_conf%id = prc_id
    prc_conf%model => model
    prc_conf%n_in = size (prt_in)
    prc_conf%n_out = size (prt_out)
    prc_conf%n_tot = prc_conf%n_in + prc_conf%n_out
    if (allocated (prc_conf%prt_in)) deallocate (prc_conf%prt_in)
    allocate (prc_conf%prt_in (prc_conf%n_in))
  end subroutine process_configuration_init

```

```

    if (allocated (prc_conf%prt_out)) deallocate (prc_conf%prt_out)
    allocate (prc_conf%prt_out (prc_conf%n_out))
    prc_conf%prt_in = prt_in
    prc_conf%prt_out = prt_out
    prc_conf%result_is_known = .false.
    prc_conf%n_calls = 0
    prc_conf%integral = 0
    prc_conf%error = 0
    prc_conf%accuracy = 0
    prc_conf%chi2 = 0
    prc_conf%efficiency = 0
    if (present (status)) then
        prc_conf%status = status
    else
        prc_conf%status = STAT_CONFIGURED
    end if
    if (present (restrictions)) then
        prc_conf%restrictions = restrictions
    else
        prc_conf%restrictions = ""
    end if
    call process_configuration_compute_md5sum (prc_conf)
end subroutine process_configuration_init

```

Compute the MD5 sum. Write all relevant information to a string.

(Process libraries: procedures)+≡

```

subroutine process_configuration_compute_md5sum (prc_conf)
    type(process_configuration_t), intent(inout) :: prc_conf
    integer :: u, i
    u = free_unit ()
    open (unit=u, status="scratch")
    write (u, "(A)") char (model_get_name (prc_conf%model))
    write (u, "(I0)") prc_conf%n_in
    write (u, "(I0)") prc_conf%n_out
    write (u, "(I0)") prc_conf%n_tot
    do i = 1, size (prc_conf%prt_in)
        write (u, "(A)") char (prc_conf%prt_in(i))
    end do
    do i = 1, size (prc_conf%prt_out)
        write (u, "(A)") char (prc_conf%prt_out(i))
    end do
    if (prc_conf%restrictions /= "") then
        write (u, "(A)") char (prc_conf%restrictions)
    end if
    rewind (u)
    prc_conf%md5sum = md5sum (u)
    close (u)
end subroutine process_configuration_compute_md5sum

```

Initialize variables that access the integration results

(Process libraries: procedures)+≡

```

subroutine process_configuration_set_variables (prc_conf, var_list)
    type(process_configuration_t), intent(in), target :: prc_conf

```

```

type(var_list_t), intent(inout) :: var_list
call set_var_int ("n_calls", prc_conf%n_calls)
call set_var_real ("integral", prc_conf%integral)
call set_var_real ("error", prc_conf%error)
call set_var_real ("accuracy", prc_conf%accuracy)
call set_var_real ("chi2", prc_conf%chi2)
call set_var_real ("efficiency", prc_conf%efficiency)
contains
subroutine set_var_int (name, ival)
character(*), intent(in) :: name
integer, intent(in), target :: ival
type(string_t) :: var_name
var_name = name // "(" // prc_conf%id // ")"
if (.not. var_list_exists (var_list, var_name)) then
call var_list_append_int_ptr (var_list, var_name, &
ival, prc_conf%result_is_known, locked=.true., intrinsic=.true.)
end if
end subroutine set_var_int
subroutine set_var_real (name, rval)
character(*), intent(in) :: name
real(default), intent(in), target :: rval
type(string_t) :: var_name
var_name = name // "(" // prc_conf%id // ")"
if (.not. var_list_exists (var_list, var_name)) then
call var_list_append_real_ptr (var_list, var_name, &
rval, prc_conf%result_is_known, locked=.true., intrinsic=.true.)
end if
end subroutine set_var_real
end subroutine process_configuration_set_variables

```

Record the results from an integration run and mark the process as integrated.

(Process libraries: procedures)+≡

```

subroutine process_configuration_record_integral &
(prc_conf, n_calls, integral, error, accuracy, chi2, efficiency)
type(process_configuration_t), intent(inout) :: prc_conf
integer, intent(in) :: n_calls
real(default), intent(in) :: integral, error, accuracy, chi2, efficiency
prc_conf%n_calls = n_calls
prc_conf%integral = integral
prc_conf%error = error
prc_conf%accuracy = accuracy
prc_conf%chi2 = chi2
prc_conf%efficiency = efficiency
prc_conf%result_is_known = .true.
prc_conf%status = STAT_INTEGRATED
end subroutine process_configuration_record_integral

```

Output (used by the 'list' command):

(Process libraries: procedures)+≡

```

subroutine process_configuration_write (prc_conf, unit)
type(process_configuration_t), intent(in) :: prc_conf
integer, intent(in), optional :: unit
character :: status

```

```

type(string_t) :: in_state, out_state
integer :: i
select case (prc_conf%status)
case (STAT_UNKNOWN);      status = "?"
case (STAT_CONFIGURED);   status = "O"
case (STAT_CODE_GENERATED); status = "G"
case (STAT_COMPILED);      status = "C"
case (STAT_LOADED);        status = "L"
case (STAT_INTEGRATED);    status = "I"
end select
in_state = prc_conf%prt_in(1)
do i = 2, size (prc_conf%prt_in)
    in_state = in_state // ", " // prc_conf%prt_in(i)
end do
out_state = prc_conf%prt_out(1)
do i = 2, size (prc_conf%prt_out)
    out_state = out_state // ", " // prc_conf%prt_out(i)
end do
if (prc_conf%restrictions == "") then
    call msg_message (" [" // status // "] " // char (prc_conf%id) // " = " &
        // char (in_state) // " -> " // char (out_state), unit)
else
    call msg_message (" [" // status // "] " // char (prc_conf%id) // " = " &
        // char (in_state) // " -> " // char (out_state) &
        // " { $restrictions = " // '""' // char (prc_conf%restrictions) &
        // '""' // " }", unit) ! $
end if
end subroutine process_configuration_write

```

13.1.3 Process library data

This object contains filenames, the complete set of process configuration data, the C filehandle interface for the shared library, and procedure pointers for the library functions.

The contents of this type are public because we do not want to have another wrapper around the procedure pointer components.

Note: The procedure pointer `prc_get_id` triggers a bug in nagfor5.2(649) [incorrect C generated], apparently related to the string argument of this procedure. Fortunately, we can live without it.

```

<Process libraries: public>+≡
    public :: process_library_t

<Process libraries: types>+≡
    type :: process_library_t
    ! private
    logical :: static = .false.
    integer :: status = STAT_UNKNOWN
    type(string_t) :: basename
    type(string_t) :: srcname
    type(string_t) :: libname
    integer :: n_prc = 0
    type(process_configuration_t), pointer :: prc_first => null ()

```

```

type(process_configuration_t), pointer :: prc_last => null ()
type(dlaccess_t) :: dlaccess
procedure(prc_get_n_processes), nopass, pointer :: get_n_prc => null ()
procedure(prc_get_stringptr), nopass, pointer :: get_process_id => null ()
procedure(prc_get_stringptr), nopass, pointer :: get_model_name => null ()
procedure(prc_get_stringptr), nopass, pointer :: &
    get_restrictions => null ()
procedure(prc_get_stringptr), nopass, pointer :: get_md5sum => null ()
procedure(prc_get_int), nopass, pointer :: get_n_in => null ()
procedure(prc_get_int), nopass, pointer :: get_n_out => null ()
procedure(prc_get_int), nopass, pointer :: get_n_flv => null ()
procedure(prc_get_int), nopass, pointer :: get_n_hel => null ()
procedure(prc_get_int), nopass, pointer :: get_n_col => null ()
procedure(prc_get_int), nopass, pointer :: get_n_cin => null ()
procedure(prc_set_int_tab1), nopass, pointer :: set_flv_state => null ()
procedure(prc_set_int_tab1), nopass, pointer :: set_hel_state => null ()
procedure(prc_set_int_tab2), nopass, pointer :: set_col_state => null ()
procedure(prc_get_fptr), nopass, pointer :: init_get_fptr => null()
procedure(prc_get_fptr), nopass, pointer :: final_get_fptr => null()
procedure(prc_get_fptr), nopass, pointer :: &
    update_alpha_s_get_fptr => null ()
procedure(prc_get_fptr), nopass, pointer :: &
    reset_helicity_selection_get_fptr => null ()
procedure(prc_get_fptr), nopass, pointer :: new_event_get_fptr => null ()
procedure(prc_get_fptr), nopass, pointer :: is_allowed_get_fptr => null ()
procedure(prc_get_fptr), nopass, pointer :: get_amplitude_get_fptr &
    => null ()
type(process_library_t), pointer :: next => null ()
end type process_library_t

```

Just allocate the configuration array and set filenames, the rest comes later.
Note that because libtool may be used, the actual `libname` can be determined
only after the library has been created.

```

<Process libraries: public>+≡
    public :: process_library_init

<Process libraries: procedures>+≡
    subroutine process_library_init (prc_lib, name, os_data)
        type(process_library_t), intent(out) :: prc_lib
        type(string_t), intent(in) :: name
        type(os_data_t), intent(in) :: os_data
        prc_lib%basename = name
        prc_lib%srcname = name // os_data%fc_src_ext
        prc_lib%status = STAT_CONFIGURED
    end subroutine process_library_init

```

Delete the process configuration list, if any.

```

<Procedures libraries: procedures>+≡
    subroutine process_library_clear_configuration (prc_lib)
        type(process_library_t), intent(inout) :: prc_lib
        type(process_configuration_t), pointer :: current
        do while (associated (prc_lib%prc_first))
            current => prc_lib%prc_first

```

```

        prc_lib%prc_first => current%next
        deallocate (current)
    end do
    prc_lib%prc_last => null ()
    prc_lib%n_prc = 0
end subroutine process_library_clear_configuration

```

Close the library access if it is open. Delete the process-configuration list.

```

<Process libraries: public>+≡
    public :: process_library_final

<Process libraries: procedures>+≡
    subroutine process_library_final (prc_lib)
        type(process_library_t), intent(inout) :: prc_lib
        if (.not. prc_lib%static) call dlaccess_final (prc_lib%dlaccess)
        call process_library_clear_configuration (prc_lib)
    end subroutine process_library_final

```

Given a pointer to a library, return the next pointer.

```

<Process libraries: public>+≡
    public :: process_library_advance

<Process libraries: procedures>+≡
    subroutine process_library_advance (prc_lib)
        type(process_library_t), pointer :: prc_lib
        prc_lib => prc_lib%next
    end subroutine process_library_advance

```

Output (called by the 'show' command):

```

<Process libraries: public>+≡
    public :: process_library_write

<Process libraries: procedures>+≡
    subroutine process_library_write (prc_lib, unit)
        type(process_library_t), intent(in) :: prc_lib
        integer, intent(in), optional :: unit
        type(string_t) :: status
        type(process_configuration_t), pointer :: current
        select case (prc_lib%status)
        case (STAT_UNKNOWN)
            status = "[unknown]"
        case (STAT_CONFIGURED)
            status = "[open]"
        case (STAT_CODE_GENERATED)
            status = "[generated code]"
        case (STAT_COMPILED)
            status = "[compiled]"
        case (STAT_LOADED)
            if (prc_lib%static) then
                status = "[static]"
            else
                status = "[loaded]"
            end if
        end select
    end subroutine process_library_write

```

```

    call msg_message ("Process library: " // char (prc_lib%basename) &
        // " " // char (status), unit)
    current => prc_lib%prc_first
    do while (associated (current))
        call process_configuration_write (current, unit)
        current => current%next
    end do
end subroutine process_library_write

```

13.1.4 Accessing contents

Tell/set if the library is static or dynamic

```

<Process libraries: public>+≡
    public :: process_library_set_static
    public :: process_library_is_static

<Process libraries: procedures>+≡
    subroutine process_library_set_static (prc_lib, flag)
        type(process_library_t), intent(inout) :: prc_lib
        logical, intent(in) :: flag
        prc_lib%static = flag
    end subroutine process_library_set_static

    function process_library_is_static (prc_lib) result (flag)
        logical :: flag
        type(process_library_t), intent(in) :: prc_lib
        flag = prc_lib%static
    end function process_library_is_static

```

Return the name of a library (the basename).

```

<Process libraries: public>+≡
    public :: process_library_get_name

<Process libraries: procedures>+≡
    function process_library_get_name (prc_lib) result (name)
        type(string_t) :: name
        type(process_library_t), intent(in) :: prc_lib
        name = prc_lib%basename
    end function process_library_get_name

```

Return the number of processes defined so far.

```

<Process libraries: public>+≡
    public :: process_library_get_n_processes

<Process libraries: procedures>+≡
    function process_library_get_n_processes (prc_lib) result (n)
        integer :: n
        type(process_library_t), intent(in) :: prc_lib
        n = prc_lib%n_prc
    end function process_library_get_n_processes

```

Return the pointer to a process with specified tag.

```

<Process libraries: procedures>+≡
function process_library_get_process_ptr (prc_lib, prc_id) result (current)
  type(process_library_t), intent(in), target :: prc_lib
  type(string_t), intent(in) :: prc_id
  type(process_configuration_t), pointer :: current
  current => prc_lib%prc_first
  do while (associated (current))
    if (current%id == prc_id) return
    current => current%next
  end do
end function process_library_get_process_ptr

```

Return the index of a process with specified tag. If the process is not found, return zero.

```

<Process libraries: public>+≡
public :: process_library_get_process_index

<Process libraries: procedures>+≡
function process_library_get_process_index (prc_lib, prc_id) result (index)
  integer :: index
  type(process_library_t), intent(in), target :: prc_lib
  type(string_t), intent(in) :: prc_id
  type(process_configuration_t), pointer :: current
  index = 0
  current => prc_lib%prc_first
  do while (associated (current))
    index = index + 1
    if (current%id == prc_id) return
    current => current%next
  end do
  index = 0
end function process_library_get_process_index

```

13.1.5 Creating a process library

Configure a specific process in the list. First check if the process exists, the either edit the existing process configuration or initiate a new one. If a status is given, mark the process configuration accordingly. Overwrite any existing configuration for the given process ID. If the `rebuild_library` flag is set, do this silently and reset the status. If it is absent or unset, we want to keep the old configuration as far as possible. If the checksum has changed issue a warning that the configuration was overwritten. If the old status was higher, keep it.

```

<Process libraries: public>+≡
public :: process_library_append

<Process libraries: procedures>+≡
subroutine process_library_append &
  (prc_lib, prc_id, model, prt_in, prt_out, var_list, &
   status, restrictions, rebuild_library, message)
  type(process_library_t), intent(inout), target :: prc_lib
  type(string_t), intent(in) :: prc_id

```

```

type(model_t), intent(in), target :: model
type(string_t), dimension(:), intent(in) :: prt_in, prt_out
type(var_list_t), intent(inout), optional :: var_list
integer, intent(in), optional :: status
type(string_t), intent(in), optional :: restrictions
logical, intent(in), optional :: rebuild_library, message
type(process_configuration_t), pointer :: current
character(32) :: old_md5sum
integer :: old_status
logical :: keep_status
logical :: msg
keep_status = .true.; if (present (rebuild_library)) keep_status = .not. rebuild_library
msg = .false.; if (present (message)) msg = message
current => process_library_get_process_ptr (prc_lib, prc_id)
if (associated (current)) then
    old_md5sum = current%md5sum
    old_status = current%status
    call process_configuration_init &
        (current, prc_id, model, prt_in, prt_out, status, restrictions)
    if (keep_status) then
        if (current%md5sum == old_md5sum) then
            if (current%status <= old_status) then
                call msg_message ("Process '" // char (prc_id) &
                    // "': keeping previous configuration")
                current%status = old_status
            else
                call msg_message ("Process '" // char (prc_id) &
                    // "': updating previous configuration")
            end if
        else
            call msg_warning ("Process '" // char (prc_id) &
                // "': overwriting previous configuration")
        end if
    else
        if (current%md5sum /= old_md5sum) then
            call msg_message ("Process '" // char (prc_id) &
                // "': ignoring previous configuration")
        end if
    end if
else
    allocate (current)
    if (associated (prc_lib%prc_last)) then
        prc_lib%prc_last%next => current
    else
        prc_lib%prc_first => current
    end if
    prc_lib%prc_last => current
    prc_lib%n_prc = prc_lib%n_prc + 1
    call process_configuration_init &
        (current, prc_id, model, prt_in, prt_out, status, restrictions)
    if (present (var_list)) &
        call process_configuration_set_variables (current, var_list)
    call process_update_code_status (current, keep_status)
    if (msg) call msg_message &

```

```

        ("Added process to library '" // char (prc_lib%basename) // "':")
    end if
    if (msg) call process_configuration_write (current)
end subroutine process_library_append

```

Look for an existing file for the current process and its MD5 signature. If successful and a rebuild flag is set, reset the status to STAT_CODE_GENERATED. Otherwise, just issue appropriate diagnostic messages.

(Process libraries: procedures)+≡

```

subroutine process_update_code_status (prc_conf, keep_status)
    type(process_configuration_t), intent(inout) :: prc_conf
    logical, intent(in) :: keep_status
    type(string_t) :: filename
    logical :: exist, found
    integer :: u, iostat
    character(80) :: buffer
    character(32) :: md5sum
    filename = prc_conf%id // ".f90"
    inquire (file=char(filename), exist=exist)
    if (exist) then
        found = .false.
        u = free_unit ()
        open (u, file=char(filename), action="read")
        SCAN_FILE: do
            read (u, "(A)", iostat=iostat) buffer
            select case (iostat)
            case (0)
                select case (buffer(1:12))
                case ("    md5sum =")
                    md5sum = buffer(15:47)
                    if (keep_status) then
                        if (prc_conf%status < STAT_CODE_GENERATED) then
                            if (md5sum == prc_conf%md5sum) then
                                call msg_message ("Process '" // char (prc_conf%id) &
                                    // "': using existing source code")
                                prc_conf%status = STAT_CODE_GENERATED
                            else
                                call msg_warning ("Process '" // char (prc_conf%id) &
                                    // "': will overwrite existing source code")
                            end if
                        else if (md5sum /= prc_conf%md5sum) then
                            call msg_warning ("Process '" // char (prc_conf%id) &
                                // "': source code and loaded checksums differ")
                        end if
                    else if (prc_conf%status < STAT_CODE_GENERATED) then
                        call msg_message ("Process '" // char (prc_conf%id) &
                            // "': ignoring existing source code")
                    end if
                    found = .true.
                    exit SCAN_FILE
                end select
            case default
                exit SCAN_FILE
            end select
        end do
    end if
end subroutine process_update_code_status

```

```

        end select
    end do SCAN_FILE
    close (u)
    if (.not. found) &
        call msg_warning ("Process '" // char (prc_conf%id) &
            // "': No MD5 sum found in source code")
    end if
end subroutine process_update_code_status

```

Recover process configuration from a loaded library. Existing configurations for processes present in the loaded library will be overwritten. Return the pointer to the model appropriate for the loaded library.

(Process libraries: procedures)+≡

```

subroutine process_library_load_configuration &
    (prc_lib, os_data, model, var_list)
    type(process_library_t), intent(inout), target :: prc_lib
    type(os_data_t), intent(in) :: os_data
    type(model_t), pointer :: model
    type(var_list_t), intent(inout), optional :: var_list
    integer :: n_prc, p, n_flv, n_in, n_out, n_tot, i
    integer(c_int) :: pid
    integer, dimension(:,:), allocatable :: flv_state
    integer(c_int), dimension(:,:), allocatable, target :: flv_state_tmp
    type(string_t) :: prc_id, model_name, filename, restrictions
    type(string_t), dimension(:), allocatable :: prt_in, prt_out
    character(32) :: md5sum
    n_prc = prc_lib% get_n_prc ()
    SCAN_PROCESSES: do p = 1, n_prc
        pid = p
        prc_id = process_library_get_process_id (prc_lib, pid)
        md5sum = process_library_get_process_md5sum (prc_lib, pid)
        model_name = process_library_get_process_model_name (prc_lib, pid)
        restrictions = process_library_get_process_restrictions (prc_lib, pid)
        filename = model_name // ".mdl"
        model => null ()
        call model_list_read_model (model_name, filename, os_data, model)
        if (.not. associated (model)) then
            call msg_error ("Process library '" // char (prc_lib%basename) &
                // "', process '" // char (prc_id) // "': " &
                // "model unavailable, process skipped")
            cycle SCAN_PROCESSES
        end if
        n_in = prc_lib% get_n_in (pid)
        n_out = prc_lib% get_n_out (pid)
        n_tot = n_in + n_out
        n_flv = prc_lib% get_n_flv (pid)
        allocate (flv_state (n_tot, n_flv))
        allocate (flv_state_tmp (n_tot, n_flv))
        allocate (prt_in (n_in ))
        allocate (prt_out (n_out))
        call prc_lib% set_flv_state (pid, &
            c_loc (flv_state_tmp), &
            int((/n_tot, n_flv/), kind=c_int))
    end do
end subroutine process_library_load_configuration

```

```

        flv_state = flv_state_tmp
        do i = 1, n_in
            prt_in(i) = particle_name_string (flv_state (i, :), model)
        end do
        do i = 1, n_out
            prt_out(i) = particle_name_string (flv_state (n_in+i, :), model)
        end do
        call process_library_append &
            (prc_lib, prc_id, model, prt_in, prt_out, var_list, &
             status=STAT_LOADED, restrictions=restrictions)
        deallocate (prt_in, prt_out, flv_state, flv_state_tmp)
    end do SCAN_PROCESSES
contains
    function particle_name_string (ff, model) result (prt)
        type(string_t) :: prt
        integer, dimension(:), intent(in) :: ff
        type(model_t), intent(in), target :: model
        type(flavor_t) :: flv
        integer :: i
        prt = ""
        do i = 1, size (ff)
            if (all (ff(i) /= ff(:i-1))) then
                call flavor_init (flv, ff(i), model)
                if (prt /= "") prt = prt // ":"
                prt = prt // flavor_get_name (flv)
            end if
        end do
    end function particle_name_string
end subroutine process_library_load_configuration

```

(Process libraries: public)+≡

```

public :: process_library_get_process_id
public :: process_library_get_process_md5sum
public :: process_library_get_process_model_name

```

(Process libraries: procedures)+≡

```

function process_library_get_process_id (prc_lib, pid) result (process_id)
    type(string_t) :: process_id
    type(process_library_t), intent(in), target :: prc_lib
    integer(c_int), intent(in) :: pid
    type(c_ptr) :: cptr
    integer(c_int) :: len
    character(kind=c_char), dimension(:), pointer :: char_array
    integer, dimension(1) :: shape
    call prc_lib% get_process_id (pid, cptr, len)
    if (c_associated (cptr)) then
        shape(1) = len
        call c_f_pointer (cptr, char_array, shape)
        process_id = char_from_array (char_array)
        call prc_lib% get_process_id (0_c_int, cptr, len)
    else
        process_id = ""
    end if
end function process_library_get_process_id

```

```

function process_library_get_process_model_name &
    (prc_lib, pid) result (model_name)
    type(string_t) :: model_name
    type(process_library_t), intent(in), target :: prc_lib
    integer(c_int), intent(in) :: pid
    type(c_ptr) :: cptr
    integer(c_int) :: len
    character(kind=c_char), dimension(:), pointer :: char_array
    integer, dimension(1) :: shape
    call prc_lib% get_model_name (pid, cptr, len)
    if (c_associated (cptr)) then
        shape(1) = len
        call c_f_pointer (cptr, char_array, shape)
        model_name = char_from_array (char_array)
        call prc_lib% get_model_name (0_c_int, cptr, len)
    else
        model_name = ""
    end if
end function process_library_get_process_model_name

function process_library_get_process_restrictions &
    (prc_lib, pid) result (restrictions)
    type(string_t) :: restrictions
    type(process_library_t), intent(in), target :: prc_lib
    integer(c_int), intent(in) :: pid
    type(c_ptr) :: cptr
    integer(c_int) :: len
    character(kind=c_char), dimension(:), pointer :: char_array
    integer, dimension(1) :: shape
    call prc_lib% get_restrictions (pid, cptr, len)
    if (c_associated (cptr)) then
        shape(1) = len
        call c_f_pointer (cptr, char_array, shape)
        restrictions = char_from_array (char_array)
        call prc_lib% get_restrictions (0_c_int, cptr, len)
    else
        restrictions = ""
    end if
end function process_library_get_process_restrictions

function process_library_get_process_md5sum (prc_lib, pid) result (md5sum)
    type(string_t) :: md5sum
    type(process_library_t), intent(in), target :: prc_lib
    integer(c_int), intent(in) :: pid
    type(c_ptr) :: cptr
    integer(c_int) :: len
    character(kind=c_char), dimension(:), pointer :: char_array
    integer, dimension(1) :: shape
    call prc_lib% get_md5sum (pid, cptr, len)
    if (c_associated (cptr)) then
        shape(1) = len
        call c_f_pointer (cptr, char_array, shape)
        md5sum = char_from_array (char_array)
    end if
end function process_library_get_process_md5sum

```

```

        call prc_lib% get_md5sum (O_c_int, cptr, len)
    else
        md5sum = ""
    end if
end function process_library_get_process_md5sum

```

Auxiliary: Transform a character array into a character string.

```

<Process libraries: procedures>+≡
function char_from_array (a) result (char)
    character(kind=c_char), dimension(:), intent(in) :: a
    character(len=size(a)) :: char
    integer :: i
    do i = 1, len (char)
        char(i:i) = a(i)
    end do
end function char_from_array

```

Generate process source code. Do this for all processes which have just been configured, unless there is a source-code file with identical MD5sum.

```

<Process libraries: public>+≡
public :: process_library_generate_code

<Process libraries: procedures>+≡
subroutine process_library_generate_code (prc_lib, os_data, simulate)
    type(process_library_t), intent(in) :: prc_lib
    type(os_data_t), intent(in) :: os_data
    logical, intent(in), optional :: simulate
    type(process_configuration_t), pointer :: current
    integer :: status
    call msg_message ("Generating code for process library '" &
        // char (process_library_get_name (prc_lib)) // "'")
    current => prc_lib%prc_first
    SCAN_PROCESSES: do while (associated (current))
        select case (current%status)
            case (STAT_CONFIGURED)
                call call_omega (current, os_data, status, simulate)
                if (status == 0) then
                    current%status = STAT_CODE_GENERATED
                else
                    call msg_error ("Process '" // char (current%id) &
                        // "': code generation failed")
                end if
            case (STAT_CODE_GENERATED:)
                call msg_message ("Skipping process '" // char (current%id) &
                    // "' (source code exists)")
            case default
                call msg_message ("Skipping process '" // char (current%id) &
                    // "' (undefined configuration)")
        end select
        current => current%next
    end do SCAN_PROCESSES
end subroutine process_library_generate_code

```

Call O'MEGA for process-code generation.

(Process libraries: procedures)+≡

```

subroutine call_omega (prc_conf, os_data, status, simulate)
  type(process_configuration_t), intent(in) :: prc_conf
  type(os_data_t), intent(in) :: os_data
  integer, intent(out) :: status
  logical, intent(in), optional :: simulate
  type(string_t) :: command_string
  type(string_t) :: model_id, omega_mode, omega_cascade
  integer :: j
  logical :: sim
  sim = .false.; if (present (simulate)) sim = simulate
  call msg_message ("Calling O'Mega for process '" &
    // char (prc_conf%id) // "'")
  model_id = model_get_name (prc_conf%model)
  select case (prc_conf%n_in)
  case (1); omega_mode = "-decay"
  case (2); omega_mode = "-scatter"
  end select
  if (prc_conf%restrictions == "") then
    omega_cascade = ""
  else
    omega_cascade = " -cascade '" // prc_conf%restrictions // "'"
  end if
  command_string = os_data%whizard_omega_binpath &
    // "/omega-" // model_id // ".opt" &
    // " -o " // prc_conf%id // ".f90" &
    // " -target:whizard" &
    // " -target:parameter_module parameters-" // model_id &
    // " -target:module " // prc_conf%id &
    // " -target:md5sum " // prc_conf%md5sum &
    // omega_cascade &
    // " -fusion:progress" &
    // " " // omega_mode
  command_string = command_string // " "
  do j = 1, prc_conf%n_in
    if (j == 1) then
      command_string = command_string // "'"
    else
      command_string = command_string // " "
    end if
    command_string = command_string // prc_conf%prt_in(j)
  end do
  command_string = command_string // " ->"
  do j = 1, prc_conf%n_out
    command_string = command_string &
      // " " // prc_conf%prt_out(j)
  end do
  command_string = command_string // "'"
  if (sim) then
    command_string = "cp " // os_data%whizard_testdatapath // "/" &
      // prc_conf%id // ".f90 ."
    call msg_message ("[call not executed, instead: copy file from " &
      // char (os_data%whizard_testdatapath) // "]")
  end if
end subroutine

```

```

end if
call os_system_call (command_string, status, verbose=.true.)
end subroutine call_omega

```

13.1.6 Interface file for the generated modules

```

<Process libraries: public>+≡
public :: process_library_write_driver

<Process libraries: procedures>+≡
subroutine process_library_write_driver (prc_lib)

  type(process_library_t), intent(inout) :: prc_lib
  type(string_t) :: filename, prefix
  type(string_t), dimension(:), allocatable :: prc_id, model, restrictions
  integer, dimension(:), allocatable :: n_par
  character(32), dimension(:), allocatable :: md5sum
  type(process_configuration_t), pointer :: current
  integer :: u, i, n_prc

  call msg_message ("Writing interface code for process library '" // &
    char (process_library_get_name (prc_lib)) // "'")
  prefix = prc_lib%basename // "_"

  n_prc = prc_lib%n_prc
  allocate (prc_id (n_prc), model (n_prc), restrictions (n_prc))
  allocate (n_par (n_prc), md5sum (n_prc))
  current => prc_lib%prc_first
  do i = 1, n_prc
    prc_id(i) = current%id
    model(i) = model_get_name (current%model)
    restrictions(i) = current%restrictions
    n_par(i) = model_get_n_parameters (current%model)
    md5sum(i) = current%md5sum
    current => current%next
  end do
  filename = prc_lib%basename // "_interface.f90"
  u = free_unit ()
  open (unit=u, file=char(prc_lib%basename // ".f90"), action="write")
  write (u, "(A)")  "!! WHIZARD process interface"
  write (u, "(A)")  "!!"
  write (u, "(A)")  "!! Automatically generated file, do not edit"
  call write_get_n_processes_fun ()
  call write_get_process_id_fun ()
  call write_get_model_name_fun ()
  call write_get_restrictions_fun ()
  call write_get_md5sum_fun ()
  call write_string_to_array_fun ()
  call write_get_int_fun ("n_in",  "number_particles_in")
  call write_get_int_fun ("n_out", "number_particles_out")
  call write_get_int_fun ("n_flv", "number_flavor_states")
  call write_get_int_fun ("n_hel", "number_spin_states")
  call write_get_int_fun ("n_col", "number_color_flows")

```

```

call write_get_int_fun ("n_cin", "number_color_indices")
call write_set_int_sub1 ("flv_state", "flavor_states")
call write_set_int_sub1 ("hel_state", "spin_states")
call write_set_int_sub2 ("col_state", "color_flows", "ghost_flag")
call write_init_get_fptr ()
call write_final_get_fptr ()
call write_update_alpha_s_get_fptr ()
call write_reset_helicity_selection_get_fptr ()
call write_new_event_get_fptr ()
call write_is_allowed_get_fptr ()
call write_get_amplitude_get_fptr ()
close (u)

```

```

prc_lib%status = max (prc_lib%status, STAT_CODE_GENERATED)

```

contains

```

subroutine write_get_n_processes_fun ()
  write (u, "(A)") ""
  write (u, "(A)") "! Return the number of processes in this library"
  write (u, "(A)") "function " // char (prefix) &
    // "get_n_processes () result (n) bind(C)"
  write (u, "(A)") " use iso_c_binding"
  write (u, "(A)") " integer(c_int) :: n"
  write (u, "(A,IO)") " n = ", n_prc
  write (u, "(A)") "end function " // char (prefix) &
    // "get_n_processes"
end subroutine write_get_n_processes_fun

```

```

subroutine write_get_process_id_fun ()
  write (u, "(A)") ""
  write (u, "(A)") "! Return the process ID of process #i (as a C pointer to a character array)"
  write (u, "(A)") "subroutine " // char (prefix) &
    // "get_process_id (i, cptr, len) bind(C)"
  write (u, "(A)") " use iso_c_binding"
  write (u, "(A)") " integer(c_int), intent(in) :: i"
  write (u, "(A)") " type(c_ptr), intent(inout) :: cptr"
  write (u, "(A)") " integer(c_int), intent(out) :: len"
  write (u, "(A)") " character(kind=c_char), dimension(:), allocatable, target, save :: a"
  call write_string_to_array_interface ()
  write (u, "(A)") " select case (i)"
  write (u, "(A)") " case (0); if (allocated (a)) deallocate (a)"
  do i = 1, n_prc
    write (u, "(A,IO,A)") " case (" , i , ") ; " &
      // "call " // char (prefix) &
      // "string_to_array (' " // char (prc_id(i)) // "', a)"
  end do
  write (u, "(A)") " end select"
  write (u, "(A)") " if (allocated (a)) then"
  write (u, "(A)") "   cptr = c_loc (a)"
  write (u, "(A)") "   len = size (a)"
  write (u, "(A)") " else"
  write (u, "(A)") "   cptr = c_null_ptr"
  write (u, "(A)") "   len = 0"

```

```

write (u, "(A)") " end if"
write (u, "(A)") "end subroutine " // char (prefix) &
// "get_process_id"
end subroutine write_get_process_id_fun

subroutine write_get_model_name_fun ()
write (u, "(A)") ""
write (u, "(A)") "! Return the model name for process #i (as a C pointer to a character array)"
write (u, "(A)") "subroutine " // char (prefix) &
// "get_model_name (i, cptr, len) bind(C)"
write (u, "(A)") " use iso_c_binding"
write (u, "(A)") " integer(c_int), intent(in) :: i"
write (u, "(A)") " type(c_ptr), intent(inout) :: cptr"
write (u, "(A)") " integer(c_int), intent(out) :: len"
write (u, "(A)") " character(kind=c_char), dimension(:), allocatable, target, save :: a"
call write_string_to_array_interface ()
write (u, "(A)") " select case (i)"
write (u, "(A)") " case (0); if (allocated (a)) deallocate (a)"
do i = 1, n_prc
write (u, "(A,IO,A)") " case (" , i, " ); " &
// "call " // char (prefix) &
// "string_to_array (' " // char (model(i)) // "', a)"
end do
write (u, "(A)") " end select"
write (u, "(A)") " if (allocated (a)) then"
write (u, "(A)") " cptr = c_loc (a)"
write (u, "(A)") " len = size (a)"
write (u, "(A)") " else"
write (u, "(A)") " cptr = c_null_ptr"
write (u, "(A)") " len = 0"
write (u, "(A)") " end if"
write (u, "(A)") "end subroutine " // char (prefix) &
// "get_model_name"
end subroutine write_get_model_name_fun

subroutine write_get_restrictions_fun ()
write (u, "(A)") ""
write (u, "(A)") "! Return the model name for process #i (as a C pointer to a character array)"
write (u, "(A)") "subroutine " // char (prefix) &
// "get_restrictions (i, cptr, len) bind(C)"
write (u, "(A)") " use iso_c_binding"
write (u, "(A)") " integer(c_int), intent(in) :: i"
write (u, "(A)") " type(c_ptr), intent(inout) :: cptr"
write (u, "(A)") " integer(c_int), intent(out) :: len"
write (u, "(A)") " character(kind=c_char), dimension(:), allocatable, target, save :: a"
call write_string_to_array_interface ()
write (u, "(A)") " select case (i)"
write (u, "(A)") " case (0); if (allocated (a)) deallocate (a)"
do i = 1, n_prc
write (u, "(A,IO,A)") " case (" , i, " ); " &
// "call " // char (prefix) &
// "string_to_array (' " // char (restrictions(i)) // "', a)"
end do
write (u, "(A)") " end select"

```

```

write (u, "(A)") " if (allocated (a)) then"
write (u, "(A)") "     cptr = c_loc (a)"
write (u, "(A)") "     len = size (a)"
write (u, "(A)") " else"
write (u, "(A)") "     cptr = c_null_ptr"
write (u, "(A)") "     len = 0"
write (u, "(A)") " end if"
write (u, "(A)") "end subroutine " // char (prefix) &
// "get_restrictions"
end subroutine write_get_restrictions_fun

subroutine write_get_md5sum_fun ()
integer :: i
write (u, "(A)") ""
write (u, "(A)") "! Return the MD5 sum for the process configuration (as a C pointer to a c
write (u, "(A)") "subroutine " // char (prefix) &
// "get_md5sum (i, cptr, len) bind(C)"
write (u, "(A)") " use iso_c_binding"
call write_use_lines ("md5sum", "md5sum")
write (u, "(A)") " integer(c_int), intent(in) :: i"
write (u, "(A)") " type(c_ptr), intent(inout) :: cptr"
write (u, "(A)") " integer(c_int), intent(out) :: len"
write (u, "(A)") " character(kind=c_char), dimension(:), allocatable, target, save :: a"
call write_string_to_array_interface ()
write (u, "(A)") " select case (i)"
write (u, "(A)") " case (0); if (allocated (a)) deallocate (a)"
do i = 1, n_prc
write (u, "(A,IO,A)") " case (" , i, "); " &
// "call " // char (prefix) &
// "string_to_array (" // char (prc_id(i)) &
// "_md5sum (), a)"
end do
write (u, "(A)") " end select"
write (u, "(A)") " if (allocated (a)) then"
write (u, "(A)") "     cptr = c_loc (a)"
write (u, "(A)") "     len = size (a)"
write (u, "(A)") " else"
write (u, "(A)") "     cptr = c_null_ptr"
write (u, "(A)") "     len = 0"
write (u, "(A)") " end if"
write (u, "(A)") "end subroutine " // char (prefix) &
// "get_md5sum"
end subroutine write_get_md5sum_fun

subroutine write_string_to_array_interface ()
write (u, "(2x,A)") "interface"
write (u, "(5x,A)") "subroutine " // char (prefix) &
// "string_to_array (string, a)"
write (u, "(5x,A)") " use iso_c_binding"
write (u, "(5x,A)") " character(*), intent(in) :: string"
write (u, "(5x,A)") " character(kind=c_char), dimension(:), allocatable, intent(out) :: a"
write (u, "(5x,A)") "end subroutine " // char (prefix) &
// "string_to_array"
write (u, "(2x,A)") "end interface"

```

```

end subroutine write_string_to_array_interface

subroutine write_string_to_array_fun ()
  write (u, "(A)") ""
  write (u, "(A)") "! Auxiliary: convert character string to array pointer"
  write (u, "(A)") "subroutine " // char (prefix) &
    // "string_to_array (string, a)"
  write (u, "(A)") "  use iso_c_binding"
  write (u, "(A)") "  character(*), intent(in) :: string"
  write (u, "(A)") "  character(kind=c_char), dimension(:), allocatable, intent(out) :: a"
  write (u, "(A)") "  integer :: i"
  write (u, "(A)") "  allocate (a (len (string)))"
  write (u, "(A)") "  do i = 1, size (a)"
  write (u, "(A)") "    a(i) = string(i:i)"
  write (u, "(A)") "  end do"
  write (u, "(A)") "end subroutine " // char (prefix) &
    // "string_to_array"
end subroutine write_string_to_array_fun

subroutine write_get_int_fun (vname, fname)
  character(*), intent(in) :: vname, fname
  write (u, "(A)") ""
  write (u, "(A)") "! Return the value of " // vname
  write (u, "(A)") "function " // char (prefix) &
    // "get_" // vname // " (pid)" &
    // " result (" // vname // ") bind(C)"
  write (u, "(A)") "  use iso_c_binding"
  call write_use_lines (vname, fname)
  write (u, "(A)") "  integer(c_int), intent(in) :: pid"
  write (u, "(A)") "  integer(c_int) :: " // vname
  call write_case_lines (vname // " = ", "_" // vname // " ()")
  write (u, "(A)") "end function " // char (prefix) &
    // "get_" // vname
end subroutine write_get_int_fun

subroutine write_set_int_sub1 (vname, fname)
  character(*), intent(in) :: vname, fname
  write (u, "(A)") ""
  write (u, "(A)") "! Set table: " // vname
  write (u, "(A)") "subroutine " // char (prefix) &
    // "set_" // vname &
    // " (pid, cptr, shape) bind(C)"
  write (u, "(A)") "  use iso_c_binding"
  call write_use_lines (vname, fname)
  write (u, "(A)") "  integer(c_int), intent(in) :: pid"
  write (u, "(A)") "  type(c_ptr), intent(in) :: cptr"
  write (u, "(A)") "  integer(c_int), dimension(2), intent(in) :: shape"
  write (u, "(A)") "  integer(c_int), dimension(:,:), pointer :: " // vname
  if (kind(1) /= c_int) then
    write (u, "(A)") "  integer, dimension(:,:), allocatable :: " &
      // vname // "_tmp"
  end if
  write (u, "(A)") "  call c_f_pointer (cptr, " // vname // ", shape)"
  if (kind(1) == c_int) then

```

```

        call write_case_lines ("call ", "_" // vname // " (" // vname // ")")
    else
        write (u, "(A)") " allocate (" &
            // vname // "_tmp (shape(1), shape(2)))"
        call write_case_lines ("call ", &
            "_" // vname // " (" // vname // "_tmp)")
        write (u, "(A)") " " // vname // " = " // vname // "_tmp"
    end if
    write (u, "(A)") "end subroutine " // char (prefix) &
        // "set_" // vname
end subroutine write_set_int_sub1

subroutine write_set_int_sub2 (vname, fname, lname)
    character(*), intent(in) :: vname, fname, lname
    write (u, "(A)") ""
    write (u, "(A)") "! Set tables: " // vname // ", " // lname
    write (u, "(A)") "subroutine " // char (prefix) &
        // "set_" // vname &
        // " (pid, cptr, shape, lcptr, lshape) bind(C)"
    write (u, "(A)") " use iso_c_binding"
    call write_use_lines (vname, fname)
    write (u, "(A)") " integer(c_int), intent(in) :: pid"
    write (u, "(A)") " type(c_ptr), intent(in) :: cptr"
    write (u, "(A)") " integer(c_int), dimension(3), intent(in) :: shape"
    write (u, "(A)") " type(c_ptr), intent(in) :: lcptr"
    write (u, "(A)") " integer(c_int), dimension(2), intent(in) :: lshape"
    write (u, "(A)") " integer(c_int), dimension(:,:), pointer :: " &
        // vname
    write (u, "(A)") " logical(c_bool), dimension(:,:), pointer :: " &
        // lname
    if (kind(1) /= c_int) then
        write (u, "(A)") " integer, dimension(:,:), allocatable :: " &
            // vname // "_tmp"
    end if
    if (kind(.true.) /= c_bool) then
        write (u, "(A)") " logical, dimension(:,:), allocatable :: " &
            // lname // "_tmp"
    end if
    write (u, "(A)") " call c_f_pointer (cptr, " // vname // ", shape)"
    write (u, "(A)") " call c_f_pointer (lcptr, " // lname // ", lshape)"
    if (kind(1) /= c_int) then
        write (u, "(A)") " allocate (" &
            // vname // "_tmp (shape(1), shape(2), shape(3)))"
    end if
    if (kind(.true.) /= c_bool) then
        write (u, "(A)") " allocate (" &
            // lname // "_tmp (lshape(1), lshape(2)))"
    end if
    if (kind(1) == c_int) then
        if (kind(.true.) == c_bool) then
            call write_case_lines ("call ", &
                "_" // vname // " (" // vname // ", " // lname // ")")
        else
            call write_case_lines ("call ", &

```

```

        "_" // vname // " (" // vname // ", " // lname // "_tmp")
write (u, "(A)") " " // lname // " = " // lname // "_tmp"
end if
else
if (kind(.true.) == c_bool) then
call write_case_lines ("call ", &
    "_" // vname // " (" // vname // "_tmp, " // lname // ")")
else
call write_case_lines ("call ", &
    "_" // vname // " (" // vname // "_tmp, " // lname // "_tmp")
write (u, "(A)") " " // lname // " = " // lname // "_tmp"
end if
write (u, "(A)") " " // vname // " = " // vname // "_tmp"
end if
write (u, "(A)") "end subroutine " // char (prefix) &
    // "set_" // vname
end subroutine write_set_int_sub2

subroutine write_init_get_fptr ()
write (u, "(A)") ""
write (u, "(A)") "! Return pointer to function: 'init'"
write (u, "(A)") "subroutine " // char (prefix) &
    // "init_get_fptr (pid, fptr) bind(C)"
write (u, "(A)") " use iso_c_binding"
write (u, "(A)") " integer(c_int), intent(in) :: pid"
write (u, "(A)") " type(c_funptr), intent(out) :: fptr"
write (u, "(A)") " abstract interface"
write (u, "(A)") "     subroutine prc_init (par) bind(C)"
write (u, "(A)") "         use iso_c_binding"
write (u, "(A)") "         use kinds"
write (u, "(A)") "         real(c_default_float), dimension(*), " &
    // "intent(in) :: par"
write (u, "(A)") "     end subroutine prc_init"
write (u, "(A)") " end interface"
do i = 1, n_prc
write (u, "(2x,A)") "procedure(prc_init), bind(C) :: " &
    // char (prc_id(i)) // "_init"
end do
call write_case_lines ("fptr = c_funloc (", "_init)")
write (u, "(A)") "end subroutine " // char (prefix) &
    // "init_get_fptr"
do i = 1, n_prc
write (u, *)
write (u, "(A)") "subroutine " // char (prc_id(i)) &
    // "_init (par) bind(C)"
write (u, "(A)") " use iso_c_binding"
write (u, "(A)") " use kinds"
write (u, "(A)") " use " // char (prc_id(i))
write (u, "(A)") " real(c_default_float), dimension(*), " &
    // "intent(in) :: par"
if (c_default_float == default) then
write (u, "(A)") " call init (par)"
else
write (u, "(A, IO)") " integer, parameter :: n_par = ", n_par(i)

```

```

        write (u, "(A)") " real(default), dimension(n_par) :: fpar"
        write (u, "(A)") " fpar = par"
        write (u, "(A)") " call init (fpar)"
    end if
    write (u, "(A)") "end subroutine " // char (prc_id(i)) // "_init"
end do
end subroutine write_init_get_fptr

subroutine write_final_get_fptr ()
    write (u, "(A)") ""
    write (u, "(A)") "! Return pointer to function: 'final'"
    write (u, "(A)") "subroutine " // char (prefix) &
        // "final_get_fptr (pid, fptr) bind(C)"
    write (u, "(A)") " use iso_c_binding"
    write (u, "(A)") " integer(c_int), intent(in) :: pid"
    write (u, "(A)") " type(c_funptr), intent(out) :: fptr"
    write (u, "(A)") " abstract interface"
    write (u, "(A)") "     subroutine prc_final () bind(C)"
    write (u, "(A)") "     end subroutine prc_final"
    write (u, "(A)") " end interface"
    do i = 1, n_prc
        write (u, "(2x,A)") "procedure(prc_final), bind(C) :: " &
            // char (prc_id(i)) // "_final"
    end do
    call write_case_lines ("fptr = c_funloc (", "_final")
    write (u, "(A)") "end subroutine " // char (prefix) &
        // "final_get_fptr"
    do i = 1, n_prc
        write (u, *)
        write (u, "(A)") "subroutine " // char (prc_id(i)) &
            // "_final () bind(C)"
        write (u, "(A)") " use " // char (prc_id(i))
        write (u, "(A)") " call final ()"
        write (u, "(A)") "end subroutine " // char (prc_id(i)) // "_final"
    end do
end subroutine write_final_get_fptr

subroutine write_update_alpha_s_get_fptr ()
    write (u, "(A)") ""
    write (u, "(A)") "! Return pointer to function: 'update_alpha_s'"
    write (u, "(A)") "subroutine " // char (prefix) &
        // "update_alpha_s_get_fptr (pid, fptr) bind(C)"
    write (u, "(A)") " use iso_c_binding"
    write (u, "(A)") " integer(c_int), intent(in) :: pid"
    write (u, "(A)") " type(c_funptr), intent(out) :: fptr"
    write (u, "(A)") " abstract interface"
    write (u, "(A)") "     subroutine prc_update_alpha_s (alpha_s) bind(C)"
    write (u, "(A)") "     use iso_c_binding"
    write (u, "(A)") "     use kinds"
    write (u, "(A)") "     real(c_default_float), " &
        // "intent(in) :: alpha_s"
    write (u, "(A)") "     end subroutine prc_update_alpha_s"
    write (u, "(A)") " end interface"
    do i = 1, n_prc

```

```

        write (u, "(2x,A)") "procedure(prc_update_alpha_s), bind(C) :: " &
            // char (prc_id(i)) // "_update_alpha_s"
    end do
    call write_case_lines ("fptr = c_funloc (", "_update_alpha_s")
    write (u, "(A)") "end subroutine " // char (prefix) &
        // "update_alpha_s_get_fptr"
    do i = 1, n_prc
        write (u, *)
        write (u, "(A)") "subroutine " // char (prc_id(i)) &
            // "_update_alpha_s (alpha_s) bind(C)"
        write (u, "(A)") " use iso_c_binding"
        write (u, "(A)") " use kinds"
        write (u, "(A)") " use " // char (prc_id(i))
        write (u, "(A)") " real(c_default_float), " &
            // "intent(in) :: alpha_s"
        if (c_default_float == default) then
            write (u, "(A)") " call update_alpha_s (alpha_s)"
        else
            write (u, "(A)") " call update_alpha_s " &
                // "(real (alpha_s, c_default_float))"
        end if
        write (u, "(A)") "end subroutine " // char (prc_id(i)) &
            // "_update_alpha_s"
    end do
end subroutine write_update_alpha_s_get_fptr

subroutine write_reset_helicity_selection_get_fptr ()
    write (u, "(A)") ""
    write (u, "(A)") "! Return pointer to function: " &
        // "'reset_helicity_selection'"
    write (u, "(A)") "subroutine " // char (prefix) &
        // "reset_helicity_selection_get_fptr (pid, fptr) bind(C)"
    write (u, "(A)") " use iso_c_binding"
    write (u, "(A)") " integer(c_int), intent(in) :: pid"
    write (u, "(A)") " type(c_funptr), intent(out) :: fptr"
    write (u, "(A)") " abstract interface"
    write (u, "(A)") " subroutine " &
        // "prc_reset_helicity_selection (threshold, cutoff) bind(C)"
    write (u, "(A)") " use iso_c_binding"
    write (u, "(A)") " use kinds"
    write (u, "(A)") " real(c_default_float), " &
        // "intent(in) :: threshold"
    write (u, "(A)") " integer(c_int), " &
        // "intent(in) :: cutoff"
    write (u, "(A)") " end subroutine prc_reset_helicity_selection"
    write (u, "(A)") " end interface"
    do i = 1, n_prc
        write (u, "(2x,A)") "procedure(prc_reset_helicity_selection), " &
            // "bind(C) :: " &
            // char (prc_id(i)) // "_reset_helicity_selection"
    end do
    call write_case_lines ("fptr = c_funloc (", "_reset_helicity_selection")
    write (u, "(A)") "end subroutine " // char (prefix) &
        // "reset_helicity_selection_get_fptr"

```

```

do i = 1, n_prc
  write (u, *)
  write (u, "(A)") "subroutine " // char (prc_id(i)) &
    // "_reset_helicity_selection (threshold, cutoff) bind(C)"
  write (u, "(A)") " use iso_c_binding"
  write (u, "(A)") " use kinds"
  write (u, "(A)") " use " // char (prc_id(i))
  write (u, "(A)") " real(c_default_float), " &
    // "intent(in) :: threshold"
  write (u, "(A)") " integer(c_int), " &
    // "intent(in) :: cutoff"
  write (u, "(A)") " real(default) :: rthreshold"
  write (u, "(A)") " integer :: icutoff"
  write (u, "(A)") " rthreshold = threshold"
  write (u, "(A)") " icutoff = cutoff"
  write (u, "(A)") " call reset_helicity_selection " &
    // "(rthreshold, icutoff)"
  write (u, "(A)") "end subroutine " // char (prc_id(i)) &
    // "_reset_helicity_selection"
end do
end subroutine write_reset_helicity_selection_get_fptr

subroutine write_new_event_get_fptr ()
  write (u, "(A)") ""
  write (u, "(A)") "! Return pointer to function: 'new_event'"
  write (u, "(A)") "subroutine " // char (prefix) &
    // "new_event_get_fptr (pid, fptr) bind(C)"
  write (u, "(A)") " use iso_c_binding"
  write (u, "(A)") " integer(c_int), intent(in) :: pid"
  write (u, "(A)") " type(c_funptr), intent(out) :: fptr"
  write (u, "(A)") " abstract interface"
  write (u, "(A)") "   subroutine prc_new_event (p) bind(C)"
  write (u, "(A)") "     use iso_c_binding"
  write (u, "(A)") "     use kinds"
  write (u, "(A)") "     real(c_default_float), dimension(0:3,*), " &
    // "intent(in) :: p"
  write (u, "(A)") "   end subroutine prc_new_event"
  write (u, "(A)") " end interface"
do i = 1, n_prc
  write (u, "(2x,A)") "procedure(prc_new_event), bind(C) :: " &
    // char (prc_id(i)) // "_new_event"
end do
call write_case_lines ("fptr = c_funloc (", "_new_event")
write (u, "(A)") "end subroutine " // char (prefix) &
  // "new_event_get_fptr"
do i = 1, n_prc
  write (u, *)
  write (u, "(A)") "subroutine " // char (prc_id(i)) &
    // "_new_event (p) bind(C)"
  write (u, "(A)") " use iso_c_binding"
  write (u, "(A)") " use kinds"
  write (u, "(A)") " use " // char (prc_id(i))
  write (u, "(A)") " real(c_default_float), dimension(0:3,*), " &
    // "intent(in) :: p"

```

```

        if (c_default_float == default) then
            write (u, "(A)") "    call new_event (p)"
        else
            write (u, "(A)") "    integer :: n_tot"
            write (u, "(A)") "    real(default), dimension(:,:), " &
                // "allocatable :: k"
            write (u, "(A)") "    n_tot = " &
                // "number_particles_in () + number_particles_out ()"
            write (u, "(A)") "    allocate (k (0:3,n_tot))"
            write (u, "(A)") "    k = p"
            write (u, "(A)") "    call new_event (k)"
        end if
        write (u, "(A)") "end subroutine " // char (prc_id(i)) // "_new_event"
    end do
end subroutine write_new_event_get_fptr

subroutine write_is_allowed_get_fptr ()
    write (u, "(A)") ""
    write (u, "(A)") "! Return pointer to function: 'is_allowed'"
    write (u, "(A)") "subroutine " // char (prefix) &
        // "is_allowed_get_fptr (pid, fptr) bind(C)"
    write (u, "(A)") "    use iso_c_binding"
    write (u, "(A)") "    integer(c_int), intent(in) :: pid"
    write (u, "(A)") "    type(c_funptr), intent(out) :: fptr"
    write (u, "(A)") "    abstract interface"
    write (u, "(A)") "        function " &
        // "prc_is_allowed (flv, hel, col) result (flag) bind(C)"
    write (u, "(A)") "        use iso_c_binding"
    write (u, "(A)") "        use kinds"
    write (u, "(A)") "        logical(c_bool) :: flag"
    write (u, "(A)") "        integer(c_int), intent(in) :: flv, hel, col"
    write (u, "(A)") "    end function prc_is_allowed"
    write (u, "(A)") "    end interface"
    do i = 1, n_prc
        write (u, "(2x,A)") "procedure(prc_is_allowed), bind(C) :: " &
            // char (prc_id(i)) // "_is_allowed"
    end do
    call write_case_lines ("fptr = c_funloc (", "_is_allowed)")
    write (u, "(A)") "end subroutine " // char (prefix) &
        // "is_allowed_get_fptr"
    do i = 1, n_prc
        write (u, *)
        write (u, "(A)") "function " // char (prc_id(i)) &
            // "_is_allowed (flv, hel, col) result (flag) bind(C)"
        write (u, "(A)") "    use iso_c_binding"
        write (u, "(A)") "    use kinds"
        write (u, "(A)") "    use " // char (prc_id(i))
        write (u, "(A)") "    logical(c_bool) :: flag"
        write (u, "(A)") "    integer(c_int), intent(in) :: flv, hel, col"
        if (c_int == kind(1)) then
            write (u, "(A)") "    flag = is_allowed (flv, hel, col)"
        else
            write (u, "(A)") "    integer :: iflv, ihel, icol"
            write (u, "(A)") "    iflv = flv; ihel = hel; icol = col"
        end if
    end do
end subroutine

```

```

        write (u, "(A)") " flag = is_allowed (iflv, ihel, icol)"
    end if
    write (u, "(A)") "end function " // char (prc_id(i)) &
        // "_is_allowed"
end do
end subroutine write_is_allowed_get_fptr

subroutine write_get_amplitude_get_fptr ()
    write (u, "(A)") ""
    write (u, "(A)") "! Return pointer to function: 'get_amplitude'"
    write (u, "(A)") "subroutine " // char (prefix) &
        // "get_amplitude_get_fptr (pid, fptr) " &
        // "bind(C)"
    write (u, "(A)") " use iso_c_binding"
    write (u, "(A)") " integer(c_int), intent(in) :: pid"
    write (u, "(A)") " type(c_funptr), intent(out) :: fptr"
    write (u, "(A)") " abstract interface"
    write (u, "(A)") " function " &
        // "prc_get_amplitude (flv, hel, col) result (amp) bind(C)"
    write (u, "(A)") " use iso_c_binding"
    write (u, "(A)") " use kinds"
    write (u, "(A)") " complex(c_default_complex) :: amp"
    write (u, "(A)") " integer(c_int), intent(in) :: flv, hel, col"
    write (u, "(A)") " end function prc_get_amplitude"
    write (u, "(A)") " end interface"
    do i = 1, n_prc
        write (u, "(2x,A)") "procedure(prc_get_amplitude), bind(C) :: " &
            // char (prc_id(i)) // "_get_amplitude"
    end do
    call write_case_lines ("fptr = c_funloc (", "_get_amplitude)")
    write (u, "(A)") "end subroutine " // char (prefix) &
        // "get_amplitude_get_fptr"
    do i = 1, n_prc
        write (u, *)
        write (u, "(A)") "function " // char (prc_id(i)) &
            // "_get_amplitude (flv, hel, col) result (amp) bind(C)"
        write (u, "(A)") " use iso_c_binding"
        write (u, "(A)") " use kinds"
        write (u, "(A)") " use " // char (prc_id(i))
        write (u, "(A)") " complex(c_default_complex) :: amp"
        write (u, "(A)") " integer(c_int), intent(in) :: flv, hel, col"
        if (c_int == kind(1)) then
            write (u, "(A)") " amp = get_amplitude (flv, hel, col)"
        else
            write (u, "(A)") " integer :: iflv, ihel, icol"
            write (u, "(A)") " iflv = flv; ihel = hel; icol = col"
            write (u, "(A)") " amp = get_amplitude (iflv, ihel, icol)"
        end if
        write (u, "(A)") "end function " // char (prc_id(i)) &
            // "_get_amplitude"
    end do
end subroutine write_get_amplitude_get_fptr

subroutine write_use_lines (vname, fname)

```

```

character(*), intent(in) :: vname, fname
integer :: i
do i = 1, n_prc
    write (u, "(2x,A)") "use " // char (prc_id(i)) // ", only: " &
        // char (prc_id(i)) // "_" // vname // " => " // fname
end do
end subroutine write_use_lines

subroutine write_case_lines (cmd1, cmd2)
character(*), intent(in) :: cmd1, cmd2
integer :: i
write (u, "(A)") " select case (pid)"
do i = 1, n_prc
    write (u, "(2x,A,I0,A)") "case(", i, "); " &
        // cmd1 // char (prc_id(i)) // cmd2
end do
write (u, "(A)") " end select"
end subroutine write_case_lines

end subroutine process_library_write_driver

```

13.1.7 Library manager

When static libraries are compiled, procedure pointer are not assigned by a dlopen mechanism, but must be done at program startup. Mainly for this task we write a library manager which links to the static libraries as they are defined by the user.

For each library, it has to assign all possible interface function to a C function pointer, which then is dereferenced in the same way as it is done for dlopened libraries.

```

<Process libraries: public>+≡
    public :: write_library_manager

<Process libraries: procedures>+≡
    subroutine write_library_manager (libname)

        type(string_t), dimension(:), intent(in) :: libname
        integer :: u, i

        call msg_message ("Writing library manager code")
        u = free_unit ()
        open (unit=u, file="libmanager.f90", action="write", status="replace")
        write (u, "(A)") " ! WHIZARD library manager"
        write (u, "(A)") " !"
        write (u, "(A)") " ! Automatically generated file, do not edit"
        write (u, "(A)") " "
        write (u, "(A)") "function libmanager_get_n_libs () result (n)"
        write (u, "(A)") " integer :: n"
        write (u, "(A,1x,I0)") " n =", size (libname)
        write (u, "(A)") "end function libmanager_get_n_libs"
        write (u, "(A)") " "
        write (u, "(A)") "function libmanager_get_libname (i) result (name)"

```

```

write (u, "(A)") " use iso_varying_string, string_t => varying_string"
write (u, "(A)") " type(string_t) :: name"
write (u, "(A)") " integer, intent(in) :: i"
write (u, "(A)") " select case (i)"
do i = 1, size (libname)
    call write_lib_name (i, libname(i))
end do
write (u, "(A)") " case default; name = ''"
write (u, "(A)") " end select"
write (u, "(A)") "end function libmanager_get_libname"
write (u, "(A)") ""
write (u, "(A)") "function libmanager_get_c_funptr (libname, fname) " &
    // "result (c_funptr)"
write (u, "(A)") " use iso_c_binding"
write (u, "(A)") " use prclib_interfaces"
write (u, "(A)") " type(c_funptr) :: c_funptr"
write (u, "(A)") " character(*), intent(in) :: libname, fname"
do i = 1, size (libname)
    call write_lib_declarations (libname(i))
end do
write (u, "(A)") " select case (libname)"
do i = 1, size (libname)
    call write_lib_code (libname(i))
end do
write (u, "(A)") " case default"
write (u, "(A)") " c_funptr = c_null_funptr"
write (u, "(A)") " end select"
write (u, "(A)") "end function libmanager_get_c_funptr"
close (u)

```

contains

```

subroutine write_lib_name (i, libname)
    integer, intent(in) :: i
    type(string_t), intent(in) :: libname
    write (u, "(A,I0,A)") " case (" , i, ")"; name = ' ' // char (libname) &
        // " '"
end subroutine write_lib_name

subroutine write_lib_declarations (libname)
    type(string_t), intent(in) :: libname
    write (u, "(A)") " procedure(prc_get_n_processes), bind(C) :: " &
        // char (libname)// "_" // "get_n_processes"
    write (u, "(A)") " procedure(prc_get_stringptr), bind(C) :: " &
        // char (libname)// "_" // "get_process_id"
    write (u, "(A)") " procedure(prc_get_stringptr), bind(C) :: " &
        // char (libname)// "_" // "get_model_name"
    write (u, "(A)") " procedure(prc_get_stringptr), bind(C) :: " &
        // char (libname)// "_" // "get_restrictions"
    write (u, "(A)") " procedure(prc_get_stringptr), bind(C) :: " &
        // char (libname)// "_" // "get_md5sum"
    write (u, "(A)") " procedure(prc_get_int), bind(C) :: " &
        // char (libname)// "_" // "get_n_in"
    write (u, "(A)") " procedure(prc_get_int), bind(C) :: " &

```

```

        // char (libname)// "_" // "get_n_out"
write (u, "(A)") "  procedure(prc_get_int), bind(C) :: " &
        // char (libname)// "_" // "get_n_flv"
write (u, "(A)") "  procedure(prc_get_int), bind(C) :: " &
        // char (libname)// "_" // "get_n_hel"
write (u, "(A)") "  procedure(prc_get_int), bind(C) :: " &
        // char (libname)// "_" // "get_n_col"
write (u, "(A)") "  procedure(prc_get_int), bind(C) :: " &
        // char (libname)// "_" // "get_n_cin"
write (u, "(A)") "  procedure(prc_set_int_tab1), bind(C) :: " &
        // char (libname)// "_" // "set_flv_state"
write (u, "(A)") "  procedure(prc_set_int_tab1), bind(C) :: " &
        // char (libname)// "_" // "set_hel_state"
write (u, "(A)") "  procedure(prc_set_int_tab2), bind(C) :: " &
        // char (libname)// "_" // "set_col_state"
write (u, "(A)") "  procedure(prc_get_fptr), bind(C) :: " &
        // char (libname)// "_" // "init_get_fptr"
write (u, "(A)") "  procedure(prc_get_fptr), bind(C) :: " &
        // char (libname)// "_" // "final_get_fptr"
write (u, "(A)") "  procedure(prc_get_fptr), bind(C) :: " &
        // char (libname)// "_" // "update_alpha_s_get_fptr"
write (u, "(A)") "  procedure(prc_get_fptr), bind(C) :: " &
        // char (libname)// "_" // "new_event_get_fptr"
write (u, "(A)") "  procedure(prc_get_fptr), bind(C) :: " &
        // char (libname)// "_" // "reset_helicity_selection_get_fptr"
write (u, "(A)") "  procedure(prc_get_fptr), bind(C) :: " &
        // char (libname)// "_" // "is_allowed_get_fptr"
write (u, "(A)") "  procedure(prc_get_fptr), bind(C) :: " &
        // char (libname)// "_" // "get_amplitude_get_fptr"
end subroutine write_lib_declarations

subroutine write_lib_code (libname)
  type(string_t), intent(in) :: libname
  write (u, "(2x,A)") "case ('" // char (libname) // "')"
  write (u, "(2x,A)") "  select case (fname)"
  call write_fun_code (char (libname), "get_n_processes")
  call write_fun_code (char (libname), "get_process_id")
  call write_fun_code (char (libname), "get_model_name")
  call write_fun_code (char (libname), "get_restrictions")
  call write_fun_code (char (libname), "get_md5sum")
  call write_fun_code (char (libname), "get_n_in")
  call write_fun_code (char (libname), "get_n_out")
  call write_fun_code (char (libname), "get_n_flv")
  call write_fun_code (char (libname), "get_n_hel")
  call write_fun_code (char (libname), "get_n_col")
  call write_fun_code (char (libname), "get_n_cin")
  call write_fun_code (char (libname), "set_flv_state")
  call write_fun_code (char (libname), "set_hel_state")
  call write_fun_code (char (libname), "set_col_state")
  call write_fun_code (char (libname), "init_get_fptr")
  call write_fun_code (char (libname), "final_get_fptr")
  call write_fun_code (char (libname), "update_alpha_s_get_fptr")
  call write_fun_code (char (libname), "reset_helicity_selection_get_fptr")
  call write_fun_code (char (libname), "new_event_get_fptr")

```

```

        call write_fun_code (char (libname), "is_allowed_get_fptr")
        call write_fun_code (char (libname), "get_amplitude_get_fptr")
        write (u, "(2x,A)") "    case default"
        write (u, "(2x,A)") "        print *, fname"
        write (u, "(2x,A)") "        stop 'WHIZARD bug: " &
            // "libmanager cannot handle this function'"
        write (u, "(2x,A)") "    end select"
    end subroutine write_lib_code

    subroutine write_fun_code (prefix, fname)
        character(*), intent(in) :: prefix, fname
        write (u, "(5x,A)") "case ('" // fname // "')"
        write (u, "(5x,A)") "    c_fptr = c_funloc (" // prefix &
            // "_" // fname // ")
    end subroutine write_fun_code

end subroutine write_library_manager

```

These are the interfaces of the functions provided by the library manager.

<Process libraries: interfaces>≡

```

interface
    function libmanager_get_n_libs () result (n)
        integer :: n
    end function libmanager_get_n_libs
end interface

```

<Process libraries: interfaces>+≡

```

interface
    function libmanager_get_libname (i) result (name)
        use iso_varying_string, string_t => varying_string !NODEP!
        type(string_t) :: name
        integer, intent(in) :: i
    end function libmanager_get_libname
end interface

```

<Process libraries: interfaces>+≡

```

interface
    function libmanager_get_c_funptr (libname, fname) result (c_fptr)
        use iso_c_binding !NODEP!
        type(c_funptr) :: c_fptr
        character(*), intent(in) :: libname, fname
    end function libmanager_get_c_funptr
end interface

```

13.1.8 Compile and link a library

The process library proper consists of the process-specific Fortran source files and the driver (interface)

<Process libraries: public>+≡

```

public :: process_library_compile

```

(Process libraries: procedures)+≡

```

subroutine process_library_compile &
    (prc_lib, os_data, recompile_library, objlist_link)
    type(process_library_t), intent(inout) :: prc_lib
    type(os_data_t), intent(in) :: os_data
    logical, intent(in) :: recompile_library
    type(string_t), intent(out) :: objlist_link
    type(string_t) :: objlist_comp
    type(process_configuration_t), pointer :: current
    type(string_t) :: ext
    integer :: i
    if (prc_lib%status == STAT_LOADED) then
        call msg_message ("Unloading process library '" // &
            char (process_library_get_name (prc_lib)) // "'")
        call dlaccess_final (prc_lib%dlaccess)
        prc_lib%status = STAT_CODE_GENERATED
    end if
    call msg_message ("Compiling process library '" // &
        char (process_library_get_name (prc_lib)) // "'")
    objlist_comp = ""
    objlist_link = ""
    if (os_data%use_libtool) then
        ext = ".lo"
    else
        ext = os_data%obj_ext
    end if
    current => prc_lib%prc_first
    SCAN_PROCESSES: do i = 1, prc_lib%n_prc
        objlist_link = objlist_link // " " // current%id // ext
        if (recompile_library) &
            current%status = min (STAT_CODE_GENERATED, current%status)
        if (current%status == STAT_CODE_GENERATED) then
            objlist_comp = objlist_comp // " " // current%id // ext
            call os_compile_shared (current%id, os_data)
            current%status = STAT_COMPILED
        else
            call msg_message ("Skipping process '" // char (current%id) &
                // "' (object code exists)")
        end if
        current => current%next
    end do SCAN_PROCESSES
    if (objlist_comp /= "") then
        call os_compile_shared (prc_lib%basename, os_data)
        objlist_link = objlist_link // " " // prc_lib%basename // ext
    else
        call msg_message ("Skipping library '" &
            // char (prc_lib%basename) &
            // "' (no processes have been recompiled)")
        objlist_link = ""
    end if
    prc_lib%status = STAT_COMPILED
end subroutine process_library_compile

```

(Process libraries: public)+≡

```

public :: process_library_link
<Process libraries: procedures>+≡
subroutine process_library_link (prc_lib, os_data, objlist)
  type(process_library_t), intent(in) :: prc_lib
  type(os_data_t), intent(in) :: os_data
  type(string_t), intent(in) :: objlist
  if (objlist /= "") then
    call os_link_shared (objlist // " " // os_data%whizard_ldflags, &
      prc_lib%basename, os_data)
  end if
end subroutine process_library_link

```

13.1.9 Standalone executable

Compile the library bundle and link with the libraries as a standalone executable

```

<Process libraries: public>+≡
public :: compile_library_manager

<Process libraries: procedures>+≡
subroutine compile_library_manager (os_data)
  type(os_data_t), intent(in) :: os_data
  call msg_message ("Compiling library manager")
  call os_compile_shared (var_str ("libmanager"), os_data)
end subroutine compile_library_manager

<Process libraries: public>+≡
public :: link_executable

<Process libraries: procedures>+≡
subroutine link_executable (libname, exec_name, os_data)
  type(string_t), dimension(:), intent(in) :: libname
  type(string_t), intent(in) :: exec_name
  type(os_data_t), intent(in) :: os_data
  type(string_t) :: objlist, ext_o, ext_a
  integer :: i
  if (os_data%use_libtool) then
    ext_o = ".lo"
    ext_a = ".la"
  else
    ext_o = ".o"
    ext_a = ".a"
  end if
  objlist = "libmanager" // ext_o
  do i = 1, size (libname)
    objlist = objlist // " " // libname(i) // ext_a
  end do
  call os_link_static (objlist, exec_name, os_data)
end subroutine link_executable

```

13.1.10 Loading a library

This loads a process library. We assume that it resides in the current directory.

Loading the library assigns all procedure pointers to procedures within the library.

Unloading is done by the finalizer.

```
(Process libraries: public)+≡
    public :: process_library_load

(Process libraries: procedures)+≡
    subroutine process_library_load (prc_lib, os_data, model, var_list, ignore)
        type(process_library_t), intent(inout), target :: prc_lib
        type(os_data_t), intent(in) :: os_data
        type(model_t), pointer, optional :: model
        type(var_list_t), intent(inout), optional :: var_list
        logical, intent(in), optional :: ignore
        type(c_funptr) :: c_funptr
        type(model_t), pointer :: mdl
        type(string_t) :: prefix
        logical :: ignore_error
        ignore_error = .false.; if (present (ignore)) ignore_error = ignore
        if (prc_lib%status == STAT_LOADED) then
            if (.not. ignore_error) then
                call msg_message ("Process library '" // char (prc_lib%basename) &
                    // "' is already loaded")
            end if
            return
        end if
        if (prc_lib%static) then
            call msg_message ("Loading static process library '" &
                // char (prc_lib%basename) // "'")
        else
            call msg_message ("Loading process library '" &
                // char (prc_lib%basename) // "'")
            prc_lib%libname = os_get_dlname (prc_lib%basename, os_data, ignore)
            if (prc_lib%libname == "") return
            call dlaccess_init (prc_lib%dlaccess, var_str ("."), &
                prc_lib%libname, os_data)
            call process_library_check_dLError (prc_lib)
        end if
        prefix = prc_lib%basename
        c_funptr = process_library_get_c_funptr &
            (prc_lib, prefix, var_str ("get_n_processes"))
        call c_f_procpointer (c_funptr, prc_lib%get_n_prc)
        c_funptr = process_library_get_c_funptr &
            (prc_lib, prefix, var_str ("get_process_id"))
        call c_f_procpointer (c_funptr, prc_lib%get_process_id)
        c_funptr = process_library_get_c_funptr &
            (prc_lib, prefix, var_str ("get_model_name"))
        call c_f_procpointer (c_funptr, prc_lib%get_model_name)
        c_funptr = process_library_get_c_funptr &
            (prc_lib, prefix, var_str ("get_restrictions"))
        call c_f_procpointer (c_funptr, prc_lib%get_restrictions)
        c_funptr = process_library_get_c_funptr &
            (prc_lib, prefix, var_str ("get_md5sum"))
```

```

call c_f_procpointer (c_fptr, prc_lib%get_md5sum)
c_fptr = process_library_get_c_funptr &
    (prc_lib, prefix, var_str ("get_n_in"))
call c_f_procpointer (c_fptr, prc_lib%get_n_in)
c_fptr = process_library_get_c_funptr &
    (prc_lib, prefix, var_str ("get_n_out"))
call c_f_procpointer (c_fptr, prc_lib%get_n_out)
c_fptr = process_library_get_c_funptr &
    (prc_lib, prefix, var_str ("get_n_flv"))
call c_f_procpointer (c_fptr, prc_lib%get_n_flv)
c_fptr = process_library_get_c_funptr &
    (prc_lib, prefix, var_str ("get_n_hel"))
call c_f_procpointer (c_fptr, prc_lib%get_n_hel)
c_fptr = process_library_get_c_funptr &
    (prc_lib, prefix, var_str ("get_n_col"))
call c_f_procpointer (c_fptr, prc_lib%get_n_col)
c_fptr = process_library_get_c_funptr &
    (prc_lib, prefix, var_str ("get_n_cin"))
call c_f_procpointer (c_fptr, prc_lib%get_n_cin)
c_fptr = process_library_get_c_funptr &
    (prc_lib, prefix, var_str ("set_flv_state"))
call c_f_procpointer (c_fptr, prc_lib%set_flv_state)
c_fptr = process_library_get_c_funptr &
    (prc_lib, prefix, var_str ("set_hel_state"))
call c_f_procpointer (c_fptr, prc_lib%set_hel_state)
c_fptr = process_library_get_c_funptr &
    (prc_lib, prefix, var_str ("set_col_state"))
call c_f_procpointer (c_fptr, prc_lib%set_col_state)
c_fptr = process_library_get_c_funptr &
    (prc_lib, prefix, var_str ("init_get_fptr"))
call c_f_procpointer (c_fptr, prc_lib%init_get_fptr)
c_fptr = process_library_get_c_funptr &
    (prc_lib, prefix, var_str ("final_get_fptr"))
call c_f_procpointer (c_fptr, prc_lib%final_get_fptr)
c_fptr = process_library_get_c_funptr &
    (prc_lib, prefix, var_str ("update_alpha_s_get_fptr"))
call c_f_procpointer (c_fptr, prc_lib%update_alpha_s_get_fptr)
c_fptr = process_library_get_c_funptr &
    (prc_lib, prefix, var_str ("new_event_get_fptr"))
call c_f_procpointer (c_fptr, prc_lib%new_event_get_fptr)
c_fptr = process_library_get_c_funptr &
    (prc_lib, prefix, var_str ("reset_helicity_selection_get_fptr"))
call c_f_procpointer (c_fptr, prc_lib%reset_helicity_selection_get_fptr)
c_fptr = process_library_get_c_funptr &
    (prc_lib, prefix, var_str ("is_allowed_get_fptr"))
call c_f_procpointer (c_fptr, prc_lib%is_allowed_get_fptr)
c_fptr = process_library_get_c_funptr &
    (prc_lib, prefix, var_str ("get_amplitude_get_fptr"))
call c_f_procpointer (c_fptr, prc_lib%get_amplitude_get_fptr)
call process_library_load_configuration (prc_lib, os_data, mdl, var_list)
prc_lib%status = STAT_LOADED
call var_list_set_string (var_list, var_str ("$library_name"), &
    process_library_get_name (prc_lib), is_known=.true.) ! $
if (present (model)) model => mdl

```

```
end subroutine process_library_load
```

Get a C function pointer to a procedure belonging to the process library interface and check for an error condition.

(Process libraries: procedures)+≡

```
function process_library_get_c_funptr &
  (prc_lib, prefix, fname) result (c_fptr)
  type(c_funptr) :: c_fptr
  type(process_library_t), intent(inout) :: prc_lib
  type(string_t), intent(in) :: prefix, fname
  type(string_t) :: full_name
  full_name = prefix // "_" // fname
  if (prc_lib%static) then
    c_fptr = libmanager_get_c_funptr (char (prefix), char (fname))
  else
    c_fptr = dlaccess_get_c_funptr (prc_lib%dlaccess, full_name)
    call process_library_check_dlerror (prc_lib)
  end if
end function process_library_get_c_funptr
```

Check for an error condition and signal it.

(Process libraries: procedures)+≡

```
subroutine process_library_check_dlerror (prc_lib)
  type(process_library_t), intent(in) :: prc_lib
  if (dlaccess_has_error (prc_lib%dlaccess)) then
    call msg_fatal (char (dlaccess_get_error (prc_lib%dlaccess)))
  end if
end subroutine process_library_check_dlerror
```

13.1.11 The library store

We want to handle several libraries in parallel, therefore we introduce a global library store, similar to the model and process lists. The store is a module variable.

(Process libraries: types)+≡

```
type :: process_library_store_t
  private
  type(process_library_t), pointer :: first => null ()
  type(process_library_t), pointer :: last => null ()
end type process_library_store_t
```

(Process libraries: variables)≡

```
type(process_library_store_t), save :: process_library_store
```

Append a new library, if it does not yet exist, and return a pointer to it.

(Process libraries: public)+≡

```
public :: process_library_store_append
```

```

<Process libraries: procedures>+≡
subroutine process_library_store_append (name, os_data, prc_lib)
  type(string_t), intent(in) :: name
  type(os_data_t), intent(in) :: os_data
  type(process_library_t), pointer :: prc_lib
  prc_lib => process_library_store_get_ptr (name)
  if (.not. associated (prc_lib)) then
    call msg_message &
      ("Initializing process library '" // char (name) // "'")
    allocate (prc_lib)
    call process_library_init (prc_lib, name, os_data)
    if (associated (process_library_store%last)) then
      process_library_store%last%next => prc_lib
    else
      process_library_store%first => prc_lib
    end if
    process_library_store%last => prc_lib
  end if
end subroutine process_library_store_append

```

Finalizer. This closes all open libraries.

```

<Process libraries: public>+≡
public :: process_library_store_final

<Process libraries: procedures>+≡
subroutine process_library_store_final ()
  type(process_library_t), pointer :: current
  do while (associated (process_library_store%first))
    current => process_library_store%first
    process_library_store%first => current%next
    call process_library_final (current)
    deallocate (current)
  end do
end subroutine process_library_store_final

```

Load all libraries

```

<Process libraries: public>+≡
public :: process_library_store_load

<Process libraries: procedures>+≡
subroutine process_library_store_load (os_data, var_list)
  type(os_data_t), intent(in) :: os_data
  type(var_list_t), intent(inout), optional :: var_list
  type(process_library_t), pointer :: current
  current => process_library_store%first
  do while (associated (current))
    call process_library_load (current, os_data, var_list=var_list)
    current => current%next
  end do
end subroutine process_library_store_load

```

Get a pointer to an existing (named) library

```

<Process libraries: public>+≡
public :: process_library_store_get_ptr

```

```

<Process libraries: procedures>+≡
function process_library_store_get_ptr (name) result (prc_lib)
  type(process_library_t), pointer :: prc_lib
  type(string_t), intent(in) :: name
  prc_lib => process_library_store%first
  do while (associated (prc_lib))
    if (prc_lib%basename == name) exit
    prc_lib => prc_lib%next
  end do
end function process_library_store_get_ptr

```

Get a pointer to the first/next library

```

<Process libraries: public>+≡
public :: process_library_store_get_first

<Process libraries: procedures>+≡
function process_library_store_get_first () result (prc_lib)
  type(process_library_t), pointer :: prc_lib
  prc_lib => process_library_store%first
end function process_library_store_get_first

```

13.1.12 Preloading static libraries

Static libraries are static, so it is sensible to load them all at startup. (By default, they are linked, but not loaded in the sense that a `process_library` object exists for them.) This can be done using this routine.

```

<Process libraries: public>+≡
public :: process_library_store_load_static

<Process libraries: procedures>+≡
subroutine process_library_store_load_static &
  (os_data, prc_lib, model, var_list)
  type(os_data_t), intent(in) :: os_data
  type(process_library_t), pointer :: prc_lib
  type(model_t), pointer :: model
  type(var_list_t), intent(inout) :: var_list
  integer :: n, i
  type(string_t), dimension(:), allocatable :: libname
  n = libmanager_get_n_libs ()
  allocate (libname (n))
  do i = 1, n
    libname(i) = libmanager_get_libname (i)
  end do
  do i = 1, n
    call process_library_store_append (libname(i), os_data, prc_lib)
    call process_library_set_static (prc_lib, .true.)
    call process_library_load (prc_lib, os_data, model, var_list)
  end do
end subroutine process_library_store_load_static

```

13.1.13 Integration results

Record integration results.

```
(Process libraries: public)+≡
    public :: process_library_record_integral

(Process libraries: procedures)+≡
    subroutine process_library_record_integral &
        (prc_lib, prc_id, n_calls, integral, error, accuracy, chi2, efficiency)
        type(process_library_t), intent(inout), target :: prc_lib
        type(string_t), intent(in) :: prc_id
        integer, intent(in) :: n_calls
        real(default), intent(in) :: integral, error, accuracy, chi2, efficiency
        type(process_configuration_t), pointer :: prc_conf
        prc_conf => process_library_get_process_ptr (prc_lib, prc_id)
        if (associated (prc_conf)) then
            if (prc_conf%status >= STAT_LOADED) then
                call process_configuration_record_integral &
                    (prc_conf, n_calls, integral, error, accuracy, chi2, efficiency)
            else
                call msg_bug ("Process '" // char (prc_id) // "': not loaded, " &
                    // "can't record integral")
            end if
        else
            call msg_bug ("Process '" // char (prc_id) // "': not associated, " &
                // "can't record integral")
        end if
    end subroutine process_library_record_integral

(Process libraries: public)+≡
    public :: process_library_get_n_calls
    public :: process_library_get_integral
    public :: process_library_get_error
    public :: process_library_get_accuracy
    public :: process_library_get_chi2
    public :: process_library_get_efficiency

(Process libraries: procedures)+≡
    function process_library_get_n_calls (prc_lib, prc_id) result (n_calls)
        integer :: n_calls
        type(process_library_t), intent(in), target :: prc_lib
        type(string_t), intent(in) :: prc_id
        type(process_configuration_t), pointer :: prc_conf
        prc_conf => process_library_get_process_ptr (prc_lib, prc_id)
        if (associated (prc_conf)) then
            n_calls = prc_conf%n_calls
        else
            n_calls = 0
        end if
    end function process_library_get_n_calls

    function process_library_get_integral (prc_lib, prc_id) result (integral)
        real(default) :: integral
        type(process_library_t), intent(in), target :: prc_lib
        type(string_t), intent(in) :: prc_id
```

```

    type(process_configuration_t), pointer :: prc_conf
    prc_conf => process_library_get_process_ptr (prc_lib, prc_id)
    if (associated (prc_conf)) then
        integral = prc_conf%integral
    else
        integral = 0
    end if
end function process_library_get_integral

function process_library_get_error (prc_lib, prc_id) result (error)
    real(default) :: error
    type(process_library_t), intent(in), target :: prc_lib
    type(string_t), intent(in) :: prc_id
    type(process_configuration_t), pointer :: prc_conf
    prc_conf => process_library_get_process_ptr (prc_lib, prc_id)
    if (associated (prc_conf)) then
        error = prc_conf%error
    else
        error = 0
    end if
end function process_library_get_error

function process_library_get_accuracy (prc_lib, prc_id) result (accuracy)
    real(default) :: accuracy
    type(process_library_t), intent(in), target :: prc_lib
    type(string_t), intent(in) :: prc_id
    type(process_configuration_t), pointer :: prc_conf
    prc_conf => process_library_get_process_ptr (prc_lib, prc_id)
    if (associated (prc_conf)) then
        accuracy = prc_conf%accuracy
    else
        accuracy = 0
    end if
end function process_library_get_accuracy

function process_library_get_chi2 (prc_lib, prc_id) result (chi2)
    real(default) :: chi2
    type(process_library_t), intent(in), target :: prc_lib
    type(string_t), intent(in) :: prc_id
    type(process_configuration_t), pointer :: prc_conf
    prc_conf => process_library_get_process_ptr (prc_lib, prc_id)
    if (associated (prc_conf)) then
        chi2 = prc_conf%chi2
    else
        chi2 = 0
    end if
end function process_library_get_chi2

function process_library_get_efficiency (prc_lib, prc_id) result (efficiency)
    real(default) :: efficiency
    type(process_library_t), intent(in), target :: prc_lib
    type(string_t), intent(in) :: prc_id
    type(process_configuration_t), pointer :: prc_conf
    prc_conf => process_library_get_process_ptr (prc_lib, prc_id)

```

```

    if (associated (prc_conf)) then
        efficiency = prc_conf%efficiency
    else
        efficiency = 0
    end if
end function process_library_get_efficiency

```

13.1.14 Test

(Process libraries: public)+≡

```
public :: process_libraries_test
```

(Procedures: procedures)+≡

```

subroutine process_libraries_test ()
    type(model_t), pointer :: model
    type(process_library_t), pointer :: prc_lib
    type(string_t), dimension(:), allocatable :: prt_in, prt_out
    type(os_data_t) :: os_data
    type(string_t) :: objlist
    call os_data_init (os_data)
    os_data%fcflags = "-gline -C=all"
    print *, "*** Read model file"
    call syntax_model_file_init ()
    call model_list_read_model &
        (var_str("QCD"), var_str("test.mdl"), os_data, model)
    call syntax_model_file_final ()
    print *, "*** Create library 'proc' with two processes"
    print *, "* Setup process configuration"
    print *, " [temporary: include zero processes because of references"
    print *, "   to omegalib, which we also need as a .so version]"
    print *, " [iso_varying_string included in libproc.so for the same reason"
    call process_library_store_append (var_str ("proc"), os_data, prc_lib)
    allocate (prt_in (1), prt_out (2))
    prt_in(1) = "Z"
    prt_out(1) = "e1"
    prt_out(2) = "E1"
    call process_library_append &
        (prc_lib, var_str ("zee"), model, prt_in, prt_out)
    deallocate (prt_in, prt_out)
    allocate (prt_in (2), prt_out (2))
    prt_in(1) = "g"
    prt_in(2) = "g"
    prt_out(1) = "u"
    prt_out(2) = "U"
    call process_library_append &
        (prc_lib, var_str ("uu"), model, prt_in, prt_out)
    print *
    print *, "* Generate code"
    call process_library_generate_code (prc_lib, os_data)
    print *
    print *, "* Write driver file 'proc_interface.f90'"
    call process_library_write_driver (prc_lib)
    print *

```

```

print *, "* Compile and link as 'libproc.so'"
call process_library_compile (prc_lib, os_data, .false., objlist)
call process_library_link (prc_lib, os_data, objlist)
print *
print *, "* Load shared libraries"
call process_library_store_load (os_data)
print *
print *, "* Execute 'get_n_processes' from the shared library named 'proc'"
print *
prc_lib => process_library_store_get_ptr (var_str ("proc"))
print *, "n_prc = ", prc_lib% get_n_prc ()
print *
print *, "* Cleanup"
call process_library_store_final
end subroutine process_libraries_test

```

13.2 Hard interactions

This module is concerned with the matrix element of an elementary interaction (typically, a hard scattering or heavy-particle decay). The module does not hold phase space information.

`<hard_interactions.f90>`≡
<File header>

```

module hard_interactions

    use iso_c_binding !NODEP!
    use kinds !NODEP!
<Use strings>
<Use file utils>
    use diagnostics !NODEP!
    use lorentz !NODEP!
    use os_interface
    use models
    use flavors
    use helicities
    use colors
    use quantum_numbers
    use interactions
    use evaluators
    use prclib_interfaces
    use process_libraries

```

<Standard module head>

<Hard interactions: public>

<Hard interactions: types>

<Hard interactions: interfaces>

```

contains

<Hard interactions: procedures>

end module hard_interactions

```

13.2.1 The hard-interaction data type

We define a special data type that accesses the process library. While constant data are stored as data, the process-specific functions for initialization, calculation and finalization are stored as procedure pointers.

```

<Hard interactions: types>≡
  type :: hard_interaction_data_t
    type(string_t) :: id
    type(model_t), pointer :: model => null ()
    integer :: n_tot, n_in, n_out
    integer :: n_flv, n_hel, n_col, n_cin
    real(default), dimension(:), allocatable :: par
    integer, dimension(:,:), allocatable :: flv_state, hel_state
    integer, dimension(:,:), allocatable :: col_state
    logical, dimension(:,:), allocatable :: ghost_flag
    procedure(prc_init), nopass, pointer :: init => null ()
    procedure(prc_final), nopass, pointer :: final => null ()
    procedure(prc_update_alpha_s), nopass, pointer :: update_alpha_s => null ()
    procedure(prc_reset_helicity_selection), nopass, pointer :: &
      reset_helicity_selection => null ()
    procedure(prc_new_event), nopass, pointer :: new_event => null ()
    procedure(prc_is_allowed), nopass, pointer :: is_allowed => null ()
    procedure(prc_get_amplitude), nopass, pointer :: get_amplitude => null ()
  end type hard_interaction_data_t

```

Initialize the hard process, using the process ID and the model parameters.

Assigning flavor/helicity/color tables: we need an intermediate allocatable array to serve as a C pointer target; the C pointer is passed to the process library where it is dereferenced and the array is filled. In principle, this copying step is necessary only if the Fortran and C types differ (which happens for the logical type). However, since this is not critical, we do it anyway.

For incoming particles, the particle color is inverted. This is useful for squaring the color flow, but has to be undone before convoluting with structure functions.

```

<Hard interactions: procedures>≡
  subroutine hard_interaction_data_init &
    (data, prc_lib, process_index, process_id, model)
    type(hard_interaction_data_t), intent(out) :: data
    type(process_library_t), intent(in) :: prc_lib
    integer, intent(in) :: process_index
    type(string_t), intent(in) :: process_id
    type(model_t), intent(in), target :: model
    integer(c_int) :: pid
    type(string_t) :: model_name
    type(c_funptr) :: fptr
    integer(c_int), dimension(:,:), allocatable, target :: flv_state, hel_state

```

```

integer(c_int), dimension(:,:,:), allocatable, target :: col_state
logical(c_bool), dimension(:,:), allocatable, target :: ghost_flag
integer :: c, i
if (.not. associated (prc_lib% get_process_id)) then
    call msg_fatal ("Process library '" // char (prc_lib%basename) // "':" &
        // " procedures unavailable (missing compile command?)")
    data%id = ""
    return
end if
pid = process_index
data%id = process_library_get_process_id (prc_lib, pid)
if (data%id /= process_id) then
    call msg_bug ("Process ID mismatch: requested '" &
        // char (process_id) // "' but found '" // char (data%id) // "'")
end if
data%model => model
model_name = process_library_get_process_model_name (prc_lib, pid)
if (model_get_name (data%model) /= model_name) then
    call msg_warning ("Process '" // char (process_id) // "': " &
        // "temporarily resetting model from '" &
        // char (model_get_name (data%model)) // "' to '" &
        // char (model_name) // "'")
    data%model => model_list_get_model_ptr (model_name)
    if (.not. associated (data%model)) then
        call msg_fatal ("Model '" // char (model_name) &
            // "' is not initialized")
    end if
end if
data%n_in = prc_lib% get_n_in (pid)
data%n_out = prc_lib% get_n_out (pid)
data%n_tot = data%n_in + data%n_out
data%n_flv = prc_lib% get_n_flv (pid)
data%n_hel = prc_lib% get_n_hel (pid)
data%n_col = prc_lib% get_n_col (pid)
data%n_cin = prc_lib% get_n_cin (pid)
call model_parameters_to_array (data%model, data%par)
allocate (data%flv_state (data%n_tot, data%n_flv))
allocate (data%hel_state (data%n_tot, data%n_hel))
allocate (data%col_state (data%n_cin, data%n_tot, data%n_col))
allocate (data%ghost_flag (data%n_tot, data%n_col))
allocate (flv_state (data%n_tot, data%n_flv))
allocate (hel_state (data%n_tot, data%n_hel))
allocate (col_state (data%n_cin, data%n_tot, data%n_col))
allocate (ghost_flag (data%n_tot, data%n_col))
call prc_lib% set_flv_state (pid, &
    c_loc (flv_state), &
    int((/data%n_tot, data%n_flv/), kind=c_int))
data%flv_state = flv_state
call prc_lib% set_hel_state (pid, &
    c_loc (hel_state), &
    int((/data%n_tot, data%n_hel/), kind=c_int))
data%hel_state = hel_state
call prc_lib% set_col_state (pid, &
    c_loc (col_state), &

```

```

        int((/data%n_cin, data%n_tot, data%n_col/), kind=c_int), &
        c_loc (ghost_flag), &
        int((/data%n_tot, data%n_col/), kind=c_int))
if (data%n_cin /= 2) &
    call msg_bug ("Process library '" // char (prc_lib%basename) // ":" &
        // " number of color indices must be two")
forall (c = 1:2, i = 1:data%n_in)
    data%col_state(c,i,:) = - col_state(3-c,i,:)
end forall
forall (i = data%n_in+1:data%n_tot)
    data%col_state(:,i,:) = col_state(:,i,:)
end forall
data%ghost_flag = ghost_flag
call prc_lib% init_get_fptr (pid, fptr)
call c_f_procpointer (fptr, data% init)
call prc_lib% final_get_fptr (pid, fptr)
call c_f_procpointer (fptr, data% final)
call prc_lib% update_alpha_s_get_fptr (pid, fptr)
call c_f_procpointer (fptr, data% update_alpha_s)
call prc_lib% reset_helicity_selection_get_fptr (pid, fptr)
call c_f_procpointer (fptr, data% reset_helicity_selection)
call prc_lib% new_event_get_fptr (pid, fptr)
call c_f_procpointer (fptr, data% new_event)
call prc_lib% is_allowed_get_fptr (pid, fptr)
call c_f_procpointer (fptr, data% is_allowed)
call prc_lib% get_amplitude_get_fptr (pid, fptr)
call c_f_procpointer (fptr, data% get_amplitude)
end subroutine hard_interaction_data_init

```

I/O:

(Hard interactions: procedures)+≡

```

subroutine hard_interaction_data_write (data, unit)
    type(hard_interaction_data_t), intent(in) :: data
    integer, intent(in), optional :: unit
    integer :: f, h, c, n, i
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write (u, *) "Process '", char (trim (data%id)), "'"
    write (u, *) "n_tot = ", data%n_tot
    write (u, *) "n_in = ", data%n_in
    write (u, *) "n_out = ", data%n_out
    write (u, *) "n_flv = ", data%n_flv
    write (u, *) "n_hel = ", data%n_hel
    write (u, *) "n_col = ", data%n_col
    write (u, *) "n_cin = ", data%n_cin
    write (u, *) "Model parameters:"
    do i = 1, size (data%par)
        write (u, *) i, data%par(i)
    end do
    write (u, *) "Flavor states:"
    do f = 1, data%n_flv
        write (u, *) f, ":", data%flv_state (:,f)
    end do
    write (u, *) "Helicity states:"

```

```

do h = 1, data%n_hel
  write (u, *) h, ":", data%hel_state (:,h)
end do
write (u, *) "Color states:"
do c = 1, data%n_col
  write (u, "(I5,A)", advance="no") c, ":"
  do n = 1, data%n_tot
    write (u, "('/'')", advance="no")
    if (data%ghost_flag (n, c)) write (u, "('*')", advance="no")
    do i = 1, data%n_cin
      if (data%col_state(i,n,c) == 0) cycle
      write (u, "(I3)", advance="no") data%col_state(i,n,c)
    end do
  end do
  write (u, "('/'')")
end do
end subroutine hard_interaction_data_write

```

13.2.2 The hard-interaction type

The type contains an interaction that is used to store the bare matrix element values. The flavor/helicity/color arrays are used to identify each matrix element for the amplitude function. Furthermore, there are three evaluators for the trace (the squared matrix element proper), the squared matrix element with color factors, possibly exclusive in some quantum numbers, and the squared matrix element broken down by color flows. The latter two are needed only for the simulation of complete events, not for integration.

```

<Hard interactions: public>≡
  public :: hard_interaction_t

<Hard interactions: types>+≡
  type :: hard_interaction_t
  private
  logical :: initialized = .false.
  type(hard_interaction_data_t) :: data
  integer :: n_values = 0
  integer, dimension(:), allocatable :: flv, hel, col
  type(interaction_t) :: int
  type(evaluator_t) :: eval_trace
  type(evaluator_t) :: eval_sqme
  type(evaluator_t) :: eval_flows
end type hard_interaction_t

```

Initializer. Set up the hard-process data and build the corresponding interaction structure. In parallel, assign the allowed flavor/helicity/color indices to the corresponding index arrays. For each valid combination, a matrix element pointer is prepared which is inserted as a new leaf in the interaction quantum-number tree.

```

<Hard interactions: public>+≡
  public :: hard_interaction_init

```

<Hard interactions: procedures>+≡

```

subroutine hard_interaction_init &
    (hi, prc_lib, process_index, process_id, model)
    type(hard_interaction_t), intent(out), target :: hi
    type(process_library_t), intent(in) :: prc_lib
    integer, intent(in) :: process_index
    type(string_t), intent(in) :: process_id
    type(model_t), intent(in), target :: model
    type(flavor_t), dimension(:), allocatable :: flv
    type(color_t), dimension(:), allocatable :: col
    type(helicity_t), dimension(:), allocatable :: hel
    type(quantum_numbers_t), dimension(:), allocatable :: qn
    integer :: f, h, c, i, n
    call hard_interaction_data_init &
        (hi%data, prc_lib, process_index, process_id, model)
    if (hi%data%id == "") return
    call hi%data%init (real (hi%data%par, c_default_float))
    call interaction_init &
        (hi%int, hi%data%n_in, 0, hi%data%n_out, set_relations=.true.)
    n = 0
    do f = 1, hi%data%n_flv
        do h = 1, hi%data%n_hel
            do c = 1, hi%data%n_col
                if (hi%data%is_allowed (f, h, c)) n = n + 1
            end do
        end do
    end do
    hi%n_values = n
    allocate (hi%flv (n), hi%hel (n), hi%col (n))
    allocate (flv (hi%data%n_tot), col (hi%data%n_tot), hel (hi%data%n_tot))
    allocate (qn (hi%data%n_tot))
    i = 0
    do f = 1, hi%data%n_flv
        do h = 1, hi%data%n_hel
            do c = 1, hi%data%n_col
                if (hi%data%is_allowed (f, h, c)) then
                    i = i + 1
                    hi%flv(i) = f
                    hi%hel(i) = h
                    hi%col(i) = c
                    call flavor_init (flv, hi%data%flv_state(:,f), hi%data%model)
                    call color_init_from_array (col, hi%data%col_state(:,c), &
                        hi%data%ghost_flag(:,c))
                    call helicity_init (hel, hi%data%hel_state(:,h))
                    call quantum_numbers_init (qn, flv, col, hel)
                    call interaction_add_state (hi%int, qn)
                end if
            end do
        end do
    end do
    call interaction_freeze (hi%int)
    hi%initialized = .true.
end subroutine hard_interaction_init

```

Finalizer:

```

<Hard interactions: public>+≡
    public :: hard_interaction_final

<Hard interactions: procedures>+≡
    subroutine hard_interaction_final (hi)
        type(hard_interaction_t), intent(inout) :: hi
        hi%initialized = .false.
        if (associated (hi%data% final)) call hi%data% final ()
        call interaction_final (hi%int)
        call evaluator_final (hi%eval_trace)
        call evaluator_final (hi%eval_flows)
        call evaluator_final (hi%eval_sqme)
        hi%n_values = 0
        if (allocated (hi%flv)) deallocate (hi%flv)
        if (allocated (hi%hel)) deallocate (hi%hel)
        if (allocated (hi%col)) deallocate (hi%col)
    end subroutine hard_interaction_final

```

I/O:

```

<Hard interactions: public>+≡
    public :: hard_interaction_write

<Hard interactions: procedures>+≡
    subroutine hard_interaction_write &
        (hi, unit, verbose, show_momentum_sum, show_mass, write_comb)
        type(hard_interaction_t), intent(in) :: hi
        integer, intent(in), optional :: unit
        logical, intent(in), optional :: verbose, show_momentum_sum, show_mass
        logical, intent(in), optional :: write_comb
        integer :: u, i
        u = output_unit (unit); if (u < 0) return
        write (u, "(1x,A)") "Hard interaction:"
        call hard_interaction_data_write (hi%data, u)
        if (present (write_comb)) then
            if (write_comb .and. hi%n_values /= 0) then
                write (u, "(1x,A)") "Allowed f/h/c index combinations:"
                do i = 1, hi%n_values
                    write (u, *) i, ":", hi%flv(i), hi%hel(i), hi%col(i)
                end do
            end if
        end if
        write (u, *)
        call interaction_write &
            (hi%int, unit, verbose, show_momentum_sum, show_mass)
        write (u, *) repeat (" ", 36)
        write (u, "(A)") "Trace including color factors (hard interaction)"
        call evaluator_write &
            (hi%eval_trace, unit, verbose, show_momentum_sum, show_mass)
        write (u, *) repeat (" ", 36)
        write (u, "(A)") "Exclusive sqme including color factors (hard interaction)"
        call evaluator_write &
            (hi%eval_sqme, unit, verbose, show_momentum_sum, show_mass)
        write (u, *) repeat (" ", 36)
    end subroutine hard_interaction_write

```

```

write (u, "(A)") "Color flow coefficients (hard interaction)"
call evaluator_write &
      (hi%eval_flows, unit, verbose, show_momentum_sum, show_mass)
end subroutine hard_interaction_write

```

Defined assignment. Deep copy (except for procedure pointers, of course).

```

<Hard interactions: public>+≡
public :: assignment(=)

<Hard interactions: interfaces>≡
interface assignment(=)
  module procedure hard_interaction_assign
end interface

<Hard interactions: procedures>+≡
subroutine hard_interaction_assign (hi_out, hi_in)
  type(hard_interaction_t), intent(out) :: hi_out
  type(hard_interaction_t), intent(in) :: hi_in
  hi_out%initialized = hi_in%initialized
  hi_out%data = hi_in%data
  hi_out%n_values = hi_in%n_values
  if (allocated (hi_in%flv)) then
    allocate (hi_out%flv (size (hi_in%flv)))
    hi_out%flv = hi_in%flv
  end if
  if (allocated (hi_in%hel)) then
    allocate (hi_out%hel (size (hi_in%hel)))
    hi_out%hel = hi_in%hel
  end if
  if (allocated (hi_in%col)) then
    allocate (hi_out%col (size (hi_in%col)))
    hi_out%col = hi_in%col
  end if
  hi_out%int = hi_in%int
  hi_out%eval_trace = hi_in%eval_trace
  hi_out%eval_sqme = hi_in%eval_sqme
  hi_out%eval_flows = hi_in%eval_flows
end subroutine hard_interaction_assign

```

13.2.3 Access contents

Whether we have a valid data set:

```

<Hard interactions: public>+≡
public :: hard_interaction_is_valid

<Hard interactions: procedures>+≡
function hard_interaction_is_valid (hi) result (flag)
  logical :: flag
  type(hard_interaction_t), intent(in) :: hi
  flag = hi%initialized
end function hard_interaction_is_valid

```

The alphanumeric ID.

```
<Hard interactions: public>+≡
    public :: hard_interaction_get_id

<Hard interactions: procedures>+≡
    function hard_interaction_get_id (hi) result (id)
        type(string_t) :: id
        type(hard_interaction_t), intent(in) :: hi
        id = hi%data%id
    end function hard_interaction_get_id
```

The model as used for the hard interaction.

```
<Hard interactions: public>+≡
    public :: hard_interaction_get_model_ptr

<Hard interactions: procedures>+≡
    function hard_interaction_get_model_ptr (hi) result (model)
        type(model_t), pointer :: model
        type(hard_interaction_t), intent(in) :: hi
        model => hi%data%model
    end function hard_interaction_get_model_ptr
```

Particle counts.

```
<Hard interactions: public>+≡
    public :: hard_interaction_get_n_in
    public :: hard_interaction_get_n_out
    public :: hard_interaction_get_n_tot

<Hard interactions: procedures>+≡
    function hard_interaction_get_n_in (hi) result (n_in)
        integer :: n_in
        type(hard_interaction_t), intent(in) :: hi
        n_in = hi%data%n_in
    end function hard_interaction_get_n_in

    function hard_interaction_get_n_out (hi) result (n_out)
        integer :: n_out
        type(hard_interaction_t), intent(in) :: hi
        n_out = hi%data%n_out
    end function hard_interaction_get_n_out

    function hard_interaction_get_n_tot (hi) result (n_tot)
        integer :: n_tot
        type(hard_interaction_t), intent(in) :: hi
        n_tot = hi%data%n_tot
    end function hard_interaction_get_n_tot
```

Quantum number counts.

```
<Hard interactions: public>+≡
    public :: hard_interaction_get_n_flv
    public :: hard_interaction_get_n_col
    public :: hard_interaction_get_n_hel
```

```

<Hard interactions: procedures>+≡
function hard_interaction_get_n_flv (hi) result (n_flv)
  integer :: n_flv
  type(hard_interaction_t), intent(in) :: hi
  n_flv = hi%data%n_flv
end function hard_interaction_get_n_flv

function hard_interaction_get_n_col (hi) result (n_col)
  integer :: n_col
  type(hard_interaction_t), intent(in) :: hi
  n_col = hi%data%n_col
end function hard_interaction_get_n_col

function hard_interaction_get_n_hel (hi) result (n_hel)
  integer :: n_hel
  type(hard_interaction_t), intent(in) :: hi
  n_hel = hi%data%n_hel
end function hard_interaction_get_n_hel

```

Particle tables.

```

<Hard interactions: public>+≡
public :: hard_interaction_get_flv_states

<Hard interactions: procedures>+≡
function hard_interaction_get_flv_states (hi) result (flv_state)
  integer, dimension(:, :), allocatable :: flv_state
  type(hard_interaction_t), intent(in) :: hi
  allocate (flv_state (size (hi%data%flv_state, 1), &
                          size (hi%data%flv_state, 2)))
  flv_state = hi%data%flv_state
end function hard_interaction_get_flv_states

```

Incoming particles. Consider only the first entry in the array of flavor combinations.

```

<Hard interactions: public>+≡
public :: hard_interaction_get_first_pdg_in

<Hard interactions: procedures>+≡
function hard_interaction_get_first_pdg_in (hi) result (pdg)
  integer, dimension(:), allocatable :: pdg
  type(hard_interaction_t), intent(in) :: hi
  allocate (pdg (hi%data%n_in))
  pdg = hi%data%flv_state (:hi%data%n_in, 1)
end function hard_interaction_get_first_pdg_in

```

13.2.4 Evaluators

This procedure initializes the evaluator that computes the matrix element squared, traced over all outgoing quantum numbers. Whether the trace over incoming quantum numbers is done, depends on the specified mask – except for color which is always summed.

```

<Hard interactions: public>+≡

```

```

public :: hard_interaction_init_trace
<Hard interactions: procedures>+≡
subroutine hard_interaction_init_trace (hi, qn_mask_in, nc)
  type(hard_interaction_t), intent(inout), target :: hi
  type(quantum_numbers_mask_t), dimension(:), intent(in) :: qn_mask_in
  integer, intent(in), optional :: nc
  type(quantum_numbers_mask_t), dimension(:), allocatable :: qn_mask
  allocate (qn_mask (hi%data%n_tot))
  qn_mask(:hi%data%n_in) = &
    new_quantum_numbers_mask (.false., .true., .false.) &
    .or. qn_mask_in
  qn_mask(hi%data%n_in+1:) = &
    new_quantum_numbers_mask (.true., .true., .true.)
  call evaluator_init_square_with_color_factors &
    (hi%eval_trace, hi%int, qn_mask, nc=nc)
end subroutine hard_interaction_init_trace

```

This procedure initializes the evaluator that computes the matrix element square separated in parts (e.g., polarization components). Polarization is kept in the initial state (if allowed by `qn_mask_in`) and for those final-state particles which are marked as unstable. The incoming-particle mask can also be used to sum over incoming flavor.

```

<Hard interactions: public>+≡
public :: hard_interaction_init_sqme
<Hard interactions: procedures>+≡
subroutine hard_interaction_init_sqme (hi, qn_mask_in, nc)
  type(hard_interaction_t), intent(inout), target :: hi
  type(quantum_numbers_mask_t), dimension(:), intent(in) :: qn_mask_in
  integer, intent(in), optional :: nc
  type(quantum_numbers_mask_t), dimension(:), allocatable :: qn_mask
  type(flavor_t), dimension(:), allocatable :: flv
  integer :: i
  allocate (qn_mask (hi%data%n_tot), flv (hi%data%n_flv))
  qn_mask(:hi%data%n_in) = &
    new_quantum_numbers_mask (.false., .true., .false.) &
    .or. qn_mask_in
  do i = hi%data%n_in + 1, hi%data%n_tot
    call flavor_init (flv, hi%data%flv_state(i,:), hi%data%model)
    qn_mask(i) = &
      new_quantum_numbers_mask (.false., .true., &
        all (flavor_is_stable (flv)))
  end do
  call evaluator_init_square_with_color_factors &
    (hi%eval_sqme, hi%int, qn_mask, nc=nc)
end subroutine hard_interaction_init_sqme

```

This procedure initializes the evaluator that computes the contributions to color flows, neglecting color interference. Polarization is summed over. The incoming-particle mask can be used to sum over incoming flavor.

```

<Hard interactions: public>+≡
public :: hard_interaction_init_flows

```

<Hard interactions: procedures>+≡

```

subroutine hard_interaction_init_flows (hi, qn_mask_in)
  type(hard_interaction_t), intent(inout), target :: hi
  type(quantum_numbers_mask_t), dimension(:), intent(in) :: qn_mask_in
  type(quantum_numbers_mask_t), dimension(:), allocatable :: qn_mask
  allocate (qn_mask (hi%data%n_tot))
  qn_mask(:hi%data%n_in) = &
    new_quantum_numbers_mask (.false., .false., .true.) &
    .or. qn_mask_in
  qn_mask(hi%data%n_in+1:) = &
    new_quantum_numbers_mask (.false., .false., .true.)
  call evaluator_init_squared_flows (hi%eval_flows, hi%int, qn_mask)
end subroutine hard_interaction_init_flows

```

Finalize the previous evaluators.

<Hard interactions: public>+≡

```

public :: hard_interaction_final_sqme
public :: hard_interaction_final_flows

```

<Hard interactions: procedures>+≡

```

subroutine hard_interaction_final_sqme (hi)
  type(hard_interaction_t), intent(inout) :: hi
  call evaluator_final (hi%eval_sqme)
end subroutine hard_interaction_final_sqme

subroutine hard_interaction_final_flows (hi)
  type(hard_interaction_t), intent(inout) :: hi
  call evaluator_final (hi%eval_flows)
end subroutine hard_interaction_final_flows

```

13.2.5 Matrix-element evaluation

Update the α_s value used by the matrix element (if any).

<Hard interactions: public>+≡

```

public :: hard_interaction_update_alpha_s

```

<Hard interactions: procedures>+≡

```

subroutine hard_interaction_update_alpha_s (hi, alpha_s)
  type(hard_interaction_t), intent(inout) :: hi
  real(default), intent(in) :: alpha_s
  real(c_default_float) :: c_alpha_s
  c_alpha_s = alpha_s
  call hi%data% update_alpha_s (c_alpha_s)
end subroutine hard_interaction_update_alpha_s

```

Reset the helicity selection counters that are used to speed up things by dropping zero helicity channels after `cutoff` tries.

<Hard interactions: public>+≡

```

public :: hard_interaction_reset_helicity_selection

```

```

<Hard interactions: procedures>+≡
subroutine hard_interaction_reset_helicity_selection (hi, threshold, cutoff)
  type(hard_interaction_t), intent(inout) :: hi
  real(default), intent(in) :: threshold
  integer, intent(in) :: cutoff
  real(c_default_float) :: c_threshold
  integer(c_int) :: c_cutoff
  c_threshold = threshold
  c_cutoff = cutoff
  call hi%data% reset_helicity_selection (c_threshold, c_cutoff)
end subroutine hard_interaction_reset_helicity_selection

```

This interfaces the matrix element proper. First, we request a new matrix element value to be computed from the given momenta. Then, we extract all values that are known to be allowed and assign them to the matrix element array. This array consists of pointers to the interaction values, so in fact the latter are calculated.

Although it may be irrelevant, this is an obvious place for parallel execution, so write a forall assignment. Making the assignment elemental is not possible because `get_amplitude` is a procedure pointer. [This is deactivated; to be checked again.]

After the matrix element data are read, we evaluate the squared matrix element (`eval_trace`). square and the color-flow coefficients.

```

<Hard interactions: public>+≡
public :: hard_interaction_evaluate

<Hard interactions: procedures>+≡
subroutine hard_interaction_evaluate (hi)
  type(hard_interaction_t), intent(inout), target :: hi
  integer :: i
  complex(default) :: val
  call hi%data% new_event &
    (array_from_vector4 (interaction_get_momenta (hi%int)))
!   forall (i = 1:hi%n_values)
!     hi%me(i) = hi%data% get_amplitude (hi%f1v(i), hi%hel(i), hi%col(i))
!   end forall
  do i = 1, hi%n_values
    val = hi%data% get_amplitude (hi%f1v(i), hi%hel(i), hi%col(i))
    call interaction_set_matrix_element (hi%int, i, val)
  end do
  call evaluator_evaluate (hi%eval_trace)
end subroutine hard_interaction_evaluate

```

The extra evaluators (squared matrix element without trace, color flows) need only be evaluated for simulation events that pass the unweighting step. This follows the previous routine.

```

<Hard interactions: public>+≡
public :: hard_interaction_evaluate_sqme
public :: hard_interaction_evaluate_flows

<Hard interactions: procedures>+≡
subroutine hard_interaction_evaluate_sqme (hi)
  type(hard_interaction_t), intent(inout), target :: hi

```

```

        call evaluator_receive_momenta (hi%eval_sqme)
        call evaluator_evaluate (hi%eval_sqme)
    end subroutine hard_interaction_evaluate_sqme

    subroutine hard_interaction_evaluate_flows (hi)
        type(hard_interaction_t), intent(inout), target :: hi
        call evaluator_receive_momenta (hi%eval_flows)
        call evaluator_evaluate (hi%eval_flows)
    end subroutine hard_interaction_evaluate_flows

```

This provides direct access to the matrix element, squared and traced over all quantum numbers. It is not used for ordinary evaluation.

```

<Hard interactions: public>+≡
    public :: hard_interaction_compute_sqme_sum

<Hard interactions: procedures>+≡
    function hard_interaction_compute_sqme_sum (hi, p) result (sqme)
        real(default) :: sqme
        type(hard_interaction_t), intent(inout), target :: hi
        type(vector4_t), dimension(:), intent(in) :: p
        call interaction_set_momenta (hi%int, p)
        call hard_interaction_evaluate (hi)
        sqme = evaluator_sum (hi%eval_trace)
    end function hard_interaction_compute_sqme_sum

```

13.2.6 Access results

```

<Hard interactions: public>+≡
    public :: hard_interaction_get_int_ptr

<Hard interactions: procedures>+≡
    function hard_interaction_get_int_ptr (hi) result (int)
        type(interaction_t), pointer :: int
        type(hard_interaction_t), intent(in), target :: hi
        int => hi%int
    end function hard_interaction_get_int_ptr

<Hard interactions: public>+≡
    public :: hard_interaction_get_eval_trace_ptr
    public :: hard_interaction_get_eval_sqme_ptr
    public :: hard_interaction_get_eval_flows_ptr

<Hard interactions: procedures>+≡
    function hard_interaction_get_eval_trace_ptr (hi) result (eval)
        type(evaluator_t), pointer :: eval
        type(hard_interaction_t), intent(in), target :: hi
        eval => hi%eval_trace
    end function hard_interaction_get_eval_trace_ptr

    function hard_interaction_get_eval_sqme_ptr (hi) result (eval)
        type(evaluator_t), pointer :: eval
        type(hard_interaction_t), intent(in), target :: hi
        eval => hi%eval_sqme
    end function hard_interaction_get_eval_sqme_ptr

```

```

end function hard_interaction_get_eval_sqme_ptr

function hard_interaction_get_eval_flows_ptr (hi) result (eval)
    type(evaluator_t), pointer :: eval
    type(hard_interaction_t), intent(in), target :: hi
    eval => hi%eval_flows
end function hard_interaction_get_eval_flows_ptr

```

13.2.7 Test

```

<Hard interactions: public>+≡
    public :: hard_interaction_test

<Hard interactions: procedures>+≡
    subroutine hard_interaction_test (model)
        type(model_t), pointer :: model
        type(process_library_t) :: prc_lib
        type(os_data_t) :: os_data
        type(hard_interaction_t), target :: hi
        type(vector4_t), dimension(4) :: p
        type(quantum_numbers_mask_t), dimension(2) :: qn_mask_in
        type(quantum_numbers_mask_t), dimension(4) :: qn_mask
        real(default) :: sqme, mh
        call os_data_init (os_data)
        call msg_message ("*** Load library 'qedtest'")
        call msg_message ("    [must exist and contain process 'eemm' (whizard.sin.qedtest)]")
        call process_library_init (prc_lib, var_str("qedtest"), os_data)
        call process_library_load (prc_lib, os_data)
        call msg_message ()
        call msg_message ("*** Create hard interaction")
        call hard_interaction_init (hi, prc_lib, 1, var_str("eemm"), model)
        qn_mask_in = new_quantum_numbers_mask (.true., .true., .true.)
        call hard_interaction_init_trace (hi, qn_mask_in)
        print *, "Interaction: n_values = ", interaction_get_n_matrix_elements (hi%int)
        qn_mask_in = new_quantum_numbers_mask (.false., .false., .false., .true.)
        call hard_interaction_init_sqme (hi, qn_mask_in)
        call hard_interaction_init_flows (hi, qn_mask_in)
        p(1) = vector4_moving (250._default, 250._default, 3)
        p(2) = vector4_moving (250._default, -250._default, 3)
        p(3) = rotation (1._default, 1) * p(1)
        p(4) = p(1) + p(2) - p(3)
        call msg_message ()
        call msg_message ("*** Evaluate new event")
        sqme = hard_interaction_compute_sqme_sum (hi, p)
        call hard_interaction_evaluate_sqme (hi)
        call hard_interaction_evaluate_flows (hi)
        call hard_interaction_write (hi)
        print *
        print *, "sqme sum =", sqme
        print *
        print *, "*** Cleanup"
        call hard_interaction_final (hi)
        call process_library_final (prc_lib)
    end subroutine

```

```
end subroutine hard_interaction_test
```

13.3 Processes

This module combines hard interactions, phase space, and (for scatterings) structure functions and interfaces them to the VAMP integration module.

```
<processes.f90>≡
  <File header>

  module processes

    <Use kinds>
    <Use strings>
    use system_dependencies !NODEP!
    use constants !NODEP!
    <Use file utils>
    use diagnostics !NODEP!
    use sm_physics !NODEP!
    use vamp_equivalences !NODEP!
    use vamp !NODEP!
    use md5
    use os_interface
    use lexers
    use parser
    use lorentz !NODEP!
    use prt_lists
    use variables
    use expressions
    use models
    use flavors
    use quantum_numbers
    use polarizations
    use interactions
    use evaluators
    use particles
    use beams
    use sf_isr
    use sf_epa
    use sf_ewa
    use sf_lhapdf
    use strfun
    use mappings
    use phs_forests
    use cascades
    use process_libraries
    use hard_interactions

    <Standard module head>

    <Processes: public>
```

```
⟨Processes: parameters⟩
```

```
⟨Processes: types⟩
```

```
⟨Processes: variables⟩
```

```
⟨Processes: interfaces⟩
```

```
contains
```

```
⟨Processes: procedures⟩
```

```
end module processes
```

13.3.1 Integration results

This object collects the results of an integration pass and makes them available to the outside.

The results object has to distinguish the process type:

```
⟨Processes: parameters⟩≡  
  integer, parameter :: PRC_UNKNOWN = 0  
  integer, parameter :: PRC_DECAY = 1  
  integer, parameter :: PRC_SCATTERING = 2
```

We store the process type, the index of the integration pass and the absolute iteration index, the number of iterations contained in this result (for averages), and the integral (cross section or partial width), error estimate and efficiency.

For intermediate results, we set a flag if this result is an improvement w.r.t. previous ones.

```
⟨Processes: types⟩≡  
  type :: integration_entry_t  
  private  
  integer :: process_type = PRC_UNKNOWN  
  integer :: pass = 0  
  integer :: it = 0  
  integer :: n_it = 0  
  integer :: n_calls = 0  
  logical :: improved = .false.  
  real(default) :: integral = 0  
  real(default) :: error = 0  
  real(default) :: efficiency = 0  
  real(default) :: chi2 = 0  
end type integration_entry_t
```

Initialize with all relevant data

```
⟨Processes: procedures⟩≡  
  subroutine integration_entry_init (entry, &  
    process_type, pass, it, n_it, n_calls, improved, &  
    integral, error, efficiency, chi2)  
    type(integration_entry_t), intent(out) :: entry  
    integer, intent(in) :: process_type, pass, it, n_it, n_calls  
    logical, intent(in) :: improved
```

```

real(default), intent(in) :: integral, error, efficiency
real(default), intent(in), optional :: chi2
entry%process_type = process_type
entry%pass = pass
entry%it = it
entry%n_it = n_it
entry%n_calls = n_calls
entry%improved = improved
entry%integral = integral
entry%error = error
entry%efficiency = efficiency
if (present (chi2)) &
    entry%chi2 = chi2
end subroutine integration_entry_init

```

Access values, some of them computed on demand:

(Processes: procedures)+≡

```

function integration_entry_get_n_calls (entry) result (n)
    integer :: n
    type(integration_entry_t), intent(in) :: entry
    n = entry%n_calls
end function integration_entry_get_n_calls

function integration_entry_get_integral (entry) result (int)
    real(default) :: int
    type(integration_entry_t), intent(in) :: entry
    int = entry%integral
end function integration_entry_get_integral

function integration_entry_get_error (entry) result (err)
    real(default) :: err
    type(integration_entry_t), intent(in) :: entry
    err = entry%error
end function integration_entry_get_error

function integration_entry_get_relative_error (entry) result (err)
    real(default) :: err
    type(integration_entry_t), intent(in) :: entry
    if (entry%integral /= 0) then
        err = entry%error / entry%integral
    else
        err = 0
    end if
end function integration_entry_get_relative_error

function integration_entry_get_accuracy (entry) result (acc)
    real(default) :: acc
    type(integration_entry_t), intent(in) :: entry
    acc = accuracy (entry%integral, entry%error, entry%n_calls)
end function integration_entry_get_accuracy

function accuracy (integral, error, n_calls) result (acc)
    real(default) :: acc
    real(default), intent(in) :: integral, error

```

```

integer, intent(in) :: n_calls
if (integral /= 0) then
    acc = error / integral * sqrt (real (n_calls, default))
else
    acc = 0
end if
end function accuracy

function integration_entry_get_efficiency (entry) result (eff)
    real(default) :: eff
    type(integration_entry_t), intent(in) :: entry
    eff = entry%efficiency
end function integration_entry_get_efficiency

function integration_entry_get_chi2 (entry) result (chi2)
    real(default) :: chi2
    type(integration_entry_t), intent(in) :: entry
    chi2 = entry%chi2
end function integration_entry_get_chi2

function integration_entry_has_improved (entry) result (flag)
    logical :: flag
    type(integration_entry_t), intent(in) :: entry
    flag = entry%improved
end function integration_entry_has_improved

```

Output. This writes the header line for the result account below:

```

<Processes: procedures>+≡
subroutine write_header (process_type, unit, logfile)
    integer, intent(in) :: process_type
    integer, intent(in), optional :: unit
    logical, intent(in), optional :: logfile
    character(5) :: phys_unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    select case (process_type)
    case (PRC_DECAY);      phys_unit = "[GeV]"
    case (PRC_SCATTERING); phys_unit = "[fb] "
    case default
        phys_unit = ""
    end select
    write (msg_buffer, "(A)") &
        "It      Calls  Integral" // phys_unit // &
        " Error" // phys_unit // &
        " Err[%]   Acc  Eff[%]  Chi2 N[It] |"
    call msg_message (unit=u, logfile=logfile)
end subroutine write_header

```

This writes a separator for result display:

```

<Processes: procedures>+≡
subroutine write_hline (unit)
    integer, intent(in), optional :: unit
    integer :: u

```

```

    u = output_unit (unit); if (u < 0) return
    write (u, "(A)") "|" // (repeat ("-", 77)) // "|"
end subroutine write_hline

subroutine write_dline (unit)
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write (u, "(A)") "|" // (repeat ("=", 77)) // "|"
end subroutine write_dline

```

This writes the standard result account into one screen line. The verbose version uses multiple lines and prints the unabridged values.

(Processes: procedures)+≡

```

subroutine integration_entry_write (entry, unit, verbose)
    type(integration_entry_t), intent(in) :: entry
    integer, intent(in), optional :: unit
    logical, intent(in), optional :: verbose
    integer :: u
    character(1) :: star
    logical :: verb
    u = output_unit (unit); if (u < 0) return
    verb = .false.; if (present (verbose)) verb = verbose
    if (.not. verb) then
        if (entry%improved) then
            star = "*"
        else
            star = " "
        end if
1   format (1x, I3, 1x, I10, 1x, 1PE14.7, 1x, 1PE9.2, 1x, 2PF7.2, &
           1x, OPF7.2, A1, 1x, 2PF6.2, 1x, OPF7.2, 1x, I3)
    if (entry%n_it /= 1) then
        write (u, 1) &
            entry%it, &
            entry%n_calls, &
            entry%integral, &
            entry%error, &
            integration_entry_get_relative_error (entry), &
            integration_entry_get_accuracy (entry), &
            star, &
            entry%efficiency, &
            entry%chi2, &
            entry%n_it
    else
        write (u, 1) &
            entry%it, &
            entry%n_calls, &
            entry%integral, &
            entry%error, &
            integration_entry_get_relative_error (entry), &
            integration_entry_get_accuracy (entry), &
            star, &
            entry%efficiency

```

```

        end if
    else
        write (u, *) "process_type = ", entry%process_type
        write (u, *) "          pass = ", entry%pass
        write (u, *) "          it = ", entry%it
        write (u, *) "          n_it = ", entry%n_it
        write (u, *) "          n_calls = ", entry%n_calls
        write (u, *) "          improved = ", entry%improved
        write (u, *) "          integral = ", entry%integral
        write (u, *) "          error = ", entry%error
        write (u, *) "          efficiency = ", entry%efficiency
        write (u, *) "          chi2 = ", entry%chi2
    end if
end subroutine integration_entry_write

```

Read the entry, assuming it has been written in verbose format.

(Processes: procedures)+≡

```

subroutine integration_entry_read (entry, unit)
    type(integration_entry_t), intent(out) :: entry
    integer, intent(in) :: unit
    character(30) :: dummy
    character :: equals
    read (unit, *) dummy, equals, entry%process_type
    read (unit, *) dummy, equals, entry%pass
    read (unit, *) dummy, equals, entry%it
    read (unit, *) dummy, equals, entry%n_it
    read (unit, *) dummy, equals, entry%n_calls
    read (unit, *) dummy, equals, entry%improved
    read (unit, *) dummy, equals, entry%integral
    read (unit, *) dummy, equals, entry%error
    read (unit, *) dummy, equals, entry%efficiency
    read (unit, *) dummy, equals, entry%chi2
end subroutine integration_entry_read

```

Compute the average for all entries in the specified integration pass. The integrals are weighted w.r.t. their individual errors, and we compute average, error of the average, and χ^2 value. All errors are assumed Gaussian, of course. The efficiency returned is the one of the last entry in the integration pass.

If any integral or error vanishes, averaging fails.

(Processes: procedures)+≡

```

function compute_average (entry, pass) result (result)
    type(integration_entry_t) :: result
    type(integration_entry_t), dimension(:), intent(in) :: entry
    integer, intent(in) :: pass
    integer :: i
    logical, dimension(size(entry)) :: mask
    real(default), dimension(size(entry)) :: ivar
    real(default) :: sum_ivar, variance
    result%process_type = entry(1)%process_type
    mask = entry%pass == pass
    result%it = maxval (entry%it, mask)
    result%n_it = count (mask)
    result%n_calls = sum (entry%n_calls, mask)

```

```

where (entry%error /= 0)
  ivar = 1 / entry%error ** 2
elsewhere
  ivar = 0
end where
sum_ivar = sum (ivar, mask)
if (sum_ivar /= 0) then
  variance = 1 / sum_ivar
else
  variance = 0
end if
result%integral = sum (entry%integral * ivar, mask) * variance
result%error = sqrt (variance)
if (result%n_it > 1) then
  result%chi2 = sum ((entry%integral - result%integral)**2 * ivar, mask) &
    / (result%n_it - 1)
end if
do i = size (entry), 1, -1
  if (mask(i)) then
    result%efficiency = entry(i)%efficiency
    exit
  end if
end do
end function compute_average

```

13.3.2 Combined integration results

We collect a list of results which grows during the execution of the program. This is implemented as an array which grows if necessary; so we can easily compute averages.

```

<Processes: public>≡
  public :: integration_results_t

<Processes: types>+≡
  type :: integration_results_t
  private
    integer :: n_pass = 0
    integer :: n_it = 0
    type(integration_entry_t), dimension(:), allocatable :: entry
    type(integration_entry_t), dimension(:), allocatable :: average
  end type integration_results_t

```

The array is extended in chunks of 10 entries.

```

<Processes: parameters>+≡
  integer, parameter :: RESULTS_CHUNK_SIZE = 10

```

The standard does not require to explicitly initialize the integers; however, some gfortran version has a bug here and misses the default initialization in the type definition.

```

<Processes: procedures>+≡
  subroutine integration_results_init (results)

```

```

type(integration_results_t), intent(out) :: results
results%n_pass = 0
results%n_it = 0
allocate (results%entry (RESULTS_CHUNK_SIZE))
allocate (results%average (RESULTS_CHUNK_SIZE))
end subroutine integration_results_init

```

Output (ASCII format).

(Processes: procedures)+≡

```

subroutine integration_results_write (results, unit, verbose)
  type(integration_results_t), intent(in) :: results
  integer, intent(in), optional :: unit
  logical, intent(in), optional :: verbose
  logical :: verb
  integer :: u, n
  u = output_unit (unit); if (u < 0) return
  verb = .false.; if (present (verbose)) verb = verbose
  if (.not. verb) then
    call write_dline (unit)
    if (results%n_it /= 0) then
      call write_header (results%entry(1)%pass, unit)
      call write_dline (unit)
      do n = 1, results%n_it
        if (n > 1) then
          if (results%entry(n)%pass /= results%entry(n-1)%pass) then
            call write_hline (unit)
            call integration_entry_write &
              (results%average(results%entry(n-1)%pass), unit)
            call write_hline (unit)
          end if
        end if
        call integration_entry_write (results%entry(n), unit)
      end do
      call write_dline(unit)
      call integration_entry_write (results%average(results%n_pass), unit)
    else
      call msg_message ("[WHIZARD integration results: empty]", unit)
    end if
    call write_dline (unit)
  else
    write (u, *) "begin(integration_results)"
    write (u, *) "  n_pass = ", results%n_pass
    write (u, *) "  n_it = ", results%n_it
    if (results%n_it > 0) then
      write (u, *) "begin(integration_pass)"
      do n = 1, results%n_it
        if (n > 1) then
          if (results%entry(n)%pass /= results%entry(n-1)%pass) then
            write (u, *) "end(integration_pass)"
            write (u, *) "begin(integration_pass)"
          end if
        end if
        write (u, *) "begin(iteration)"
        call integration_entry_write (results%entry(n), unit, verb)
      end do
    end if
  end if
end subroutine integration_results_write

```

```

        write (u, *) "end(iteration)"
    end do
    write (u, *) "end(integration_pass)"
end if
write (u, *) "end(integration_results)"
end if
end subroutine integration_results_write

```

Incremental output: Write specific / last line. separator if appropriate.

(Processes: procedures)+≡

```

subroutine integration_results_write_entry (results, it, unit)
    type(integration_results_t), intent(in) :: results
    integer, intent(in) :: it
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    if (it /= 0) call integration_entry_write (results%entry(it), unit)
end subroutine integration_results_write_entry

subroutine integration_results_write_current (results, unit)
    type(integration_results_t), intent(in) :: results
    integer, intent(in), optional :: unit
    integer :: u, n
    u = output_unit (unit); if (u < 0) return
    n = results%n_it
    if (n /= 0) call integration_entry_write (results%entry(n), unit)
end subroutine integration_results_write_current

```

Write one line for the average

(Processes: procedures)+≡

```

subroutine integration_results_write_average (results, pass, unit)
    type(integration_results_t), intent(in) :: results
    integer, intent(in) :: pass
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    if (pass /= 0) call integration_entry_write (results%average(pass), unit)
end subroutine integration_results_write_average

subroutine integration_results_write_current_average (results, unit)
    type(integration_results_t), intent(in) :: results
    integer, intent(in), optional :: unit
    integer :: u, n
    u = output_unit (unit); if (u < 0) return
    n = results%n_pass
    if (n /= 0) call integration_entry_write (results%average(n), unit)
end subroutine integration_results_write_current_average

```

Read the list from file. The file must be written using the verbose option of the writing routine.

(Processes: procedures)+≡

```

subroutine integration_results_read (results, unit)

```

```

type(integration_results_t), intent(out) :: results
integer, intent(in) :: unit
character(80) :: buffer
character :: equals
integer :: pass, it
read (unit, *) buffer
if (trim (adjustl (buffer)) /= "begin(integration_results)") then
    call read_err (); return
end if
read (unit, *) buffer, equals, results%n_pass
read (unit, *) buffer, equals, results%n_it
allocate (results%entry (results%n_it + RESULTS_CHUNK_SIZE))
allocate (results%average (results%n_it + RESULTS_CHUNK_SIZE))
it = 0
do pass = 1, results%n_pass
    read (unit, *) buffer
    if (trim (adjustl (buffer)) /= "begin(integration_pass)") then
        call read_err (); return
    end if
    READ_ENTRIES: do
        read (unit, *) buffer
        if (trim (adjustl (buffer)) /= "begin(iteration)") then
            exit READ_ENTRIES
        end if
        it = it + 1
        call integration_entry_read (results%entry(it), unit)
        read (unit, *) buffer
        if (trim (adjustl (buffer)) /= "end(iteration)") then
            call read_err (); return
        end if
    end do READ_ENTRIES
    if (trim (adjustl (buffer)) /= "end(integration_pass)") then
        call read_err (); return
    end if
    results%average(pass) = compute_average (results%entry, pass)
end do
read (unit, *) buffer
if (trim (adjustl (buffer)) /= "end(integration_results)") then
    call read_err (); return
end if
contains
subroutine read_err ()
    call msg_fatal ("Reading integration results from file: syntax error")
end subroutine read_err
end subroutine integration_results_read

```

Check integration results for consistency. We compare against an array of pass indices and call numbers. If there is a difference, up to the number of iterations done so far, we return failure.

(Processes: procedures)+≡

```

function integration_results_iterations_are_consistent &
    (results, pass, n_calls) result (flag)
    logical :: flag

```

```

type(integration_results_t), intent(in) :: results
integer, dimension(:), intent(in) :: pass, n_calls
flag = all (results%entry(:results%n_it)%pass == pass(:results%n_it)) &
      .and. all (results%entry(:results%n_it)%n_calls &
                == n_calls(:results%n_it))
end function integration_results_iterations_are_consistent

```

Expand the list of entries if the limit has been reached:

(Processes: procedures)+≡

```

subroutine integration_results_expand (results)
  type(integration_results_t), intent(inout) :: results
  type(integration_entry_t), dimension(:), allocatable :: entry_tmp
  if (results%n_it == size (results%entry)) then
    allocate (entry_tmp (results%n_it))
    entry_tmp = results%entry
    deallocate (results%entry)
    allocate (results%entry (results%n_it + RESULTS_CHUNK_SIZE))
    results%entry(:results%n_it) = entry_tmp
    deallocate (entry_tmp)
  end if
  if (results%n_pass == size (results%average)) then
    allocate (entry_tmp (results%n_pass))
    entry_tmp = results%average
    deallocate (results%average)
    allocate (results%average (results%n_it + RESULTS_CHUNK_SIZE))
    results%average(:results%n_pass) = entry_tmp
    deallocate (entry_tmp)
  end if
end subroutine integration_results_expand

```

Append a new entry to the list and, if appropriate, compute the average.

(Processes: procedures)+≡

```

subroutine integration_results_append_entry (results, entry)
  type(integration_results_t), intent(inout) :: results
  type(integration_entry_t), intent(in) :: entry
  if (results%n_it == 0) then
    call integration_results_init (results)
    results%n_it = 1
    results%n_pass = 1
  else
    call integration_results_expand (results)
    if (entry%pass /= results%entry(results%n_it)%pass) &
      results%n_pass = results%n_pass + 1
    results%n_it = results%n_it + 1
  end if
  results%entry(results%n_it) = entry
  results%average(results%n_pass) = &
    compute_average (results%entry, entry%pass)
end subroutine integration_results_append_entry

```

Enter results into the results list.

(Processes: public)+≡

```

public :: integration_results_append

```

```

<Processes: procedures>+=
  subroutine integration_results_append (results, &
    process_type, pass, n_it, n_calls, &
    integral, error, efficiency)
    type(integration_results_t), intent(inout) :: results
    integer, intent(in) :: process_type, pass, n_it, n_calls
    real(default), intent(in) :: integral, error, efficiency
    logical :: improved
    type(integration_entry_t) :: entry
    if (results%n_it /= 0) then
      improved = accuracy (integral, error, n_calls) &
        < integration_entry_get_accuracy (results%entry(results%n_it))
    else
      improved = .true.
    end if
    call integration_entry_init (entry, &
      process_type, pass, results%n_it+1, n_it, n_calls, improved, &
      integral, error, efficiency)
    call integration_results_append_entry (results, entry)
  end subroutine integration_results_append

```

13.3.3 Access results

Get the last average of the integral.

```

<Processes: procedures>+=
  function integration_results_get_n_calls (results) result (n_calls)
    integer :: n_calls
    type(integration_results_t), intent(in) :: results
    if (results%n_pass > 0) then
      n_calls = &
        integration_entry_get_n_calls (results%average(results%n_pass))
    else
      n_calls = 0
    end if
  end function integration_results_get_n_calls

  function integration_results_get_integral (results) result (integral)
    real(default) :: integral
    type(integration_results_t), intent(in) :: results
    if (results%n_pass > 0) then
      integral = &
        integration_entry_get_integral (results%average(results%n_pass))
    else
      integral = 0
    end if
  end function integration_results_get_integral

  function integration_results_get_error (results) result (error)
    real(default) :: error
    type(integration_results_t), intent(in) :: results
    if (results%n_pass > 0) then
      error = &

```

```

        integration_entry_get_error (results%average(results%n_pass))
    else
        error = 0
    end if
end function integration_results_get_error

function integration_results_get_accuracy (results) result (accuracy)
    real(default) :: accuracy
    type(integration_results_t), intent(in) :: results
    if (results%n_pass > 0) then
        accuracy = &
            integration_entry_get_accuracy (results%average(results%n_pass))
    else
        accuracy = 0
    end if
end function integration_results_get_accuracy

function integration_results_get_chi2 (results) result (chi2)
    real(default) :: chi2
    type(integration_results_t), intent(in) :: results
    if (results%n_pass > 0) then
        chi2 = &
            integration_entry_get_chi2 (results%average(results%n_pass))
    else
        chi2 = 0
    end if
end function integration_results_get_chi2

function integration_results_get_efficiency (results) result (efficiency)
    real(default) :: efficiency
    type(integration_results_t), intent(in) :: results
    if (results%n_pass > 0) then
        efficiency = &
            integration_entry_get_efficiency (results%average(results%n_pass))
    else
        efficiency = 0
    end if
end function integration_results_get_efficiency

```

Return the last pass index and the index of the last iteration *within* the last pass.

(Processes: procedures)+≡

```

function integration_results_get_current_pass (results) result (pass)
    integer :: pass
    type(integration_results_t), intent(in) :: results
    pass = results%n_pass
end function integration_results_get_current_pass

function integration_results_get_current_it (results) result (it)
    integer :: it
    type(integration_results_t), intent(in) :: results
    if (allocated (results%entry)) then
        it = count (results%entry%pass == results%n_pass)
    end if
end function integration_results_get_current_it

```

```

else
    it = 0
end if
end function integration_results_get_current_it

```

Compute the MD5 sum by printing everything and checksumming the resulting file.

```

<Processes: procedures>+≡
function integration_results_get_md5sum (results) result (md5sum_results)
character(32) :: md5sum_results
type(integration_results_t), intent(in) :: results
integer :: u
u = free_unit ()
open (unit = u, status = "scratch", action = "readwrite")
call integration_results_write (results, u, verbose=.true.)
rewind (u)
md5sum_results = md5sum (u)
close (u)
end function integration_results_get_md5sum

```

13.3.4 The process type

The process object holds virtually everything that is connected to a particular process; it is the workspace for integration and event generation.

Each process has a type (decay or scattering). For the purpose of generating cascades, we may need multiple copies of a particular (decay) process, which are implemented as a linked list. These store copies of, e.g., the hard-interaction object, the phase space and the VAMP grids. For read-only information they point back to the original.

```

<Processes: public>+≡
public :: process_t

<Processes: types>+≡
type :: process_t
private
integer :: type = PRC_UNKNOWN
type(process_t), pointer :: copy => null ()
logical :: is_original = .true.
type(process_t), pointer :: original => null ()
type(process_t), pointer :: working_copy => null ()
logical :: in_use = .true.
logical :: initialized = .false.
logical :: use_beams = .true.
logical :: has_extra_evaluators = .true.
logical :: beams_are_set = .false.
type(flavor_t), dimension(:), allocatable :: flv_in
type(beam_data_t) :: beam_data
type(string_t) :: id
character(32) :: md5sum = ""
type(process_library_t), pointer :: prc_lib => null ()
integer :: lib_index = 0
integer :: store_index = 0

```

```

type(model_t), pointer :: model
integer :: n_strfun = 0
integer :: n_par_strfun = 0
integer :: n_par_hi = 0
integer :: n_par = 0
logical :: azimuthal_dependence = .false.
logical :: vamp_grids_defined = .false.
logical :: sqrts_known = .false.
logical :: sqrts_hat_known = .false.
real(default) :: sqrts = 0
real(default) :: sqrts_hat = 0
real(default), dimension(:), allocatable :: x_strfun
real(default), dimension(:), allocatable :: x_hi
integer :: n_channels = 0
integer :: n_bins = 0
integer :: channel = 0
logical :: lab_is_cm_frame = .true.
type(lorentz_transformation_t) :: lt_cm_to_lab = identity
real(default), dimension(:, :), allocatable :: x
real(default), dimension(:), allocatable :: phs_factor
real(default), dimension(:), allocatable :: mass_in
real(default) :: flux_factor = 0
real(default) :: averaging_factor = 0
real(default) :: sf_mapping_factor = 0
real(default) :: phs_volume = 0
real(default) :: vamp_phs_factor = 0
real(default) :: sqme = 0
real(default) :: reweighting_factor = 0
real(default) :: sample_function_value = 0
real(default) :: scale = 0
logical :: alpha_s_is_fixed = .true.
integer :: alpha_s_order = 0
integer :: alpha_s_nf = 0
logical :: alpha_s_from_mz = .true.
logical :: mz_is_known = .false.
real(default) :: mz = 0
logical :: alpha_s_mz_is_known = .false.
real(default) :: alpha_s_mz = 0
real(default) :: lambda_qcd = 0
real(default) :: alpha_s_at_scale = 0
logical :: alpha_s_from_lhapdf = .false.
type(strfun_chain_t) :: sfchain
type(hard_interaction_t) :: hi
type(evaluator_t) :: eval_trace
type(evaluator_t) :: eval_beam_flows
type(evaluator_t) :: eval_sqme
type(evaluator_t) :: eval_flows
type(phs_forest_t) :: forest
character(32) :: md5sum_phs = ""
type(vamp_equivalences_t) :: vamp_eq
type(prt_list_t) :: prt_list
type(var_list_t) :: var_list
type(eval_tree_t) :: cut_expr
type(eval_tree_t) :: reweighting_expr

```

```

type(eval_tree_t) :: scale_expr
type(eval_tree_t) :: analysis_expr
logical, dimension(:), allocatable :: active_channel
type(vamp_grids) :: grids
type(integration_results_t) :: results
end type process_t

```

Initialization. We set up the hard-interaction parameters and make them available in the variable list (which extends the variable list of the current model). Finally, we initialize the particle list that is used for evaluating expressions.

The flag `use_beams` may be set false. In that case, beam (and structure function) data are meaningless or are skipped. For a scattering process, a head-to-head collision is assumed. For a decay process, the particle is assumed to decay in its rest frame. The initial state is assumed unpolarized.

If a variable list is provided as an argument, it replaces the model variable list. This implies that it should be linked to the model variable list.

(Processes: procedures)+≡

```

subroutine process_init &
  (process, prc_lib, process_lib_index, process_store_index, &
   process_id, model, lhpdf_status, var_list, use_beams)
type(process_t), intent(out), target :: process
type(process_library_t), intent(in), target :: prc_lib
integer, intent(in) :: process_lib_index
integer, intent(in) :: process_store_index
type(string_t), intent(in) :: process_id
type(model_t), intent(in), target :: model
type(lhpdf_status_t), intent(inout) :: lhpdf_status
type(var_list_t), intent(in), optional, target :: var_list
logical, intent(in), optional :: use_beams
integer :: n_in, n_out, n_tot
integer :: lhpdf_set, lhpdf_member
type(string_t) :: lhpdf_prefix, lhpdf_file
type(var_list_t), pointer :: var_list_snapshot
process%prc_lib => prc_lib
process%lib_index = process_lib_index
process%store_index = process_store_index
process%id = process_id
process%md5sum = process_library_get_process_md5sum &
  (process%prc_lib, process%lib_index)
call hard_interaction_init &
  (process%hi, prc_lib, process_lib_index, process_id, model)
process%model => hard_interaction_get_model_ptr (process%hi)
if (.not. hard_interaction_is_valid (process%hi)) return
process%id = hard_interaction_get_id (process%hi)
if (present (use_beams)) then
  process%use_beams = use_beams
  process%has_extra_evaluators = use_beams
end if
n_in = hard_interaction_get_n_in (process%hi)
n_out = hard_interaction_get_n_out (process%hi)
n_tot = hard_interaction_get_n_tot (process%hi)
select case (n_in)
case (1); process%type = PRC_DECAY

```

```

case (2); process%type = PRC_SCATTERING
end select
allocate (process%flv_in (n_in), process%mass_in (n_in))
call flavor_init (process%flv_in, &
    hard_interaction_get_first_pdg_in (process%hi), process%model)
process%mass_in = flavor_get_mass (process%flv_in)
if (process%use_beams) then
    process%averaging_factor = 1
else
    process%averaging_factor = &
        1._default / product (flavor_get_multiplicity (process%flv_in))
end if
allocate (var_list_snapshot)
call var_list_link (process%var_list, var_list_snapshot)
if (present (var_list)) then
    call var_list_init_snapshot (var_list_snapshot, var_list)
else
    call var_list_init_snapshot (var_list_snapshot, &
        model_get_var_list_ptr (process%model))
end if
process%alpha_s_is_fixed = &
    var_list_get_lval (process%var_list, var_str ("?alpha_s_is_fixed"))
process%alpha_s_order = &
    var_list_get_ival (process%var_list, var_str ("alpha_s_order"))
process%alpha_s_nf = &
    var_list_get_ival (process%var_list, var_str ("alpha_s_nf"))
process%alpha_s_from_mz = &
    var_list_get_lval (process%var_list, var_str ("?alpha_s_from_mz"))
process%alpha_s_from_lhapdf = &
    var_list_get_lval (process%var_list, var_str ("?alpha_s_from_lhapdf"))
if (process%alpha_s_from_lhapdf) then
    if (LHAPDF_AVAILABLE) then
        lhpdf_set = 1
        lhpdf_prefix = LHAPDF_PDFSETS_PATH // "/"
        lhpdf_file = var_list_get_sval (var_list, &
            var_str ("lhpdf_file")) ! $
        lhpdf_member = var_list_get_ival (var_list, &
            var_str ("lhpdf_member"))
        call lhpdf_init (lhpdf_status, &
            lhpdf_set, lhpdf_prefix, lhpdf_file, lhpdf_member)
    else
        call msg_error &
            ("LHAPDF not linked: reset alpha_s_from_lhapdf to false")
        process%alpha_s_from_lhapdf = .false.
    end if
end if
process%mz_is_known = &
    var_list_is_known (process%var_list, var_str ("mZ"))
if (process%mz_is_known) process%mz = &
    var_list_get_rval (process%var_list, var_str ("mZ"))
process%alpha_s_mz_is_known = &
    var_list_is_known (process%var_list, var_str ("gs"))
if (process%alpha_s_mz_is_known) process%alpha_s_mz = &
    var_list_get_rval (process%var_list, var_str ("gs")) ** 2 &

```

```

        / (2 * twopi)
process%lambda_qcd = &
    var_list_get_rval (process%var_list, var_str ("lambda_qcd"))
call var_list_append_int (process%var_list, &
    var_str ("n_in"), n_in, intrinsic=.true.)
call var_list_append_int (process%var_list, &
    var_str ("n_out"), n_out, intrinsic=.true.)
call var_list_append_int (process%var_list, &
    var_str ("n_tot"), n_tot, intrinsic=.true.)
call var_list_append_real_ptr (process%var_list, &
    var_str ("sqrts"), process%sqrts, process%sqrts_known, &
    intrinsic=.true.)
call var_list_append_real_ptr (process%var_list, &
    var_str ("sqrts_hat"), process%sqrts_hat, process%sqrts_hat_known, &
    intrinsic=.true.)
call interaction_init_prt_list &
    (hard_interaction_get_int_ptr (process%hi), process%prt_list)
call integration_results_init (process%results)
process%initialized = .true.
end subroutine process_init

```

Finalization. In process copies, some components are just pointers to the original, so they should not be finalized separately.

(Processes: procedures)+=

```

recursive subroutine process_final (process)
    type(process_t), intent(inout), target :: process
    if (associated (process%copy)) then
        call process_final (process%copy)
        deallocate (process%copy)
    end if
    process%initialized = .false.
    process%type = PRC_UNKNOWN
    process%sqrts_known = .false.
    process%sqrts_hat_known = .false.
    call strfun_chain_final (process%sfchain)
    call hard_interaction_final (process%hi)
    call evaluator_final (process%eval_trace)
    call evaluator_final (process%eval_beam_flows)
    call evaluator_final (process%eval_sqme)
    call evaluator_final (process%eval_flows)
    call phs_forest_final (process%forest)
    call vamp_equivalences_final (process%vamp_eq)
    if (process%is_original) then
        call var_list_final (process%var_list)
        call eval_tree_final (process%cut_expr)
        call eval_tree_final (process%reweighting_expr)
        call eval_tree_final (process%scale_expr)
        call eval_tree_final (process%analysis_expr)
    end if
    if (process%vamp_grids_defined) then
        call vamp_delete_grids (process%grids)
    end if
end subroutine process_final

```

Output. This prints lots of stuff. The `verbose` option is for state matrices, the `show_momentum_sum` option prints the sums of incoming and outgoing momenta for all interactions, and the `show_mass` option computes and prints the signed invariant mass for all four-momenta.

```

(Processes: public)+≡
    public :: process_write

(Processes: procedures)+≡
    subroutine process_write &
        (process, unit, verbose, show_momentum_sum, show_mass)
        type(process_t), intent(in) :: process
        integer, intent(in), optional :: unit
        logical, intent(in), optional :: verbose, show_momentum_sum, show_mass
        integer :: u, i
        u = output_unit (unit); if (u < 0) return
        write (u, "(A)") repeat ("=", 72)
        write (u, *) "Process data:", process%lib_index, &
            "(" , char (process%id), ")"
        select case (process%type)
        case (PRC_UNKNOWN); write (u, *) " [unknown]"
        case (PRC_DECAY); write (u, *) " [decay]"
        case (PRC_SCATTERING); write (u, *) " [scattering]"
        end select
        write (u, *) " use separate beam setup = ", process%use_beams
        call beam_data_write (process%beam_data, u)
        if (process%use_beams) then
            write (u, *) " number of structure functions = ", process%n_strfun
            write (u, *) " number of strfun parameters = ", process%n_par_strfun
        end if
        write (u, *) " number of process parameters = ", process%n_par_hi
        write (u, *) " number of parameters total = ", process%n_par
        write (u, *) " number of integration channels = ", process%n_channels
        write (u, *) " number of bins per channel = ", process%n_bins
        if (process%sqrts_known) then
            write (u, *) " c.m. energy (sqrts) = ", process%sqrts
        else
            write (u, *) " c.m. energy (sqrts) = [unknown]"
        end if
        if (process%sqrts_hat_known) then
            write (u, *) " c.m. energy (sqrts_hat) = ", process%sqrts_hat
        else
            write (u, *) " c.m. energy (sqrts_hat) = [unknown]"
        end if
        write (u, "(1x,A)", advance="no") " Colliding partons = "
        if (allocated (process%flv_in)) then
            do i = 1, size (process%flv_in)
                if (i == 2) write (u, "(1x)", advance="no")
                call flavor_write (process%flv_in(i), u)
            end do
            write (u, *)
        else
            write (u, *) "[undefined]"
        end if
    end if
end subroutine process_write

```

```

if (allocated (process%mass_in)) then
  write (u, *) " Incoming parton masses = ", process%mass_in
else
  write (u, *) " Incoming parton masses = [unknown]"
end if
write (u, *) " In-state flux factor = ", process%flux_factor
write (u, *) " Strfun mapping factor = ", process%sf_mapping_factor
if (.not. process%use_beams) then
  write (u, *) " Spin averaging factor = ", process%averaging_factor
end if
write (u, *) " VAMP phs factor = ", process%vamp_phs_factor
write (u, *) " Phase-space volume = ", process%phs_volume
write (u, *) " Squared matrix element = ", process%sqme
write (u, *) " Reweighting factor = ", process%reweighting_factor
write (u, *) " Sample-function value = ", &
  process%sample_function_value
write (u, *) repeat("-", 72)
if (process%use_beams) then
  write (u, *) "Structure function parameters ="
  if (allocated (process%x_strfun)) then
    write (u, *) process%x_strfun
  else
    write (u, *) "[empty]"
  end if
end if
write (u, *) " Process energy scale = ", process%scale
write (u, *) repeat("-", 72)
write (u, *) "QCD coupling parameters ="
write (u, *) " alpha-s is fixed = ", process%alpha_s_is_fixed
if (.not. process%alpha_s_is_fixed) then
  if (process%alpha_s_from_lhapdf) then
    write (u, *) " alpha-s from LHAPDF"
  else
    write (u, *) " LLA order = ", process%alpha_s_order
    write (u, *) " active flavors = ", process%alpha_s_nf
    write (u, *) " use alpha-s (mZ) = ", process%alpha_s_from_mz
    if (process%alpha_s_from_mz) then
      write (u, *) " mZ is known = ", process%mz_is_known
      if (process%mz_is_known) then
        write (u, *) " mZ = ", process%mz
      end if
      write (u, *) " as(mZ) is known = ", process%alpha_s_mz_is_known
      if (process%alpha_s_mz_is_known) then
        write (u, *) " alpha-s (mZ) = ", process%alpha_s_mz
      end if
    else
      write (u, *) " Lambda_QCD = ", process%lambda_qcd
    end if
  end if
  write (u, *) " alpha-s (scale) = ", process%alpha_s_at_scale
end if
write (u, *) repeat("-", 72)
write (u, *) "Phase-space integration parameters (input) ="
if (allocated (process%x_hi)) then

```

```

        write (u, *) process%x_hi
    else
        write (u, *) "[empty]"
    end if
    write (u, *) "Integration channel =", process%channel
    write (u, *) "Phase-space integration parameters (complete) ="
    if (allocated (process%x)) then
        do i = 1, size (process%x, 2)
            write (u, *) process%x(:,i)
        end do
    else
        write (u, *) "[empty]"
    end if
    if (.not. process%lab_is_cm_frame) then
        write (u, *) "Transformation c.m. -> lab ="
        call lorentz_transformation_write (process%lt_cm_to_lab, u)
    end if
    write (u, *) "Channels: phase-space factors ="
    if (allocated (process%phs_factor)) then
        write (u, *) process%phs_factor
    else
        write (u, *) "[not allocated]"
    end if
    write (u, "(A)") repeat("-", 72)
    if (process%use_beams) then
        call strfun_chain_write &
            (process%sfchain, unit, verbose, show_momentum_sum, show_mass)
        write (u, "(A)") repeat("-", 72)
        write (u, "(A)") "Incoming beams with all color contractions"
        call evaluator_write &
            (process%eval_beam_flows, unit, verbose, show_momentum_sum, show_mass)
        write (u, "(A)") repeat("-", 72)
    end if
    call hard_interaction_write &
        (process%hi, unit, verbose, show_momentum_sum, show_mass)
    write (u, "(A)") repeat("-", 72)
    if (process%has_extra_evaluators) then
        write (u, "(A)") "Trace including color factors (beams + strfun + hard interaction)"
        call evaluator_write &
            (process%eval_trace, unit, verbose, show_momentum_sum, show_mass)
        write (u, "(A)") repeat("-", 72)
        write (u, "(A)") "Exclusive sqme including color factors (beams + strfun + hard interaction)"
        call evaluator_write &
            (process%eval_sqme, unit, verbose, show_momentum_sum, show_mass)
        write (u, "(A)") repeat("-", 72)
        write (u, "(A)") "Color flow coefficients (beams + strfun + hard interaction)"
        call evaluator_write &
            (process%eval_flows, unit, verbose, show_momentum_sum, show_mass)
        write (u, "(A)") repeat("-", 72)
    end if
    call phs_forest_write (process%forest, unit)
    write (u, "(A)") repeat("-", 72)
    call vamp_equivalences_write (process%vamp_eq, unit)
    write (u, "(A)") repeat("-", 72)

```

```

call prt_list_write (process%prt_list, unit)
write (u, "(A)") repeat ("-", 72)
call var_list_write (process%var_list, unit)
write (u, "(A)") repeat ("-", 72)
write (u, "(A)") "Cut expression:"
call eval_tree_write (process%cut_expr, unit)
write (u, "(A)") repeat ("-", 72)
write (u, "(A)") "Weight expression:"
call eval_tree_write (process%reweighting_expr, unit)
write (u, "(A)") repeat ("-", 72)
write (u, "(A)") "Scale expression:"
call eval_tree_write (process%scale_expr, unit)
write (u, "(A)") repeat ("-", 72)
write (u, "(A)") "Analysis expression:"
call eval_tree_write (process%analysis_expr, unit)
write (u, "(A)") repeat ("-", 72)
if (process%vamp_grids_defined) then
    call vamp_write_grids (process%grids, u)
else
    write (u, "(A)") "VAMP grids: [empty]"
end if
write (u, *)
call integration_results_write (process%results, unit)
end subroutine process_write

```

13.3.5 Accessing contents

Check if the process has been successfully initialized:

```

<Processes: public>+≡
    public :: process_is_valid

<Processes: procedures>+≡
    function process_is_valid (process) result (flag)
        logical :: flag
        type(process_t), intent(in) :: process
        flag = process%initialized
    end function process_is_valid

```

Return the process ID.

```

<Processes: public>+≡
    public :: process_get_id

<Processes: procedures>+≡
    function process_get_id (process) result (process_id)
        type(string_t) :: process_id
        type(process_t), intent(in) :: process
        process_id = process%id
    end function process_get_id

```

Return the index in the process store:

```

<Processes: public>+≡
    public :: process_get_store_index

```

```

<Processes: procedures>+≡
function process_get_store_index (process) result (index)
integer :: index
type(process_t), intent(in) :: process
index = process%store_index
end function process_get_store_index

```

Return the MD5 sum of the process configuration.

```

<Processes: public>+≡
public :: process_get_md5sum
public :: process_get_md5sum_parameters
public :: process_get_md5sum_results

<Processes: procedures>+≡
function process_get_md5sum (process) result (md5sum)
character(32) :: md5sum
type(process_t), intent(in) :: process
md5sum = process%md5sum
end function process_get_md5sum

function process_get_md5sum_parameters (process) result (md5sum)
character(32) :: md5sum
type(process_t), intent(in) :: process
md5sum = model_get_parameters_md5sum (process%model)
end function process_get_md5sum_parameters

function process_get_md5sum_results (process) result (md5sum)
character(32) :: md5sum
type(process_t), intent(in) :: process
md5sum = integration_results_get_md5sum (process%results)
end function process_get_md5sum_results

```

Return the model pointer.

```

<Processes: public>+≡
public :: process_get_model_ptr

<Processes: procedures>+≡
function process_get_model_ptr (process) result (model)
type(model_t), pointer :: model
type(process_t), intent(in) :: process
model => process%model
end function process_get_model_ptr

```

Return the number of incoming partons for the hard interaction

```

<Processes: public>+≡
public :: process_get_n_in
public :: process_get_n_out

<Processes: procedures>+≡
function process_get_n_in (process) result (n)
integer :: n
type(process_t), intent(in) :: process
n = hard_interaction_get_n_in (process%hi)
end function process_get_n_in

```

```

function process_get_n_out (process) result (n)
  integer :: n
  type(process_t), intent(in) :: process
  n = hard_interaction_get_n_out (process%hi)
end function process_get_n_out

```

Return the beam/incoming particle flavors and energies.

```

<Processes: public>+≡
  public :: process_get_beam_flv
  public :: process_get_beam_energy

<Processes: procedures>+≡
  function process_get_beam_flv (process) result (flv_in)
    type(flavor_t), dimension(:), allocatable :: flv_in
    type(process_t), intent(in) :: process
    allocate (flv_in (process_get_n_in (process)))
    if (process%beam_data%initialized) flv_in = process%beam_data%flv
  end function process_get_beam_flv

  function process_get_beam_energy (process) result (energy)
    real(default), dimension(:), allocatable :: energy
    type(process_t), intent(in) :: process
    allocate (energy (process_get_n_in (process)))
    energy = beam_data_get_energy (process%beam_data)
  end function process_get_beam_energy

```

Return the number of integration parameters.

```

<Processes: public>+≡
  public :: process_get_n_parameters

<Processes: procedures>+≡
  function process_get_n_parameters (process) result (n)
    integer :: n
    type(process_t), intent(in) :: process
    n = process%n_par
  end function process_get_n_parameters

```

Return the number of integration channels.

```

<Processes: public>+≡
  public :: process_get_n_channels

<Processes: procedures>+≡
  function process_get_n_channels (process) result (n)
    integer :: n
    type(process_t), intent(in) :: process
    n = process%n_channels
  end function process_get_n_channels

```

Return the number of bins per integration channel.

```

<Processes: public>+≡
  public :: process_get_n_bins

```

```

<Processes: procedures>+≡
function process_get_n_bins (process) result (n)
  integer :: n
  type(process_t), intent(in) :: process
  n = process%n_bins
end function process_get_n_bins

```

Return the process energy scale and the α_s value.

```

<Processes: public>+≡
public :: process_get_scale
public :: process_get_alpha_s

<Processes: procedures>+≡
function process_get_scale (process) result (scale)
  real(default) :: scale
  type(process_t), intent(in) :: process
  scale = process%scale
end function process_get_scale

function process_get_alpha_s (process) result (alpha_s)
  real(default) :: alpha_s
  type(process_t), intent(in) :: process
  alpha_s = process%alpha_s_at_scale
end function process_get_alpha_s

```

Return the squared matrix element. This includes structure function factors and the hard interaction squared matrix element, traced over all quantum numbers, but no phase space factors.

```

<Processes: public>+≡
public :: process_get_sqme

<Processes: procedures>+≡
function process_get_sqme (process) result (sqme)
  real(default) :: sqme
  type(process_t), intent(in) :: process
  sqme = process%sqme
end function process_get_sqme

```

Return the final integration results.

```

<Processes: public>+≡
public :: process_get_n_calls
public :: process_get_integral
public :: process_get_error
public :: process_get_accuracy
public :: process_get_chi2
public :: process_get_efficiency

<Processes: procedures>+≡
function process_get_n_calls (process) result (n_calls)
  integer :: n_calls
  type(process_t), intent(in) :: process
  n_calls = integration_results_get_n_calls (process%results)
end function process_get_n_calls

```

```

function process_get_integral (process) result (integral)
  real(default) :: integral
  type(process_t), intent(in) :: process
  integral = integration_results_get_integral (process%results)
end function process_get_integral

function process_get_error (process) result (error)
  real(default) :: error
  type(process_t), intent(in) :: process
  error = integration_results_get_error (process%results)
end function process_get_error

function process_get_accuracy (process) result (accuracy)
  real(default) :: accuracy
  type(process_t), intent(in) :: process
  accuracy = integration_results_get_accuracy (process%results)
end function process_get_accuracy

function process_get_chi2 (process) result (chi2)
  real(default) :: chi2
  type(process_t), intent(in) :: process
  chi2 = integration_results_get_chi2 (process%results)
end function process_get_chi2

function process_get_efficiency (process) result (efficiency)
  real(default) :: efficiency
  type(process_t), intent(in) :: process
  efficiency = integration_results_get_efficiency (process%results)
end function process_get_efficiency

```

Return the current (i.e., last) integration pass index, and the index of the last iteration *within* this pass.

```

<Processes: public>+≡
  public :: process_get_current_pass
  public :: process_get_current_it

<Processes: procedures>+≡
  function process_get_current_pass (process) result (pass)
    integer :: pass
    type(process_t), intent(in) :: process
    pass = integration_results_get_current_pass (process%results)
  end function process_get_current_pass

  function process_get_current_it (process) result (it)
    integer :: it
    type(process_t), intent(in) :: process
    it = integration_results_get_current_it (process%results)
  end function process_get_current_it

```

Return pointers to the sqme and flows evaluators. If no beams are used, these are identical to the evaluators of the hard interaction.

```

<Processes: public>+≡

```

```

public :: process_get_eval_sqme_ptr
public :: process_get_eval_flows_ptr

<Processes: procedures>+≡
function process_get_eval_sqme_ptr (process) result (eval)
  type(evaluator_t), pointer :: eval
  type(process_t), intent(in), target :: process
  if (process%has_extra_evaluators) then
    eval => process%eval_sqme
  else
    eval => hard_interaction_get_eval_sqme_ptr (process%hi)
  end if
end function process_get_eval_sqme_ptr

function process_get_eval_flows_ptr (process) result (eval)
  type(evaluator_t), pointer :: eval
  type(process_t), intent(in), target :: process
  if (process%has_extra_evaluators) then
    eval => process%eval_flows
  else
    eval => hard_interaction_get_eval_flows_ptr (process%hi)
  end if
end function process_get_eval_flows_ptr

```

Return pointers to the interaction and to the sqme and flows evaluators of the hard interaction.

```

<Processes: public>+≡
public :: process_get_hi_int_ptr
public :: process_get_hi_eval_sqme_ptr
public :: process_get_hi_eval_flows_ptr

<Processes: procedures>+≡
function process_get_hi_int_ptr (process) result (int)
  type(interaction_t), pointer :: int
  type(process_t), intent(in), target :: process
  int => hard_interaction_get_int_ptr (process%hi)
end function process_get_hi_int_ptr

function process_get_hi_eval_sqme_ptr (process) result (eval)
  type(evaluator_t), pointer :: eval
  type(process_t), intent(in), target :: process
  eval => hard_interaction_get_eval_sqme_ptr (process%hi)
end function process_get_hi_eval_sqme_ptr

function process_get_hi_eval_flows_ptr (process) result (eval)
  type(evaluator_t), pointer :: eval
  type(process_t), intent(in), target :: process
  eval => hard_interaction_get_eval_flows_ptr (process%hi)
end function process_get_hi_eval_flows_ptr

```

13.3.6 Setting values directly

Some values can be set directly; this is used when reading an event from file.

```

<Processes: public>+≡
  public :: process_set_scale
  public :: process_set_alpha_s
  public :: process_set_sqme

<Processes: procedures>+≡
  subroutine process_set_scale (process, scale)
    type(process_t), intent(inout) :: process
    real(default), intent(in) :: scale
    process%scale = scale
  end subroutine process_set_scale

  subroutine process_set_alpha_s (process, alpha_s)
    type(process_t), intent(inout) :: process
    real(default), intent(in) :: alpha_s
    process%alpha_s_at_scale = alpha_s
  end subroutine process_set_alpha_s

  subroutine process_set_sqme (process, sqme)
    type(process_t), intent(inout) :: process
    real(default), intent(in) :: sqme
    process%sqme = sqme
  end subroutine process_set_sqme

```

13.3.7 Process preparation: beams and structure functions

Set up the chain of structure functions. The individual types of structure functions need specific instances. These are just wrappers around the corresponding `strfun_chain` procedures.

If `use_beams` is false, only `sqrts` and `flv` is set, using the decaying particle mass (decay) or the `sqrts` value in the argument list (scattering) to set up a local beam record.

```

<Processes: public>+≡
  public :: process_setup_beams

<Processes: procedures>+≡
  subroutine process_setup_beams &
    (process, beam_data, n_strfun, n_mapping, sqrts, flv)
    type(process_t), intent(inout), target :: process
    type(beam_data_t), intent(in) :: beam_data
    integer, intent(in) :: n_strfun, n_mapping
    real(default), intent(in), optional :: sqrts
    type(flavor_t), dimension(:), intent(in), optional :: flv
    if (process%use_beams) then
      process%beam_data = beam_data
      process%sqrts = beam_data%sqrts
      process%sqrts_known = .true.
      process%n_strfun = n_strfun
      process%azimuthal_dependence = &
        .not. all (polarization_is_diagonal (beam_data%pol))
      process%lab_is_cm_frame = beam_data%lab_is_cm_frame .and. n_strfun == 0
      call strfun_chain_init (process%sfchain, beam_data, n_strfun, n_mapping)
    end if
  end subroutine process_setup_beams

```

```

else
  select case (process%type)
  case (PRC_DECAY)
    process%sqrts = process%mass_in(1)
    call beam_data_init_decay (process%beam_data, process%flv_in)
  case (PRC_SCATTERING)
    if (present (sqrts)) then
      process%sqrts = sqrts
      call beam_data_init_sqrts &
        (process%beam_data, process%sqrts, process%flv_in)
    else
      call msg_fatal ("Process setup: neither beams nor sqrts are known")
      process%sqrts = 0
    end if
  end select
  process%sqrts_known = .true.
end if
end subroutine process_setup_beams

```

Set the beam momenta directly without changing anything else. This is a short-cut that is needed for initiating cascade decays (i.e., the single beam is the decaying particle).

```

<Processes: public>+≡
  public :: process_set_beam_momenta

<Processes: procedures>+≡
  subroutine process_set_beam_momenta (process, p)
    type(process_t), intent(inout), target :: process
    type(vector4_t), dimension(:), intent(in) :: p
    type(interaction_t), pointer :: hi_int
    if (process%use_beams) then
      call strfun_chain_set_beam_momenta (process%sfchain, p)
    else
      hi_int => hard_interaction_get_int_ptr (process%hi)
      call interaction_set_momenta (hi_int, p, outgoing=.false.)
    end if
    process%sqrts_hat = process%sqrts
    process%lab_is_cm_frame = .false.
    process%beams_are_set = .true.
  end subroutine process_set_beam_momenta

```

Configure structure functions. EPA: support only a single data set.

The index *i* is the overall structure function counter. *line* indicates the beam(s) for which the structure function applies, either 1 or 2, or 0 for both beams.

```

<Processes: public>+≡
  public :: process_set_strfun

<Processes: interfaces>≡
  interface process_set_strfun
    module procedure process_set_strfun_isr
    module procedure process_set_strfun_epa
    module procedure process_set_strfun_lhapdf

```

end interface

(Processes: procedures)+≡

```

subroutine process_set_strfun_isr &
  (process, i, line, isr_data, n_parameters)
  type(process_t), intent(inout), target :: process
  integer, intent(in) :: i, line, n_parameters
  type(isr_data_t), intent(in) :: isr_data
  if (process%use_beams) then
    call strfun_chain_set_strfun &
      (process%sfchain, i, line, isr_data, n_parameters)
  end if
end subroutine process_set_strfun_isr

subroutine process_set_strfun_epa &
  (process, i, line, epa_data, n_parameters)
  type(process_t), intent(inout), target :: process
  integer, intent(in) :: i, line, n_parameters
  ! type(epa_data_t), dimension(:), intent(in) :: epa_data
  type(epa_data_t), intent(in) :: epa_data
  if (process%use_beams) then
    call strfun_chain_set_strfun &
      (process%sfchain, i, line, epa_data, n_parameters)
  end if
end subroutine process_set_strfun_epa

subroutine process_set_strfun_lhapdf &
  (process, i, line, lhpdf_data, n_parameters)
  type(process_t), intent(inout), target :: process
  integer, intent(in) :: i, line, n_parameters
  type(lhapdf_data_t), intent(in) :: lhpdf_data
  if (process%use_beams) then
    call strfun_chain_set_strfun &
      (process%sfchain, i, line, lhpdf_data, n_parameters)
  end if
end subroutine process_set_strfun_lhapdf

```

Configure structure function mappings.

(Processes: public)+≡

public :: process_set_strfun_mapping

(Processes: procedures)+≡

```

subroutine process_set_strfun_mapping (process, i, index, type, par)
  type(process_t), intent(inout) :: process
  integer, intent(in) :: i
  integer, intent(in) :: type
  integer, dimension(:), intent(in) :: index
  real(default), dimension(:), intent(in) :: par
  if (process%use_beams) then
    call strfun_chain_set_mapping (process%sfchain, i, index, type, par)
  end if
end subroutine process_set_strfun_mapping

```

Complete structure function initialization. Make evaluators within the structure function chain, and the trace evaluator within the hard interaction. Connect the two, and make another trace evaluator which sums over all quantum numbers. This evaluator should have only a single matrix element.

(Processes: public)+≡

public :: process_connect_strfun

(Processes: procedures)+≡

```
subroutine process_connect_strfun (process, ok)
  type(process_t), intent(inout), target :: process
  logical, intent(out), optional :: ok
  integer, dimension(:), allocatable :: coll_index
  type(quantum_numbers_mask_t), dimension(:), allocatable :: mask_in
  type(quantum_numbers_mask_t) :: mask_tr
  type(evaluator_t), pointer :: eval_sfchain, eval_hi
  type(interaction_t), pointer :: int_beam, int_hi
  integer :: n_in, i
  n_in = hard_interaction_get_n_in (process%hi)
  allocate (mask_in (n_in))
  if (process%use_beams) then
    call strfun_chain_make_evaluators (process%sfchain, ok)
    allocate (coll_index (n_in))
    coll_index = strfun_chain_get_colliding_particles (process%sfchain)
    mask_in = strfun_chain_get_colliding_particles_mask (process%sfchain)
  else
    mask_in = new_quantum_numbers_mask (.true., .true., .true.)
  end if
  call hard_interaction_init_trace (process%hi, mask_in)
  if (process%use_beams) then
    int_beam => strfun_chain_get_beam_int_ptr (process%sfchain)
    eval_sfchain => strfun_chain_get_last_evaluator_ptr (process%sfchain)
    eval_hi => hard_interaction_get_eval_trace_ptr (process%hi)
    int_hi => hard_interaction_get_int_ptr (process%hi)
    mask_tr = new_quantum_numbers_mask (.true., .true., .true.)
    if (associated (eval_sfchain)) then
      do i = 1, n_in
        call interaction_set_source_link &
          (int_hi, i, eval_sfchain, coll_index(i))
        call evaluator_set_source_link &
          (eval_hi, i, eval_sfchain, coll_index(i))
      end do
      call evaluator_init_product &
        (process%eval_trace, eval_sfchain, eval_hi, mask_tr, mask_tr)
      if (evaluator_is_empty (process%eval_trace)) then
        call msg_fatal ("Mismatch between structure functions and hard process")
        if (present (ok)) ok = .false.
        return
      end if
    else
      do i = 1, n_in
        call interaction_set_source_link &
          (int_hi, i, int_beam, coll_index(i))
        call evaluator_set_source_link &
          (eval_hi, i, int_beam, coll_index(i))
      end do
    end if
  end if
end subroutine process_connect_strfun
```

```

end do
call evaluator_init_product &
    (process%eval_trace, int_beam, eval_hi, mask_tr, mask_tr)
if (evaluator_is_empty (process%eval_trace)) then
    call msg_fatal ("Mismatch between beams and hard process")
    if (present (ok)) ok = .false.
    return
end if
end if
process%n_par_strfun = &
    strfun_chain_get_n_parameters_tot (process%sfchain)
allocate (process%x_strfun (process%n_par_strfun))
end if
process%n_par = process%n_par_strfun + process%n_par_hi
if (present (ok)) ok = .true.
end subroutine process_connect_strfun

```

13.3.8 Process preparation: phase space

Initialize the phase-space forest. First check whether the process exists in `filename_in`, if present, and try to read it there. If this fails, generate a new phase-space forest and write it to `filename_out`, if present, otherwise to a temporary file. Then read again.

Because `variable_limits` depends on the structure function setup, structure functions should be done first.

```

<Processes: public>+≡
    public :: process_setup_phase_space

<Processes: procedures>+≡
    subroutine process_setup_phase_space (process, rebuild_phs, &
        phs_par, mapping_defaults, filename_out, filename_in, ok)
        type(process_t), intent(inout), target :: process
        logical, intent(in) :: rebuild_phs
        type(phs_parameters_t), intent(inout) :: phs_par
        type(mapping_defaults_t), intent(in) :: mapping_defaults
        type(string_t), intent(in), optional :: filename_out, filename_in
        logical, intent(out), optional :: ok
        type(string_t) :: filename
        logical :: exist, check
        integer :: extra_off_shell
        type(cascade_set_t) :: cascade_set
        logical :: variable_limits
        integer :: n_in, n_out, n_tot, n_flv
        type(flavor_t), dimension(:,:), allocatable :: flv
        integer :: n_par_strfun
        logical, dimension(:), allocatable :: strfun_rigid
        character(32) :: md5sum_process, md5sum_model, md5sum_parameters
        integer :: unit
        logical :: phs_ok, phs_match, wrote_file
        phs_ok = .false.
        phs_match = .false.
        variable_limits = process%n_strfun /= 0
    end subroutine process_setup_phase_space

```

```

n_in = hard_interaction_get_n_in (process%hi)
n_out = hard_interaction_get_n_out (process%hi)
n_tot = hard_interaction_get_n_tot (process%hi)
n_flv = hard_interaction_get_n_flv (process%hi)
allocate (flv (n_tot, n_flv))
call flavor_init (flv, &
    hard_interaction_get_flv_states (process%hi), process%model)
md5sum_process = process%md5sum
md5sum_model = model_get_md5sum (process%model)
md5sum_parameters = model_get_parameters_md5sum (process%model)
phs_par%sqrts = process%sqrts
if (present (filename_in)) then
    filename = filename_in
    call msg_message ("Reading phase-space configuration from file '" &
        // char (filename) // "'")
    check = .false.
else if (.not. rebuild_phs .and. present (filename_out)) then
    filename = filename_out
    check = .true.
else
    filename = ""
end if
if (filename /= "") then
    inquire (file=char(filename), exist=exist)
    if (exist) then
        unit = free_unit ()
        open (unit, file=char(filename), action="read", status="old")
        if (check) then
            call phs_forest_read (process%forest, unit, &
                process%id, n_in, n_out, process%model, phs_ok, &
                md5sum_process, md5sum_model, md5sum_parameters, phs_par, &
                phs_match)
        else
            call phs_forest_read (process%forest, unit, &
                process%id, n_in, n_out, process%model, phs_ok)
            phs_match = .true.
        end if
        if (phs_match) &
            call msg_message ("Read phase-space configuration from file '" &
                // char (filename) // "'...")
        rewind (unit)
        process%md5sum_phs = md5sum (unit)
        close (unit)
        if (.not. phs_ok) then
            call msg_fatal ("Phase space file '" // char (filename) &
                // "': No valid phase space for process '" &
                // char (process%id) // "'")
            if (present (ok)) ok = .false.
            return
        end if
    else
        call msg_message ("Phase space file '" // char (filename) &
            // "' not found.")
        phs_match = .false.
    end if
end if

```

```

        end if
    end if
    wrote_file = .false.
    if (.not. phs_match) then
        call msg_message ("Generating phase space configuration ...")
        LOOP_OFF_SHELL: do extra_off_shell = 0, max (n_tot - 3, 0)
            call cascade_set_generate (cascade_set, &
                process%model, n_in, n_out, flv, phs_par)
            if (cascade_set_is_valid (cascade_set)) then
                exit LOOP_OFF_SHELL
            else if (phs_par%off_shell >= max (n_tot - 3, 0)) then
                call msg_error ("Process '" // char (process%id) &
                    // "' : no valid phase-space channels found")
                if (present (ok)) ok = .false.
                call cascade_set_final (cascade_set)
                return
            else
                write (msg_buffer, "(A,1x,I0)" &
                    "Process '" // char (process%id) &
                    // "' : no valid phase-space channels found for " &
                    // "phs_off_shell =", phs_par%off_shell)
                call msg_warning ()
                call msg_message ("Increasing phs_off_shell")
                phs_par%off_shell = phs_par%off_shell + 1
            end if
        end do LOOP_OFF_SHELL
        unit = free_unit ()
        if (present (filename_out)) then
            open (unit, file=char(filename_out), &
                action="readwrite", status="replace")
        else
            open (unit, action="readwrite", status="scratch")
        end if
        write (unit, *) "process ", char (process%id)
        write (unit, *) " md5sum_process   = ", "'", md5sum_process, "'"
        write (unit, *) " md5sum_model     = ", "'", md5sum_model, "'"
        write (unit, *) " md5sum_parameters = ", "'", md5sum_parameters, "'"
        call phs_parameters_write (phs_par, unit)
        call cascade_set_write_file_format (cascade_set, unit)
        call cascade_set_final (cascade_set)
        rewind (unit)
        call phs_forest_read (process%forest, unit, &
            process%id, n_in, n_out, process%model, phs_ok)
        rewind (unit)
        process%md5sum_phs = md5sum (unit)
        close (unit)
        wrote_file = present (filename_out)
        if (.not. phs_ok) then
            call msg_bug ("Generated phase space file: " &
                // "No valid phase space for process '" &
                // char (process%id) // "'")
        end if
    end if
end if
call phs_forest_set_flavors (process%forest, flv(:,1))

```

```

call phs_forest_set_parameters &
    (process%forest, mapping_defaults, variable_limits)
call phs_forest_set_equivalences (process%forest)
if (process%use_beams) then
    n_par_strfun = strfun_chain_get_n_parameters_tot (process%sfchain)
    allocate (strfun_rigid (n_par_strfun))
    strfun_rigid = strfun_chain_dimension_is_rigid (process%sfchain)
else
    n_par_strfun = 0
    allocate (strfun_rigid (0))
end if
call phs_forest_setup_vamp_equivalences (process%forest, &
    n_par_strfun, strfun_rigid, &
    process%azimuthal_dependence, &
    process%vamp_eq)
process%n_channels = phs_forest_get_n_channels (process%forest)
process%n_par_hi = phs_forest_get_n_parameters (process%forest)
process%n_par = process%n_par_strfun + process%n_par_hi
allocate (process%x_hi (process%n_par_hi))
allocate (process%x (process%n_par, process%n_channels))
allocate (process%phs_factor (process%n_channels))
allocate (process%active_channel (process%n_channels))
process%active_channel = .true.
write (msg_buffer, "(A,IO,A)") "... found ", process%n_channels, &
    " phase space channels."
call msg_message ()
if (wrote_file) &
    call msg_message ("Wrote phase-space configuration file '" &
        // char (filename_out) // "'.")
if (present (ok)) ok = .true.
end subroutine process_setup_phase_space

```

13.3.9 Process preparation: cuts, weight and scale

Compile the cut expression and store it as an evaluation tree inside the process object.

```

<Processes: public>+≡
    public :: process_setup_cuts

<Processes: procedures>+≡
    subroutine process_setup_cuts (process, parse_node)
        type(process_t), intent(inout), target :: process
        type(parse_node_t), intent(in), target :: parse_node
        call eval_tree_init_lexpr &
            (process%cut_expr, parse_node, process%var_list, process%prt_list)
    end subroutine process_setup_cuts

```

Compile the weight expression and store it as an evaluation tree inside the process object.

```

<Processes: public>+≡
    public :: process_setup_weight

```

```

<Processes: procedures>+≡
  subroutine process_setup_weight (process, parse_node)
    type(process_t), intent(inout), target :: process
    type(parse_node_t), intent(in), target :: parse_node
    call eval_tree_init_expr &
      (process%reweighting_expr, parse_node, process%var_list, &
        process%prt_list)
  end subroutine process_setup_weight

```

Compile the scale expression and store it as an evaluation tree inside the process object.

```

<Processes: public>+≡
  public :: process_setup_scale

<Processes: procedures>+≡
  subroutine process_setup_scale (process, parse_node)
    type(process_t), intent(inout), target :: process
    type(parse_node_t), intent(in), target :: parse_node
    call eval_tree_init_expr &
      (process%scale_expr, parse_node, process%var_list, process%prt_list)
  end subroutine process_setup_scale

```

Compile the analysis expression and store it as an evaluation tree inside the process object.

```

<Processes: public>+≡
  public :: process_setup_analysis

<Processes: procedures>+≡
  subroutine process_setup_analysis (process, parse_node)
    type(process_t), intent(inout), target :: process
    type(parse_node_t), intent(in), target :: parse_node
    call eval_tree_init_lexpr &
      (process%analysis_expr, parse_node, process%var_list, process%prt_list)
  end subroutine process_setup_analysis

```

13.3.10 Process preparation: VAMP grids

Grid parameters: transparent container.

```

<Processes: public>+≡
  public :: grid_parameters_t

<Processes: types>+≡
  type :: grid_parameters_t
    integer :: threshold_calls = 0
    integer :: min_calls_per_channel = 10
    integer :: min_calls_per_bin = 10
    integer :: min_bins = 3
    integer :: max_bins = 20
    logical :: stratified = .true.
    real(default) :: channel_weights_power = 0.25_default
  end type grid_parameters_t

```

I/O:

(Processes: procedures)+≡

```
subroutine grid_parameters_write (grid_par, unit)
  type(grid_parameters_t), intent(in) :: grid_par
  integer, intent(in), optional :: unit
  integer :: u
  u = output_unit (unit)
  write (u, *) "threshold_calls      = ", grid_par%threshold_calls
  write (u, *) "min_calls_per_channel = ", grid_par%min_calls_per_channel
  write (u, *) "min_calls_per_bin    = ", grid_par%min_calls_per_bin
  write (u, *) "min_bins              = ", grid_par%min_bins
  write (u, *) "max_bins              = ", grid_par%max_bins
  write (u, *) "stratified            = ", grid_par%stratified
  write (u, *) "channel_weights_power = ", grid_par%channel_weights_power
end subroutine grid_parameters_write
```

(Processes: procedures)+≡

```
subroutine grid_parameters_read (grid_par, unit)
  type(grid_parameters_t), intent(out) :: grid_par
  integer, intent(in) :: unit
  character(30) :: dummy
  character :: equals
  read (unit, *) dummy, equals, grid_par%threshold_calls
  read (unit, *) dummy, equals, grid_par%min_calls_per_channel
  read (unit, *) dummy, equals, grid_par%min_calls_per_bin
  read (unit, *) dummy, equals, grid_par%min_bins
  read (unit, *) dummy, equals, grid_par%max_bins
  read (unit, *) dummy, equals, grid_par%stratified
  read (unit, *) dummy, equals, grid_par%channel_weights_power
end subroutine grid_parameters_read
```

(Processes: interfaces)+≡

```
interface operator(==)
  module procedure grid_parameters_eq
end interface
```

(Processes: procedures)+≡

```
function grid_parameters_eq (gp1, gp2) result (eq)
  logical :: eq
  type(grid_parameters_t), intent(in) :: gp1, gp2
  eq = gp1%threshold_calls == gp2%threshold_calls &
    .and. gp1%min_calls_per_channel == gp2%min_calls_per_channel &
    .and. gp1%min_calls_per_bin == gp2%min_calls_per_bin &
    .and. gp1%min_bins == gp2%min_bins &
    .and. gp1%max_bins == gp2%max_bins &
    .and. gp1%stratified .eqv. gp2%stratified &
    .and. gp1%channel_weights_power == gp2%channel_weights_power
end function grid_parameters_eq
```

(Processes: interfaces)+≡

```
interface operator(/=)
  module procedure grid_parameters_ne
end interface
```

```

<Processes: procedures>+≡
function grid_parameters_ne (gp1, gp2) result (ne)
  logical :: ne
  type(grid_parameters_t), intent(in) :: gp1, gp2
  ne = gp1%threshold_calls == gp2%threshold_calls &
    .or. gp1%min_calls_per_channel == gp2%min_calls_per_channel &
    .or. gp1%min_calls_per_bin == gp2%min_calls_per_bin &
    .or. gp1%min_bins == gp2%min_bins &
    .or. gp1%max_bins == gp2%max_bins &
    .or. gp1%stratified .neqv. gp2%stratified &
    .or. gp1%channel_weights_power == gp2%channel_weights_power
end function grid_parameters_ne

```

Initialize the grids with uniform channel weight.

```

<Processes: public>+≡
public :: process_setup_grids

<Processes: procedures>+≡
subroutine process_setup_grids (process, grid_parameters, calls)
  type(process_t), intent(inout), target :: process
  type(grid_parameters_t), intent(in) :: grid_parameters
  integer, intent(in) :: calls
  integer, dimension(:), allocatable :: num_div
  real(default), dimension(:), allocatable :: weights
  real(default), dimension(:,:), allocatable :: region
  integer :: min_calls
  allocate (num_div (process%n_par))
  min_calls = grid_parameters%min_calls_per_bin * process%n_channels
  if (min_calls /= 0) then
    process%n_bins = max (grid_parameters%min_bins, &
      min (calls / min_calls, grid_parameters%max_bins))
  else
    process%n_bins = grid_parameters%max_bins
  end if
  allocate (region (2, process%n_par))
  region(1,:) = 0
  region(2,:) = 1
  allocate (weights (process%n_channels))
  weights = 1
  num_div = process%n_bins
  call msg_message ("Creating grids")
  call vamp_create_grids (process%grids, region, calls, weights, &
    num_div=num_div, stratified=grid_parameters%stratified)
  process%vamp_grids_defined = .true.
end subroutine process_setup_grids

```

13.3.11 Process preparation: Helicity selection counters

The helicity selection counters can be activated and reset at startup, removing unnecessary helicities after `cutoff` tries.

```

<Processes: public>+≡
public :: process_reset_helicity_selection

```

(Processes: procedures)+≡

```

subroutine process_reset_helicity_selection (process, threshold, cutoff)
  type(process_t), intent(inout) :: process
  real(default), intent(in) :: threshold
  integer, intent(in) :: cutoff
  call hard_interaction_reset_helicity_selection &
    (process%hi, threshold, cutoff)
end subroutine process_reset_helicity_selection

```

13.3.12 Matrix element evaluation

Kinematics. This evaluates structure functions as far as momenta are concerned. The evaluator links automatically transfer the incoming momenta to the hard interaction. All phase space factors are evaluated, and the resulting momenta are stored back in the hard interaction, from there transferred to the appropriate evaluators.

Once the particle momenta are known, they are transferred to the `prt_list` that is used for cut/weight/scale evaluation. The energy scale is computed right here.

If `ok` is false, there is no valid momentum assignment for the given x parameters, and the event must be dropped.

(Processes: procedures)+≡

```

subroutine process_set_kinematics (process, x_in, channel, ok)
  type(process_t), intent(inout), target :: process
  real(default), dimension(:), intent(in) :: x_in
  integer, intent(in) :: channel
  logical, intent(out) :: ok
  type(interaction_t), pointer :: int
  type(evaluator_t), pointer :: eval
  integer :: i
  process%x_hi = x_in(:process%n_par_hi)
  process%x_strfun = x_in(process%n_par_hi+1:)
!   process%x_strfun = x_in(:process%n_par_strfun)
!   process%x_hi = x_in(process%n_par_strfun+1:)
  process%channel = channel
  int => hard_interaction_get_int_ptr (process%hi)
  eval => hard_interaction_get_eval_trace_ptr (process%hi)
  if (process%use_beams) then
    call strfun_chain_set_kinematics (process%sfchain, process%x_strfun)
    call interaction_receive_momenta (int)
    process%beams_are_set = .true.
    process%sqrts_hat = sqrt (max (interaction_get_s (int), 0._default))
  else if (.not. process%beams_are_set) then
    select case (process%type)
    case (PRC_DECAY)
      call interaction_set_momenta (int, &
        (/ vector4_at_rest (process%mass_in(1)) /), &
        outgoing=.false.)
    case (PRC_SCATTERING)
      call interaction_set_momenta (int, &
        colliding_momenta (process%sqrts, process%mass_in), &

```

```

        outgoing=.false.)
    end select
    process%sqrts_hat = process%sqrts
end if
select case (process%type)
case (PRC_DECAY)
    process%flux_factor = &
        twopi4 / (2 * process%mass_in(1))
case (PRC_SCATTERING)
    process%flux_factor = &
        conv * twopi4 &
        / (2 * sqrt (lambda (process%sqrts_hat ** 2, &
            process%mass_in(1) ** 2, &
            process%mass_in(2) ** 2)))
end select
process%sqrts_hat_known = .true.
if (.not. process%lab_is_cm_frame) then
    process%lt_cm_to_lab = interaction_get_cm_transformation (int)
    call phs_forest_set_prt_in (process%forest, int, process%lt_cm_to_lab)
else
    call phs_forest_set_prt_in (process%forest, int)
end if
process%x(:process%n_par_hi,channel) = process%x_hi
forall (i = 1 : process%n_par_strfun)
    process%x(process%n_par_hi+i,:) = process%x_strfun(i)
end forall
call phs_forest_evaluate_phase_space (process%forest, &
    channel, process%active_channel, process%sqrts_hat, &
    process%x, process%phs_factor, process%phs_volume, ok)
if (ok) then
    if (process%lab_is_cm_frame) then
        call phs_forest_get_prt_out (process%forest, int)
    else
        call phs_forest_get_prt_out &
            (process%forest, int, process%lt_cm_to_lab)
    end if
    call interaction_momenta_to_prt_list (int, process%prt_list)
    call process_compute_scale (process)
end if
call evaluator_receive_momenta (eval)
if (process%use_beams) &
    call evaluator_receive_momenta (process%eval_trace)
end subroutine process_set_kinematics

```

Evaluate the (jacobian) factor associated to the VAMP grids and the phase-space factor array for the given integration channel.

(Processes: procedures)+≡

```

subroutine process_compute_vamp_phs_factor (process, weights)
    type(process_t), intent(inout), target :: process
    real(default), dimension(:), intent(in) :: weights
    real(default), dimension(process%n_channels) :: vamp_prob
    real(default) :: dp
    integer :: i

```

```

do i = 1, process%n_channels
  if (process%active_channel(i)) then
    vamp_prob(i) = &
      vamp_probability (process%grids%grids(i), process%x(:,i))
  else
    vamp_prob(i) = 0
  end if
end do
dp = dot_product (weights, vamp_prob / process%phs_factor)
if (dp /= 0) then
  process%vamp_phs_factor = vamp_prob(process%channel) / dp
else
  process%vamp_phs_factor = 0
end if
end subroutine process_compute_vamp_phs_factor

```

Evaluate the cut expression and return a boolean flag (true means to continue evaluation, false to drop the event).

```

(Processes: procedures)+≡
function process_passes_cuts (process) result (flag)
  logical :: flag
  type(process_t), intent(inout), target :: process
  if (eval_tree_is_defined (process%cut_expr)) then
    call eval_tree_evaluate (process%cut_expr)
    if (eval_tree_result_is_known (process%cut_expr)) then
      flag = eval_tree_get_log (process%cut_expr)
    else
      flag = .true.
    end if
  else
    flag = .true.
  end if
end function process_passes_cuts

```

Evaluate the weight expression and set the value.

```

(Processes: procedures)+≡
subroutine process_compute_reweighting_factor (process)
  type(process_t), intent(inout), target :: process
  if (eval_tree_is_defined (process%reweighting_expr)) then
    call eval_tree_evaluate (process%reweighting_expr)
    if (eval_tree_result_is_known (process%reweighting_expr)) then
      process%reweighting_factor = &
        eval_tree_get_real (process%reweighting_expr)
    else
      process%reweighting_factor = 1
    end if
  else
    process%reweighting_factor = 1
  end if
end subroutine process_compute_reweighting_factor

```

Evaluate the analysis expression. The return value is logical, but always true

and should be ignored.

```

<Processes: public>+≡
    public :: process_do_analysis

<Processes: procedures>+≡
    subroutine process_do_analysis (process)
        type(process_t), intent(inout), target :: process
        if (eval_tree_is_defined (process%analysis_expr)) then
            call eval_tree_evaluate (process%analysis_expr)
        end if
    end subroutine process_do_analysis

```

Evaluate the scale expression and return a real value. If the scale expression is undefined, return the c.m. energy of the hard interaction.

```

<Processes: procedures>+≡
    subroutine process_compute_scale (process)
        type(process_t), intent(inout), target :: process
        if (eval_tree_is_defined (process%scale_expr)) then
            call eval_tree_evaluate (process%scale_expr)
            if (eval_tree_result_is_known (process%scale_expr)) then
                process%scale = eval_tree_get_real (process%scale_expr)
            else
                process%scale = process%sqrts_hat
            end if
        else
            process%scale = process%sqrts_hat
        end if
    end subroutine process_compute_scale

```

Update the α_s value used by the matrix element code, depending on the computed scale.

```

<Processes: interfaces>+≡
    interface
        double precision function alphasPDF (Q)
            double precision, intent(in) :: Q
        end function alphasPDF
    end interface

<Processes: procedures>+≡
    subroutine process_update_alpha_s (process)
        type(process_t), intent(inout) :: process
        real(default) :: scale, nf, as_mz, mz, lambda, alpha_s
        integer :: order
        scale = process%scale
        as_mz = process%alpha_s_mz
        mz = process%mz
        lambda = process%lambda_qcd
        order = process%alpha_s_order
        nf = process%alpha_s_nf
        if (.not. process%alpha_s_is_fixed) then
            if (process%alpha_s_from_lhapdf) then
                alpha_s = alphasPDF (dble (scale))
            else

```

```

    if (process%alpha_s_from_mz) then
      if (process%alpha_s_mz_is_known) then
        if (process%mz_is_known) then
          alpha_s = running_as (scale, &
                                al_mz=as_mz, mz=mz, order=order, nf=nf)
        else
          alpha_s = running_as (scale, &
                                al_mz=as_mz, order=order, nf=nf)
        end if
      else
        if (process%mz_is_known) then
          alpha_s = running_as (scale, &
                                mz=mz, order=order, nf=nf)
        else
          alpha_s = running_as (scale, &
                                order=order, nf=nf)
        end if
      end if
    else
      alpha_s = running_as_lam (nf, scale, lambda, order=order)
    end if
  end if
  process%alpha_s_at_scale = alpha_s
  call hard_interaction_update_alpha_s (process%hi, alpha_s)
end if
end subroutine process_update_alpha_s

```

Evaluate the structure function values, the hard matrix element, and the follow-up evaluators. We obtain the squared matrix element value for the current event.

```

(Processes: procedures) +=
  subroutine process_evaluate (process)
    type(process_t), intent(inout), target :: process
    if (process%use_beams) then
      call strfun_chain_evaluate (process%sfchain, process%scale)
      process%sf_mapping_factor = &
        strfun_chain_get_mapping_factor (process%sfchain)
    else
      process%sf_mapping_factor = 1
    end if
    call hard_interaction_evaluate (process%hi)
    if (process%has_extra_evaluators) then
      call evaluator_evaluate (process%eval_trace)
      process%sqme = evaluator_sum (process%eval_trace)
    else
      process%sqme = evaluator_sum &
        (hard_interaction_get_eval_trace_ptr (process%hi)) &
        * process%averaging_factor
    end if
    ! call process_write (process, 66); stop
  end subroutine process_evaluate

```

Return the squared matrix element of the hard interaction for the given mo-

menta, traced over all quantum numbers. This is independent of beam setup, structure functions, phase space etc.

(Processes: procedures)+≡

```
function process_compute_sqme_sum (process, p) result (sqme)
  real(default) :: sqme
  type(process_t), intent(inout), target :: process
  type(vector4_t), dimension(:), intent(in) :: p
  sqme = hard_interaction_compute_sqme_sum (process%hi, p)
end function process_compute_sqme_sum
```

13.3.13 Access VAMP data

Compute the reweighting efficiency for the current grids, suitable averaged over all active channels.

(Processes: procedures)+≡

```
function process_get_vamp_efficiency_array (process) result (efficiency)
  real(default), dimension(:), allocatable :: efficiency
  type(process_t), intent(in) :: process
  allocate (efficiency (process%n_channels))
  where (process%grids%grids%f_max /= 0)
    efficiency = process%grids%grids%mu(1) / abs (process%grids%grids%f_max)
  elsewhere
    efficiency = 0
  end where
end function process_get_vamp_efficiency_array

function process_get_vamp_efficiency (process) result (efficiency)
  real(default) :: efficiency
  type(process_t), intent(in) :: process
  real(default), dimension(:), allocatable :: weight
  real(default) :: norm
  allocate (weight (process%n_channels))
  weight = process%grids%weights * abs (process%grids%grids%f_max)
  norm = sum (weight)
  if (norm /= 0) then
    efficiency = &
      dot_product (process_get_vamp_efficiency_array (process), weight) &
      / norm
  else
    efficiency = 1
  end if
end function process_get_vamp_efficiency
```

13.3.14 Integration

This executes one or more iterations of the VAMP integration routine. The flags determine whether to discard previous results, to adapt grids before integration, and to adapt the relative channel weights. The final result is entered into the results record.

(Processes: public)+≡

```

public :: process_integrate
<Processes: procedures>+=
  subroutine process_integrate (process, rng, &
    grid_parameters, pass, it1, it2, calls, &
    discard_integrals, adapt_grids, adapt_weights, print_current, &
    grids_filename, md5sum_beams, md5sum_sf_list, &
    md5sum_cuts, md5sum_weight, md5sum_scale)
    type(process_t), intent(inout), target :: process
    type(tao_random_state), intent(inout) :: rng
    type(grid_parameters_t), intent(in) :: grid_parameters
    integer, intent(in) :: pass, it1, it2, calls
    logical, intent(in) :: discard_integrals
    logical, intent(in) :: adapt_grids
    logical, intent(in) :: adapt_weights
    logical, intent(in) :: print_current
    type(string_t), intent(in), optional :: grids_filename
    character(32), intent(in), optional :: md5sum_beams, md5sum_sf_list
    character(32), intent(in), optional :: &
      md5sum_cuts, md5sum_weight, md5sum_scale
    integer :: it
    real(default) :: integral, error, efficiency
    character(32) :: md5sum_process, md5sum_model, md5sum_parameters
    character(32) :: md5sum_phs
    real(default) :: sqrts
    integer :: u
    if (it1 > it2) return
    u = logfile_unit ()
    md5sum_process = process%md5sum
    md5sum_model = model_get_md5sum (process%model)
    md5sum_parameters = model_get_parameters_md5sum (process%model)
    md5sum_phs = process%md5sum_phs
    sqrts = process%sqrts
    if (discard_integrals .and. it1==1) then
      call vamp_discard_integrals (process%grids, &
        calls, stratified=grid_parameters%stratified, eq=process%vamp_eq)
    end if
    process%beams_are_set = .false.
    do it = it1, it2
      if (adapt_grids) then
        call process_adapt_grids (process)
      end if
      if (adapt_weights) then
        call process_adapt_channel_weights (process, grid_parameters, calls)
      end if
      call vamp_sample_grids &
        (rng, process%grids, sample_function, process%store_index, 1, &
          integral=integral, std_dev=error)
      efficiency = process_get_vamp_efficiency (process)
      call integration_results_append (process%results, &
        process%type, pass, 1, calls, &
          integral, error, efficiency)
    end do
    if (present (grids_filename)) then
      call write_grid_file (grids_filename, process%id, &
        md5sum_process, md5sum_model, md5sum_parameters, md5sum_phs, &

```

```

        md5sum_beams, md5sum_sf_list, &
        md5sum_cuts, md5sum_weight, md5sum_scale, &
        grid_parameters, process%results, process%grids)
    end if
    if (print_current) then
        call integration_results_write_current (process%results)
        call integration_results_write_current (process%results, unit=u)
        flush (u)
    end if
end do
end subroutine process_integrate

```

Write the VAMP grid file including a header containing metadata.

(Processes: procedures)+≡

```

subroutine write_grid_file (filename, process_id, &
    md5sum_process, md5sum_model, md5sum_parameters, md5sum_phs, &
    md5sum_beams, md5sum_sf_list, &
    md5sum_cuts, md5sum_weight, md5sum_scale, &
    grid_parameters, results, grids)
    type(string_t), intent(in) :: filename, process_id
    character(32), intent(in) :: md5sum_process, md5sum_model
    character(32), intent(in) :: md5sum_phs, md5sum_parameters
    character(32), intent(in) :: md5sum_beams, md5sum_sf_list
    character(32), intent(in) :: md5sum_cuts, md5sum_weight, md5sum_scale
    type(grid_parameters_t), intent(in) :: grid_parameters
    type(integration_results_t), intent(in) :: results
    type(vamp_grids), intent(in) :: grids
    integer :: u
    u = free_unit ()
    open (file = char (filename), unit = u, &
        action = "write", status = "replace")
    write (u, *) "process ", char (process_id)
    write (u, *) " md5sum_process      = ", "'", md5sum_process, "'"
    write (u, *) " md5sum_model      = ", "'", md5sum_model, "'"
    write (u, *) " md5sum_parameters = ", "'", md5sum_parameters, "'"
    write (u, *) " md5sum_phase_space = ", "'", md5sum_phs, "'"
    write (u, *) " md5sum_beams      = ", "'", md5sum_beams, "'"
    write (u, *) " md5sum_sf_list    = ", "'", md5sum_sf_list, "'"
    write (u, *) " md5sum_cuts      = ", "'", md5sum_cuts, "'"
    write (u, *) " md5sum_weight    = ", "'", md5sum_weight, "'"
    write (u, *) " md5sum_scale     = ", "'", md5sum_scale, "'"
    write (u, *)
    call grid_parameters_write (grid_parameters, u)
    write (u, *)
    call integration_results_write &
        (results, u, verbose = .true.)
    write (u, *)
    call vamp_write_grids (grids, u, write_integrals = .true.)
    close (u)
end subroutine write_grid_file

```

Attempt to read the VAMP grid file, checking metadata for consistency. Also read the integration results as far as they are known.

```

<Processes: procedures>+≡
subroutine read_grid_file (filename, process_id, &
    md5sum_process, md5sum_model, md5sum_parameters, md5sum_phs, &
    md5sum_beams, md5sum_sf_list, &
    md5sum_cuts, md5sum_weight, md5sum_scale, &
    grid_parameters, results, grids, &
    pass, n_calls, ok)
type(string_t), intent(in) :: filename, process_id
character(32), intent(in) :: md5sum_process, md5sum_model
character(32), intent(in) :: md5sum_phs, md5sum_parameters
character(32), intent(in) :: md5sum_beams, md5sum_sf_list
character(32), intent(in) :: md5sum_cuts, md5sum_weight, md5sum_scale
type(grid_parameters_t), intent(in) :: grid_parameters
type(integration_results_t), intent(out) :: results
type(vamp_grids), intent(inout) :: grids
integer, dimension(:), intent(in) :: pass, n_calls
logical, intent(out) :: ok
integer :: u
logical :: exist
character(80) :: buffer
character :: equals
character(32) :: md5sum
type(grid_parameters_t) :: grid_parameters_file
type(integration_results_t) :: results_file
ok = .false.
inquire (file = char (filename), exist = exist)
if (.not. exist) return
call msg_message ("Reading integration grids and results from file '" &
    // char (filename) // "'")
u = free_unit ()
open (file = char (filename), unit = u, action = "read", status = "old")
read (u, *) buffer
if (trim (adjustl (buffer)) /= "process") then
    call msg_fatal ("Grid file: missing 'process' tag")
    close (u); return
end if
read (u, *) buffer, equals, md5sum
if (md5sum /= md5sum_process) then
    call msg_message &
        ("Process configuration has changed, discarding old grid file")
    close (u); return
end if
read (u, *) buffer, equals, md5sum
if (md5sum /= md5sum_model) then
    call msg_message &
        ("Model has changed, discarding old grid file")
    close (u); return
end if
read (u, *) buffer, equals, md5sum
if (md5sum /= md5sum_parameters) then
    call msg_message &
        ("Model parameters have changed, discarding old grid file")
    close (u); return
end if

```

```

read (u, *) buffer, equals, md5sum
if (md5sum /= md5sum_phs) then
  call msg_message &
    ("Phase-space setup has changed, discarding old grid file")
  close (u); return
end if
read (u, *) buffer, equals, md5sum
if (md5sum /= md5sum_beams) then
  call msg_message &
    ("Beam setup has changed, discarding old grid file")
  close (u); return
end if
read (u, *) buffer, equals, md5sum
if (md5sum /= md5sum_sf_list) then
  call msg_message &
    ("Structure-function setup has changed, discarding old grid file")
  close (u); return
end if
read (u, *) buffer, equals, md5sum
if (md5sum /= md5sum_cuts) then
  call msg_message &
    ("Cut configuration has changed, discarding old grid file")
  close (u); return
end if
read (u, *) buffer, equals, md5sum
if (md5sum /= md5sum_weight) then
  call msg_message &
    ("Weight expression has changed, discarding old grid file")
  close (u); return
end if
read (u, *) buffer, equals, md5sum
if (md5sum /= md5sum_scale) then
  call msg_message &
    ("Scale expression have changed, discarding old grid file")
  close (u); return
end if
read (u, *)
call grid_parameters_read (grid_parameters_file, u)
if (grid_parameters_file /= grid_parameters) then
  call msg_message &
    ("Grid parameters have changed, discarding old grid file")
  close (u); return
end if
read (u, *)
call integration_results_read (results_file, u)
if (.not. integration_results_iterations_are_consistent &
    (results_file, pass, n_calls)) then
  call msg_message &
    ("Iteration parameters have changed, discarding old grid file")
  close (u); return
end if
results = results_file
read (u, *)
call vamp_read_grids (grids, u)

```

```

        close (u)
        ok = .true.
    end subroutine read_grid_file

```

Wrapper for grid file reading.

```

<Processes: public>+≡
    public :: process_read_grid_file

<Processes: procedures>+≡
    subroutine process_read_grid_file (process, filename, &
        md5sum_beams, md5sum_sf_list, md5sum_cuts, md5sum_weight, md5sum_scale,&
        grid_parameters, pass, n_calls, ok)
        type(process_t), intent(inout) :: process
        type(string_t), intent(in) :: filename
        character(32), intent(in) :: md5sum_beams, md5sum_sf_list
        character(32), intent(in) :: md5sum_cuts, md5sum_weight, md5sum_scale
        type(grid_parameters_t), intent(in) :: grid_parameters
        integer, dimension(:), intent(in) :: pass, n_calls
        logical, intent(out) :: ok
        character(32) :: md5sum_process, md5sum_model
        character(32) :: md5sum_parameters, md5sum_phs
        md5sum_process = process%md5sum
        md5sum_model = model_get_md5sum (process%model)
        md5sum_parameters = model_get_parameters_md5sum (process%model)
        md5sum_phs = process%md5sum_phs
        call read_grid_file (filename, process%id, &
            md5sum_process, md5sum_model, md5sum_parameters, md5sum_phs, &
            md5sum_beams, md5sum_sf_list, &
            md5sum_cuts, md5sum_weight, md5sum_scale, &
            grid_parameters, process%results, process%grids, &
            pass, n_calls, ok)
    end subroutine process_read_grid_file

```

Adapt the binning of the VAMP grids. This is just a wrapper.

```

<Processes: procedures>+≡
    subroutine process_adapt_grids (process)
        type(process_t), intent(inout), target :: process
        call vamp_refine_grids (process%grids)
    end subroutine process_adapt_grids

```

Refine the channel weights. We use a power weight just as for the individual bins. The results are averaged within each grove. Then, we check if the resulting weights would lead to a too small number of calls within any channel, which is corrected. The result is fed into VAMP.

```

<Processes: procedures>+≡
    subroutine process_adapt_channel_weights (process, grid_parameters, calls)
        type(process_t), intent(inout), target :: process
        type(grid_parameters_t), intent(in) :: grid_parameters
        integer, intent(in) :: calls
        real(default), dimension(:), allocatable :: weights
        integer :: g, i0, i1, n
        real(default) :: sum_weights, weight_min

```

```

logical, dimension(:), allocatable :: weight_underflow
real(default) :: sum_weight_underflow
integer :: n_underflow
allocate (weights (process%n_channels))
weights = process%grids%weights &
    * vamp_get_variance (process%grids%grids) &
    ** grid_parameters%channel_weights_power
do g = 1, phs_forest_get_n_groves (process%forest)
    call phs_forest_get_grove_bounds (process%forest, g, i0, i1, n)
    weights(i0:i1) = sum (weights(i0:i1)) / n
end do
sum_weights = sum (weights)
if (sum_weights /= 0) then
    weights = weights / sum (weights)
    if (grid_parameters%threshold_calls /= 0) then
        weight_min = &
            real (grid_parameters%threshold_calls, default) &
            / calls
        weight_underflow = weights /= 0 .and. weights < weight_min
        n_underflow = count (weight_underflow)
        sum_weight_underflow = sum (weights, mask=weight_underflow)
        where (weight_underflow)
            weights = weight_min
        elsewhere
            weights = weights &
                * (1 - n_underflow * weight_min) / (1 - sum_weight_underflow)
        end where
    end if
    call vamp_update_weights (process%grids, weights)
end if
end subroutine process_adapt_channel_weights

```

13.3.15 Event generation

Initialize event generation. For the process setup, this means that the evaluators for the exclusive matrix element with and without color-flow decomposition is activated.

For the hard-interaction evaluators, we select only those entries which are supported by the beam/structure function setup. E.g., we select diagonal helicity only, or sum over helicity if the beams are unpolarized. When constructing the process evaluators, we multiply the beams by the hard-interaction evaluators and trace over all incoming-particle quantum numbers (except for color in the color-flow evaluator).

```

<Processes: public>+≡
    public :: process_setup_event_generation

<Processes: procedures>+≡
    subroutine process_setup_event_generation (process, qn_mask_in)
        type(process_t), intent(inout), target :: process
        type(quantum_numbers_mask_t), intent(in), optional :: qn_mask_in
        integer, dimension(:), allocatable :: coll_index
        type(quantum_numbers_mask_t), dimension(:), allocatable :: mask_in
    end subroutine

```

```

type(quantum_numbers_mask_t) :: mask_conn_sqme, mask_conn_flows
type(evaluator_t), pointer :: eval_sfchain, eval_sqme, eval_flows
type(interaction_t), pointer :: int_hi, int_beam
integer :: n_in, n_out, n_tot, i
type(evaluator_t), target :: eval_con
call hard_interaction_final_sqme (process%hi)
call hard_interaction_final_flows (process%hi)
call evaluator_final (process%eval_beam_flows)
call evaluator_final (process%eval_sqme)
call evaluator_final (process%eval_flows)
n_in = hard_interaction_get_n_in (process%hi)
n_out = hard_interaction_get_n_out (process%hi)
n_tot = hard_interaction_get_n_tot (process%hi)
int_hi => hard_interaction_get_int_ptr (process%hi)
call interaction_reset_momenta (int_hi)
allocate (mask_in (n_in))
if (process%use_beams) then
    allocate (coll_index (n_in))
    coll_index = strfun_chain_get_colliding_particles (process%sfchain)
    mask_in = strfun_chain_get_colliding_particles_mask (process%sfchain)
    mask_conn_sqme = new_quantum_numbers_mask (.true., .true., .true.)
    mask_conn_flows = new_quantum_numbers_mask (.true., .false., .true.)
else if (present (qn_mask_in)) then
    mask_in = qn_mask_in
else
    mask_in = new_quantum_numbers_mask (.false., .false., .true.)
end if
call hard_interaction_init_sqme (process%hi, mask_in)
call hard_interaction_init_flows (process%hi, mask_in)
int_beam => strfun_chain_get_beam_int_ptr (process%sfchain)
eval_sfchain => strfun_chain_get_last_evaluator_ptr (process%sfchain)
eval_sqme => hard_interaction_get_eval_sqme_ptr (process%hi)
eval_flows => hard_interaction_get_eval_flows_ptr (process%hi)
! print *, "Hard interaction"
! call interaction_write (int_hi)
! print *, "Evaluator: HI: SQME"
! call evaluator_write (eval_sqme)
! print *, "Evaluator: HI: flows"
! call evaluator_write (eval_flows)
if (process%use_beams) then
    if (associated (eval_sfchain)) then
        call evaluator_init_color_contractions &
            (process%eval_beam_flows, evaluator_get_int_ptr (eval_sfchain))
        do i = 1, n_in
            call evaluator_set_source_link &
                (eval_sqme, i, eval_sfchain, coll_index(i))
            call evaluator_set_source_link &
                (eval_flows, i, process%eval_beam_flows, coll_index(i))
        end do
    if (process%has_extra_evaluators) then
        call evaluator_init_product (process%eval_sqme, &
            eval_sfchain, eval_sqme, mask_conn_sqme)
        call evaluator_init_product (process%eval_flows, &
            process%eval_beam_flows, eval_flows, mask_conn_flows)
    end if
end if

```

```

        end if
    else
        call evaluator_init_color_contractions &
            (process%eval_beam_flows, int_beam)
        do i = 1, n_in
            call evaluator_set_source_link &
                (eval_sqme, i, int_beam, coll_index(i))
            call evaluator_set_source_link &
                (eval_flows, i, process%eval_beam_flows, coll_index(i))
        end do
        if (process%has_extra_evaluators) then
            call evaluator_init_product (process%eval_sqme, &
                int_beam, eval_sqme, mask_conn_sqme)
            call evaluator_init_product (process%eval_flows, &
                process%eval_beam_flows, eval_flows, mask_conn_flows)
        end if
    end if
    !      print *, "Evaluator: Beams+HI: SQME"
    !      call evaluator_write (process%eval_sqme)
    !      print *, "Evaluator: Beams+HI: flows"
    !      call evaluator_write (process%eval_flows)
    !      call process_write (process, 77)
end if
end subroutine process_setup_event_generation

```

Generate a weighted event. We have to select a channel. The output is the event weight, unmodified. The `sample_function` fully constructs the event in the `process` object, so the output `x` array is not needed.

Analysis is not yet implemented; we need a means to pass the event weight to the recording functions.

```

<Processes: public>+≡
    public :: process_generate_weighted_event

<Processes: procedures>+≡
    subroutine process_generate_weighted_event (process, rng, channel, weight)
        type(process_t), intent(inout), target :: process
        type(tao_random_state), intent(inout) :: rng
        integer, intent(in) :: channel
        real(default), intent(out) :: weight
        real(default), dimension(process%n_par) :: x
        call vamp_next_event &
            (x, rng, process%grids%grids(channel), &
                sample_function, process%store_index, &
                weight, channel, process%grids%weights, process%grids%grids)
        call process_complete_evaluators (process)
    !      call process_do_analysis (process, weight)
    end subroutine process_generate_weighted_event

```

Generate an unweighted event. Rejection is done by `VAMP`. The optional `excess` is nonzero by the excess weight if an event weight exceeds the precalculated maximum that is used for rejection. After the event has been generated, it can be analyzed.

The transformation function `phi` is trivial but has to be supplied.

```

<Processes: public>+≡
    public :: process_generate_unweighted_event

<Processes: procedures>+≡
    subroutine process_generate_unweighted_event (process, rng, excess)
        type(process_t), intent(inout), target :: process
        type(tao_random_state), intent(inout) :: rng
        real(default), intent(out), optional :: excess
        real(default), dimension(process%n_par) :: x
        call vamp_next_event &
            (x, rng, process%grids, &
             sample_function, process%store_index, phi_trivial, &
             excess=excess)
        call process_complete_evaluators (process)
        call process_do_analysis (process)
    end subroutine process_generate_unweighted_event

    function phi_trivial (xi, channel_dummy) result (x)
        real(default), dimension(:), intent(in) :: xi
        integer, intent(in) :: channel_dummy
        real(default), dimension(size(xi)) :: x
        x = xi
    end function phi_trivial

```

Complete the event: compute amplitudes/probabilities for exclusive quantum numbers.

```

<Processes: procedures>+≡
    subroutine process_complete_evaluators (process)
        type(process_t), intent(inout), target :: process
        if (process%use_beams) then
            call evaluator_receive_momenta (process%eval_beam_flows)
            call evaluator_evaluate (process%eval_beam_flows)
        end if
        call hard_interaction_evaluate_sqme (process%hi)
        call hard_interaction_evaluate_flows (process%hi)
        if (process%has_extra_evaluators) then
            call evaluator_receive_momenta (process%eval_sqme)
            call evaluator_receive_momenta (process%eval_flows)
            call evaluator_evaluate (process%eval_sqme)
            call evaluator_evaluate (process%eval_flows)
        end if
    end subroutine process_complete_evaluators

```

When the event is generated externally (e.g., read from file), we need to fill the particle list with the process record in order to analyze it. This is done here:

```

<Processes: public>+≡
    public :: process_set_particles

<Processes: procedures>+≡
    subroutine process_set_particles (process, particle_set)
        type(process_t), intent(inout) :: process
        type(particle_set_t), intent(in) :: particle_set
    end subroutine process_set_particles

```

```

        call particle_set_to_prt_list (particle_set, process%prt_list)
    end subroutine process_set_particles

```

13.3.16 Results output

(Processes: public)+≡

```

    public :: process_results_write_header
    public :: process_results_write_entry
    public :: process_results_write_current
    public :: process_results_write_average
    public :: process_results_write_current_average
    public :: process_results_write_footer
    public :: process_results_write

```

(Processes: procedures)+≡

```

    subroutine process_results_write_header (process, unit, logfile)
        type(process_t), intent(in) :: process
        integer, intent(in), optional :: unit
        logical, intent(in), optional :: logfile
        call write_dline (unit)
        call write_header (process%type, unit, logfile)
        call write_dline (unit)
    end subroutine process_results_write_header

```

```

    subroutine process_results_write_entry (process, it, unit)
        type(process_t), intent(in) :: process
        integer, intent(in) :: it
        integer, intent(in), optional :: unit
        call integration_results_write_entry (process%results, it, unit)
    end subroutine process_results_write_entry

```

```

    subroutine process_results_write_current (process, unit)
        type(process_t), intent(in) :: process
        integer, intent(in), optional :: unit
        call integration_results_write_current (process%results, unit)
    end subroutine process_results_write_current

```

```

    subroutine process_results_write_average (process, pass, unit)
        type(process_t), intent(in) :: process
        integer, intent(in) :: pass
        integer, intent(in), optional :: unit
        call write_hline (unit)
        call integration_results_write_average (process%results, pass, unit)
        call write_hline (unit)
    end subroutine process_results_write_average

```

```

    subroutine process_results_write_current_average (process, unit)
        type(process_t), intent(in) :: process
        integer, intent(in), optional :: unit
        call write_hline (unit)
        call integration_results_write_current_average (process%results, unit)
        call write_hline (unit)
    end subroutine process_results_write_current_average

```

```

subroutine process_results_write_footer (process, unit)
  type(process_t), intent(in) :: process
  integer, intent(in), optional :: unit
  call write_dline (unit)
  call integration_results_write_current_average (process%results, unit)
  call write_dline (unit)
end subroutine process_results_write_footer

subroutine process_results_write (process, unit)
  type(process_t), intent(in) :: process
  integer, intent(in), optional :: unit
  call integration_results_write (process%results, unit)
end subroutine process_results_write

```

Record the integration results in the process library entry.

```

<Processes: public>+≡
  public :: process_record_integral

<Processes: procedures>+≡
  subroutine process_record_integral (process)
    type(process_t), intent(inout) :: process
    call process_library_record_integral &
      (process%prc_lib, process%id, &
        integration_results_get_n_calls (process%results), &
        integration_results_get_integral (process%results), &
        integration_results_get_error (process%results), &
        integration_results_get_accuracy (process%results), &
        integration_results_get_chi2 (process%results), &
        integration_results_get_efficiency (process%results))
  end subroutine process_record_integral

```

13.3.17 Copies

Process copies are used for decay chains (and such). We deep-copy most components, in particular the hard-interaction and decay-forest workspaces. Read-only components (variable list) and eval trees are transferred as shallow copies.

We do not copy the extra evaluators that convolute beams and hard matrix elements. Actually, beams should not be defined for a cascade decay process in the first place, but we do not enforce this. We also skip the integration results.

Furthermore, we have to reassign all external links between interactions within the process copy to point to the copy, not the original.

The copy is linked to the original by a pointer. Its initial state is `in_use`.

```

<Processes: procedures>+≡
  subroutine process_make_copy (process, original)
    type(process_t), intent(inout), target :: process
    type(process_t), intent(in), target, optional :: original
    type(process_t), pointer :: copy
    type(interaction_t), pointer :: beam_int, copy_beam_int
    type(interaction_t), pointer :: hi_int, copy_hi_int
    type(evaluator_t), pointer :: hi_eval_trace, copy_hi_eval_trace

```

```

type(evaluator_t), pointer :: hi_eval_sqme, copy_hi_eval_sqme
type(evaluator_t), pointer :: hi_eval_flows, copy_hi_eval_flows
allocate (copy)
copy%type = process%type
copy%is_original = .false.
if (present (original)) then
    copy%original => original
else
    copy%original => process
end if
copy%initialized = process%initialized
copy%use_beams = process%use_beams
copy%has_extra_evaluators = .false.
copy%id = process%id
copy%prc_lib => process%prc_lib
copy%lib_index = process%lib_index
copy%store_index = process%store_index
copy%model => process%model
if (process%use_beams) then
    copy%n_strfun = process%n_strfun
    copy%n_par_strfun = process%n_par_strfun
end if
copy%n_par_hi = process%n_par_hi
copy%n_par = process%n_par
copy%azimuthal_dependence = process%azimuthal_dependence
copy%vamp_grids_defined = process%vamp_grids_defined
copy%sqrts_known = process%sqrts_known
copy%sqrts = process%sqrts
if (process%use_beams) then
    if (allocated (process%x_strfun)) &
        allocate (copy%x_strfun (size (process%x_strfun)))
end if
if (allocated (process%x_hi)) &
    allocate (copy%x_hi (size (process%x_hi)))
copy%n_channels = process%n_channels
if (allocated (process%x)) &
    allocate (copy%x (size (process%x, 1), size (process%x, 2)))
if (allocated (process%phs_factor)) &
    allocate (copy%phs_factor (size (process%phs_factor)))
if (allocated (process%mass_in)) then
    allocate (copy%mass_in (size (process%mass_in)))
    copy%mass_in = process%mass_in
end if
copy%averaging_factor = process%averaging_factor
if (process%use_beams) copy%sfchain = process%sfchain
copy%hi = process%hi
if (process%use_beams) copy%eval_trace = process%eval_trace
! copy%eval_beam_flows = process%eval_beam_flows
! copy%eval_sqme = process%eval_sqme
! copy%eval_flows = process%eval_flows
copy%forest = process%forest
copy%vamp_eq = process%vamp_eq
copy%prt_list = process%prt_list
copy%var_list = process%var_list

```

```

copy%cut_expr = process%cut_expr
copy%reweighting_expr = process%reweighting_expr
copy%scale_expr = process%scale_expr
if (allocated (process%active_channel)) then
    allocate (copy%active_channel (size (process%active_channel)))
    copy%active_channel = process%active_channel
end if
call vamp_copy_grids (copy%grids, process%grids)
beam_int => strfun_chain_get_beam_int_ptr (process%sfchain)
hi_int => hard_interaction_get_int_ptr (process%hi)
hi_eval_trace => hard_interaction_get_eval_trace_ptr (process%hi)
hi_eval_sqme => hard_interaction_get_eval_sqme_ptr (process%hi)
hi_eval_flows => hard_interaction_get_eval_flows_ptr (process%hi)
copy_beam_int => strfun_chain_get_beam_int_ptr (copy%sfchain)
copy_hi_int => hard_interaction_get_int_ptr (copy%hi)
copy_hi_eval_trace => hard_interaction_get_eval_trace_ptr (copy%hi)
copy_hi_eval_sqme => hard_interaction_get_eval_sqme_ptr (copy%hi)
copy_hi_eval_flows => hard_interaction_get_eval_flows_ptr (copy%hi)
select case (process%type)
case (PRC_SCATTERING)
    call msg_bug ("Process copy for scattering processes not implemented")
case (PRC_DECAY)
    call interaction_reassign_links &
        (copy_hi_int, beam_int, copy_beam_int)
    call evaluator_reassign_links &
        (copy_hi_eval_trace, beam_int, copy_beam_int)
    call evaluator_reassign_links &
        (copy_hi_eval_sqme, beam_int, copy_beam_int)
    call evaluator_reassign_links &
        (copy_hi_eval_flows, beam_int, copy_beam_int)
    call evaluator_reassign_links &
        (copy_hi_eval_trace, hi_int, copy_hi_int)
    call evaluator_reassign_links &
        (copy_hi_eval_sqme, hi_int, copy_hi_int)
    call evaluator_reassign_links &
        (copy_hi_eval_flows, hi_int, copy_hi_int)
    call evaluator_reassign_links &
        (copy%eval_trace, beam_int, copy_beam_int)
    call evaluator_reassign_links &
        (copy%eval_sqme, beam_int, copy_beam_int)
    call evaluator_reassign_links &
        (copy%eval_flows, beam_int, copy_beam_int)
    call evaluator_reassign_links &
        (copy%eval_trace, hi_eval_trace, copy_hi_eval_trace)
    call evaluator_reassign_links &
        (copy%eval_sqme, hi_eval_sqme, copy_hi_eval_sqme)
    call evaluator_reassign_links &
        (copy%eval_flows, hi_eval_flows, copy_hi_eval_flows)
end select
process%copy => copy
end subroutine process_make_copy

```

Request a process copy. If there is a copy currently not in use, activate it. Otherwise, make a new copy. In the original process, point to this copy as the

working copy.

```
<Processes: public>+≡
    public :: process_request_copy

<Processes: procedures>+≡
    recursive subroutine process_request_copy (process, copy, original)
        type(process_t), intent(inout), target :: process
        type(process_t), pointer :: copy
        type(process_t), intent(inout), target, optional :: original
        if (associated (process%copy)) then
            if (process%copy%in_use) then
                call process_request_copy (process%copy, copy, process)
            else
                copy => process%copy
                copy%in_use = .true.
                if (present (original)) then
                    original%working_copy => copy
                else
                    process%working_copy => copy
                end if
            end if
        else
            call process_make_copy (process, original)
            copy => process%copy
            copy%in_use = .true.
            if (present (original)) then
                original%working_copy => copy
            else
                process%working_copy => copy
            end if
        end if
    end subroutine process_request_copy
```

Return the working copy of a process. If there is none, return the process itself.

```
<Processes: procedures>+≡
    function process_get_working_copy_ptr (process) result (copy)
        type(process_t), intent(in), target :: process
        type(process_t), pointer :: copy
        if (associated (process%working_copy)) then
            copy => process%working_copy
        else
            copy => process
        end if
    end function process_get_working_copy_ptr
```

Mark this copy of the current process as not in use, so it can be requested again.

```
<Processes: public>+≡
    public :: process_copy_free

<Processes: procedures>+≡
    subroutine process_copy_free (process)
        type(process_t), intent(inout), target :: process
        process%in_use = .false.
        if (associated (process%original)) then
```

```

        process%original%working_copy => null ()
    end if
end subroutine process_copy_free

```

13.3.18 Process store

The process store is a container for the list of all processes. The list is expanded as needed during program execution. The container is implemented as a module variable. Thus, there is only one process store in the program.

The reason for this is the sampling function, which needs to access it without referencing it as an argument. Instead, it takes an integer argument which identifies the process. For direct access, we maintain a process pointer array as a shortcut to the list.

Type and object

```

<Processes: types>+≡
    type :: process_entry_t
        type(process_t) :: process
        type(process_entry_t), pointer :: next => null ()
    end type process_entry_t

<Processes: types>+≡
    type :: process_p
        type(process_t), pointer :: ptr => null ()
    end type process_p

<Processes: types>+≡
    type :: process_store_t
        integer :: n = 0
        type(process_entry_t), pointer :: first => null ()
        type(process_entry_t), pointer :: last => null ()
        type(process_p), dimension(:), allocatable :: proc
    end type process_store_t

<Processes: variables>≡
    type(process_store_t), save :: store

```

Finalize. Delete the list explicitly, the pointer array is just deallocated.

```

<Processes: public>+≡
    public :: process_store_final

<Processes: procedures>+≡
    subroutine process_store_final ()
        type(process_entry_t), pointer :: current
        if (allocated (store%proc)) deallocate (store%proc)
        store%last => null ()
        do while (associated (store%first))
            current => store%first
            store%first => current%next
        end do
    end subroutine process_store_final

```

```

        call process_final (current%process)
        deallocate (current)
    end do
    store%n = 0
end subroutine process_store_final

```

Write all contents. This produces lots of output.

```

<Processes: public>+≡
    public :: process_store_write

<Processes: procedures>+≡
    subroutine process_store_write (unit)
        integer, intent(in), optional :: unit
        type(process_t), pointer :: process
        integer :: u, i
        u = output_unit (unit); if (u < 0) return
        write (u, *) repeat (" ", 78)
        write (u, *) "Process store contents"
        do i = 1, store%n
            write (u, *) repeat (" ", 78)
            write (u, *) "Process No.", i
            process => store%proc(i)%ptr
            call process_write (process, unit)
        end do
        write (u, *) "Process store end"
        write (u, *) repeat (" ", 78)
    end subroutine process_store_write

```

Write integration results (summary)

```

<Processes: public>+≡
    public :: process_store_write_results

<Processes: procedures>+≡
    subroutine process_store_write_results (unit)
        integer, intent(in), optional :: unit
        type(process_t), pointer :: process
        type(string_t), dimension(:), allocatable :: process_id
        real(default), dimension(:), allocatable :: integral, error
        type(string_t), dimension(:), allocatable :: phys_unit
        integer :: u, i, process_id_len
        character(12) :: fmt
        u = output_unit (unit); if (u < 0) return
        allocate (process_id (store%n), phys_unit (store%n))
        allocate (integral (store%n), error (store%n))
        do i = 1, store%n
            process => store%proc(i)%ptr
            if (process%initialized) then
                process_id(i) = process%id
                integral(i) = process_get_integral (process)
                error(i) = process_get_error (process)
                select case (process%type)
                    case (PRC_DECAY);      phys_unit(i) = "GeV"
                    case (PRC_SCATTERING);  phys_unit(i) = "fb"
                    case default;            phys_unit(i) = "[undefined]"
                end select
            end if
        end do
    end subroutine process_store_write_results

```

```

        end select
    else
        process_id(i) = ""
    end if
end do
write (u, "(A)")  "|===== Results Summary ====="
if (store%n == 0) then
    write (u, *) "[empty]"
else
    process_id_len = maxval (len (process_id))
    write (fmt, "(A,IO,A)"  "(1x,A", process_id_len + 1, ")")
    do i = 1, store%n
        if (process_id(i) /= "") then
            write (u, fmt, advance="no")  char (process_id(i)) // ":"
            write (u, "(1x, 1PE15.8, 1x, '+-', 1x, 1PE8.2)", advance="no") &
                integral(i), error(i)
            write (u, "(1x, A)"  char (phys_unit(i))
        end if
    end do
end if
write (u, "(A)")  "|=====
end subroutine process_store_write_results

```

Accessing contents

Return the current number of processes.

```

<Processes: procedures>+≡
function process_store_get_n_processes () result (n)
    integer :: n
    n = store%n
end function process_store_get_n_processes

```

Return a pointer to the process entry with given ID. If it does not exist, return a null pointer.

```

<Processes: procedures>+≡
function process_store_get_entry_ptr (process_id) result (entry)
    type(process_entry_t), pointer :: entry
    type(string_t), intent(in) :: process_id
    entry => store%first
    do while (associated (entry))
        if (entry%process%id == process_id) exit
        entry => entry%next
    end do
end function process_store_get_entry_ptr

```

Return the index of the process entry with given ID within the process store. If it does not exist, return zero.

```

<Processes: procedures>+≡
function process_store_get_process_index (process_id) result (process_index)
    integer :: process_index
    type(string_t), intent(in) :: process_id

```

```

    type(process_entry_t), pointer :: entry
    entry => process_store_get_entry_ptr (process_id)
    if (associated (entry)) then
        process_index = entry%process%store_index
    else
        process_index = 0
    end if
end function process_store_get_process_index

```

Return a pointer to the process with index *i* or alphanumeric ID.

```

<Processes: public>+≡
    public :: process_store_get_process_ptr

<Processes: interfaces>+≡
    interface process_store_get_process_ptr
        module procedure process_store_get_process_ptr_int
        module procedure process_store_get_process_ptr_id
    end interface

<Processes: procedures>+≡
    function process_store_get_process_ptr_int (i) result (process)
        type(process_t), pointer :: process
        integer, intent(in) :: i
        if (i > 0 .and. i <= size (store%proc)) then
            process => store%proc(i)%ptr
        else
            process => null ()
        end if
    end function process_store_get_process_ptr_int

    function process_store_get_process_ptr_id (id) result (process)
        type(process_t), pointer :: process
        type(string_t), intent(in) :: id
        integer :: i
        do i = 1, store%n
            process => store%proc(i)%ptr
            if (process%id == id) return
        end do
        process => null ()
    end function process_store_get_process_ptr_id

```

Filling the process store

Append a new process entry and return a pointer to it, unless the process already exists. If the process exists, finalize it and return the pointer for fresh initialization. If it does not exist, allocate a new entry and update the shortcut array. If the latter is full, expand by a fixed block size.

```

<Processes: procedures>+≡
    function process_store_get_fresh_process_ptr (process_id) result (process)
        type(process_t), pointer :: process
        type(string_t), intent(in) :: process_id
        type(process_entry_t), pointer :: current, entry

```

```

integer :: i
integer, parameter :: BLOCK_SIZE = 10
current => process_store_get_entry_ptr (process_id)
if (associated (current)) then
    call process_final (current%process)
else
    allocate (current)
    if (store%n == 0) then
        allocate (store%proc (BLOCK_SIZE))
        store%first => current
    else
        store%last%next => current
    end if
    store%last => current
    store%n = store%n + 1
    if (store%n <= size (store%proc)) then
        store%proc(store%n)%ptr => current%process
    else
        deallocate (store%proc)
        allocate (store%proc (store%n + BLOCK_SIZE))
        i = 1
        entry => store%first
        do while (associated (entry))
            store%proc(i)%ptr => entry%process; i = i + 1
            entry => entry%next
        end do
    end if
end if
process => current%process
end function process_store_get_fresh_process_ptr

```

Append a new process entry (or find an existing one) and initialize it with a particular hard process, model pointer and total energy. Return a pointer to the process object, so further process preparation can be done by the caller. Allocate or expand the array as needed.

<Processes: public>+≡

```
public :: process_store_init_process
```

<Processes: procedures>+≡

```

subroutine process_store_init_process (process, &
    prc_lib, process_id, model, lhpdf_status, var_list, use_beams)
    type(process_t), pointer :: process
    type(process_library_t), intent(in), target :: prc_lib
    type(string_t), intent(in) :: process_id
    type(model_t), intent(in), target :: model
    type(lhpdf_status_t), intent(inout) :: lhpdf_status
    type(var_list_t), intent(in), optional, target :: var_list
    logical, intent(in), optional :: use_beams
    integer :: process_lib_index, process_store_index
    process_lib_index = process_library_get_process_index (prc_lib, process_id)
    if (process_lib_index == 0) then
        call msg_fatal ("Process '" // char (process_id) &
            // "' is not available.")
    end if

```

```

process_store_index = process_store_get_process_index (process_id)
process => process_store_get_fresh_process_ptr (process_id)
if (process_store_index == 0) then
    process_store_index = process_store_get_n_processes ()
end if
call process_init &
    (process, prc_lib, process_lib_index, process_store_index, &
     process_id, model, lhpdf_status, var_list, use_beams)
end subroutine process_store_init_process

```

13.3.19 Sampling function

This is the function that computes the squared matrix element in the form needed for VAMP integration. It computes and multiplies the flux factor for the incoming particles, the phase-space factors of the integration channels combined with the VAMP grid jacobians to a common phase-space factor, the phase-space volume, and the squared matrix element of the hard interaction. The latter is only evaluated if the event passes cuts.

```

(Processes: procedures) +=
function sample_function (xi, prc_index, weights, channel, grids) result (f)
    real(default) :: f
    real(default), dimension(:), intent(in) :: xi
    integer, intent(in) :: prc_index
    real(default), dimension(:), intent(in), optional :: weights
    integer, intent(in), optional :: channel
    type(vamp_grid), dimension(:), intent(in), optional :: grids
    type(process_t), pointer :: process
    logical :: ok
    process => process_get_working_copy_ptr (store%proc(prc_index)%ptr)
    call process_set_kinematics (process, xi, channel, ok)
    if (ok) ok = process_passes_cuts (process)
    if (ok) then
        call process_compute_vamp_phs_factor (process, weights)
        call process_update_alpha_s (process)
        call process_evaluate (process)
        call process_compute_reweighting_factor (process)
        process%sample_function_value = &
            process%flux_factor &
            * process%sf_mapping_factor &
            * process%vamp_phs_factor &
            * process%phs_volume &
            * process%sqme &
            * process%reweighting_factor
    else
        process%sample_function_value = 0
    end if
    f = process%sample_function_value
end function sample_function

```

13.3.20 Test

```

<Processes: public>+=
  public :: process_test

<Processes: procedures>+=
  subroutine process_test ()
    type(os_data_t) :: os_data
    type(process_library_t) :: prc_lib
    type(model_t), pointer :: model
    print *, "*** Load process library"
    call process_library_init (prc_lib, var_str("proc"), os_data)
    call process_library_load (prc_lib, os_data)
    print *
    print *, "*** Read model file"
    call syntax_model_file_init ()
    call model_list_read_model &
      (var_str("QCD"), var_str("test.mdl"), os_data, model)
    call syntax_pexpr_init ()
    call syntax_phs_forest_init ()
    print *
    call process_test1 (prc_lib, model)
    print *
    call process_test2 (prc_lib, model)
    print *
    call process_test3 (prc_lib, model)
    !   print *
    !   call process_test4 (prc_lib, model)
    print *
    print *, "* Cleanup"
    call process_store_final ()
    call syntax_pexpr_final ()
    call syntax_phs_forest_final ()
    call syntax_model_file_final ()
    call process_library_final (prc_lib)
  end subroutine process_test

```

Test decay process: $Z \rightarrow e^+e^-$ (colorless); polarized and unpolarized

```

<Processes: procedures>+=
  subroutine process_test1 (prc_lib, model)
    type(process_library_t), intent(in) :: prc_lib
    type(model_t), intent(in), target :: model
    type(process_t), pointer :: process
    type(lhapdf_status_t) :: lhpdf_status
    type(phs_parameters_t) :: phs_par
    type(mapping_defaults_t) :: mapping_defaults
    type(flavor_t), dimension(1) :: flv
    type(polarization_t), dimension(1) :: pol
    type(beam_data_t) :: beam_data
    type(grid_parameters_t) :: grid_parameters
    type(tao_random_state) :: rng
    integer :: i
    logical :: rebuild_phs = .true.
    logical :: discard_integrals, adapt_grids, adapt_weights, print_current

```

```

print *, "*** Test decay process"
print *
print *, "* Initialization"
call tao_random_create (rng, 0)
call process_store_init_process &
    (process, prc_lib, var_str ("zee"), model, lhpdf_status)
print *, " Process ID = ", char (process%id)
print *
print *, "*** Beam/strfun setup (unpolarized)"
print *
call flavor_init (flv, (/ 23 /), model)
call polarization_init_unpolarized (pol(1), flv(1))
call beam_data_init_decay (beam_data, flv, pol)
call process_setup_beams (process, beam_data, 0, 0)
call process_connect_strfun (process)
print *
print *, "* Phase space setup"
call process_setup_phase_space (process, rebuild_phs, &
    phs_par, mapping_defaults, filename_out=var_str("zee.phs"))
print *
print *, "*** Test integration"
print *, "* Grids setup"
grid_parameters%stratified = .false.
call process_setup_grids (process, grid_parameters, calls=1000)
print *
print *, "* 1 iteration with minimal number of calls"
call process_results_write_header (process)
do i = 1, 1
    discard_integrals = i==1
    adapt_grids = .true.
    adapt_weights = .true.
    print_current = .true.
    call process_integrate (process, rng, grid_parameters, &
        1, 1, 1, 9, &
        discard_integrals, adapt_grids, adapt_weights, print_current)
end do
call process_results_write_footer (process)
print *
print *, "* Process written to 'fort.60'"
call process_write (process, 60)
print *
print *, "*** Beam/strfun setup (polarized)"
call process_store_init_process &
    (process, prc_lib, var_str ("zee"), model, lhpdf_status)
call flavor_init (flv, (/ 23 /), model)
call polarization_init_axis &
    (pol(1), flv(1), (/ 0._default, 0._default, 1._default/))
call beam_data_init_decay (beam_data, flv, pol)
call process_setup_beams (process, beam_data, 0, 0)
call process_connect_strfun (process)
print *
print *, "* Phase space setup"
call process_setup_phase_space (process, rebuild_phs, &
    phs_par, mapping_defaults, filename_out=var_str("zee.phs"))

```

```

print *
print *, "*** Test integration"
print *, "* Grids setup"
grid_parameters%stratified = .false.
call process_setup_grids (process, grid_parameters, calls=1000)
print *
print *, "* 3 + 3 iterations"
call process_results_write_header (process)
do i = 1, 3
  discard_integrals = i==1
  adapt_grids = .true.
  adapt_weights = .true.
  print_current = .true.
  call process_integrate (process, rng, grid_parameters, &
    1, 1, 1, 10000, &
    discard_integrals, adapt_grids, adapt_weights, print_current)
end do
call process_results_write_current_average (process)
call process_integrate (process, rng, grid_parameters, &
  2, 1, 3, 10000, &
  .true., .true., .false., .true.)
call process_results_write_footer (process)
print *
print *, "* Process written to 'fort.61'"
call process_write (process, 61)
end subroutine process_test1

```

Test decay process: $Z \rightarrow qq$ with $q = u, d$.

(Processes: procedures)+≡

```

subroutine process_test2 (prc_lib, model)
  type(process_library_t), intent(in) :: prc_lib
  type(model_t), intent(in), target :: model
  type(lhapdf_status_t) :: lhpdf_status
  type(process_t), pointer :: process
  type(phs_parameters_t) :: phs_par
  type(mapping_defaults_t) :: mapping_defaults
  type(flavor_t), dimension(1) :: flv
  type(polarization_t), dimension(1) :: pol
  type(beam_data_t) :: beam_data
  type(grid_parameters_t) :: grid_parameters
  type(tao_random_state) :: rng
  real(default) :: weight
  integer :: i
  logical :: rebuild_phs = .true.
  logical :: discard_integrals, adapt_grids, adapt_weights, print_current
  print *, "*** Test decay process"
  print *
  print *, "* Initialization"
  call tao_random_create (rng, 0)
  call process_store_init_process &
    (process, prc_lib, var_str ("zqq"), model, lhpdf_status, &
    use_beams=.false.)
  print *, " Process ID = ", char (process%id)
  print *

```

```

print *, "*** Beam/strfun setup (unpolarized)"
print *
call flavor_init (flv, (/ 23 /), model)
call polarization_init_unpolarized (pol(1), flv(1))
call beam_data_init_decay (beam_data, flv, pol)
call process_setup_beams (process, beam_data, 0, 0)
call process_connect_strfun (process)
print *
print *, "* Phase space setup"
call process_setup_phase_space (process, rebuild_phs, &
    phs_par, mapping_defaults, filename_out=var_str("zee.phs"))
print *
print *, "*** Test integration"
print *, "* Grids setup"
grid_parameters%stratified = .false.
call process_setup_grids (process, grid_parameters, calls=1000)
print *
print *, "* 1 iteration with minimal number of calls"
call process_results_write_header (process)
do i = 1, 1
    discard_integrals = i==1
    adapt_grids = .true.
    adapt_weights = .true.
    print_current = .true.
    call process_integrate (process, rng, grid_parameters, &
        1, 1, 1, 9, &
        discard_integrals, adapt_grids, adapt_weights, print_current)
end do
call process_results_write_footer (process)
print *
print *, "* Process written to 'fort.62'"
call process_write (process, 62)
print *
print *, "*** Event generation"
call process_setup_event_generation (process)
print *
print *, "* Generate weighted event"
call process_generate_weighted_event (process, rng, 1, weight)
print *
print *, "* Process written to 'fort.63'"
call process_write (process, 63)
print *, "weight =", weight
print *
print *, "* Generate unweighted event"
call process_generate_unweighted_event (process, rng, weight)
print *
print *, "* Process written to 'fort.64'"
call process_write (process, 64)
print *, "excess weight =", weight
end subroutine process_test2

```

Test scattering process: ee- γ nnh (colorless)

(*Processes: procedures*)+ \equiv

```
subroutine process_test3 (prc_lib, model)
```

```

type(process_library_t), intent(in) :: prc_lib
type(model_t), intent(in), target :: model
type(lhapdf_status_t) :: lhpdf_status
type(process_t), pointer :: process
type(phs_parameters_t) :: phs_par
type(mapping_defaults_t) :: mapping_defaults
type(flavor_t), dimension(2) :: flv
type(polarization_t), dimension(2) :: pol
type(beam_data_t) :: beam_data
type(grid_parameters_t) :: grid_parameters
real(default), dimension(:), allocatable :: x
integer :: channel
logical :: ok
integer :: i
type(tao_random_state) :: rng
logical :: rebuild_phs = .true.
logical :: discard_integrals, adapt_grids, adapt_weights, print_current
print *, "*** Test scattering process"
print *
print *, "* Initialization"
call tao_random_create (rng, 0)
call process_store_init_process &
    (process, prc_lib, var_str ("nnh"), model, lhpdf_status)
print *, " Process ID = ", char (process%id)
print *
print *, "* Beam/strfun setup"
print *
call flavor_init (flv, (/ 11, -11 /), model)
call polarization_init_unpolarized (pol(1), flv(1))
call polarization_init_unpolarized (pol(2), flv(2))
call beam_data_init_sqrts (beam_data, 500._default, flv, pol)
call process_setup_beams (process, beam_data, 0, 0)
call process_connect_strfun (process)
print *
print *, "* Phase space setup"
call process_setup_phase_space (process, rebuild_phs, &
    phs_par, mapping_defaults, filename_out=var_str("nnh.phs"))
print *
print *, "* Kinematics setup"
allocate (x (process_get_n_parameters (process)))
do i = 1, size (x)
    x(i) = (i - 0.5_default) * (1._default / size (x))
end do
channel = 1
call process_set_kinematics (process, x, channel, ok)
print *
print *, "* Process written to 'fort.70'"
call process_write (process, 70)
print *
print *, "*** Test process evaluation"
call process_evaluate (process)
print *
print *, "* Process written to 'fort.71'"
call process_write (process, 71)

```

```

print *
print *, "*** Test integration"
print *, "* Grids setup"
call process_setup_grids (process, grid_parameters, calls=10000)
print *
print *, "* 5 + 3 iterations"
call process_results_write_header (process)
do i = 1, 5
  discard_integrals = i==1
  adapt_grids = .true.
  adapt_weights = .true.
  print_current = .true.
  call process_integrate (process, rng, grid_parameters, &
    1, 1, 1, 10000, &
    discard_integrals, adapt_grids, adapt_weights, print_current)
end do
call process_results_write_current_average (process)
call process_integrate (process, rng, grid_parameters, &
  2, 1, 3, 20000, .true., .false., .false., .true.)
call process_results_write_footer (process)
print *
print *, "* Process written to 'fort.72'"
call process_write (process, 72)
end subroutine process_test3

```

Test scattering process: $gg \rightarrow qq$ with $q = u, d$.

$\langle Processes: procedures \rangle + =$

```

subroutine process_test4 (prc_lib, model)
  type(process_library_t), intent(in) :: prc_lib
  type(model_t), intent(in), target :: model
  type(lhapdf_status_t) :: lhpdf_status
  type(process_t), pointer :: process
  type(phs_parameters_t) :: phs_par
  type(mapping_defaults_t) :: mapping_defaults
  type(flavor_t), dimension(2) :: flv
  type(polarization_t), dimension(2) :: pol
  type(beam_data_t) :: beam_data
  type(lhapdf_data_t), dimension(2) :: data
  type(stream_t) :: stream
  type(parse_tree_t) :: parse_tree
  type(grid_parameters_t) :: grid_parameters
  integer :: i
  type(tao_random_state) :: rng
  logical :: rebuild_phs = .true.
  print *, "*** Test process setup"
  print *
  print *, "* Initialization"
  call tao_random_create (rng, 0)
  call process_store_init_process &
    (process, prc_lib, var_str ("qq"), model, lhpdf_status)
  print *, " Process ID = ", char (process%id)
  print *
  print *, "* Beam/strfun setup"
  print *

```

```

!   call flavor_init (flv, (/ 21, 21 /), model)
   call flavor_init (flv, (/ PROTON, PROTON /), model)
   call polarization_init_unpolarized (pol(1), flv(1))
   call polarization_init_unpolarized (pol(2), flv(2))
   call beam_data_init_sqrts (beam_data, 14000._default, flv, pol)
!   call process_setup_beams (process, beam_data, 0, 0)
   call process_setup_beams (process, beam_data, 2, 0)
   call lhpdf_data_init (data(1), lhpdf_status, model, flv(1))
   call lhpdf_data_init (data(2), lhpdf_status, model, flv(2))
   call process_set_strfun (process, 1, 1, data(1), 1)
   call process_set_strfun (process, 2, 2, data(2), 1)
   call process_connect_strfun (process)
   print *
   print *, "* Phase space setup"
   call process_setup_phase_space (process, rebuild_phs, &
     phs_par, mapping_defaults, filename_out=var_str("qq.phs"))
   print *
   print *, "* Cuts setup"
   call stream_init (stream, var_str ("all Pt > 50 GeV (outgoing u:d:U:D)"))
   call parse_tree_init_lexpr (parse_tree, stream, .true.)
   call process_setup_cuts (process, parse_tree_get_root_ptr (parse_tree))
   call parse_tree_final (parse_tree)
   call stream_final (stream)
   print *
   print *, "* Scale setup"
   call stream_init (stream, var_str ("1 TeV"))
   call parse_tree_init_expr (parse_tree, stream, .true.)
   call process_setup_scale (process, parse_tree_get_root_ptr (parse_tree))
   call parse_tree_final (parse_tree)
   call stream_final (stream)
   print *
   print *, "*** Test integration"
   print *, "* Grids setup"
   call process_setup_grids (process, grid_parameters, calls=10000)
   print *
   print *, "* 15 + 3 iterations"
   call process_results_write_header (process)
   do i = 1, 15
     call process_integrate (process, rng, grid_parameters, &
       1, 1, 1, 50000, i==1, .true., i>2, .true.)
   end do
   call process_results_write_current_average (process)
   call process_integrate (process, rng, grid_parameters, &
     2, 1, 3, 50000, .true., .false., .true., .true.)
   call process_results_write_footer (process)
   print *
   print *, "* Process written to 'fort.90'"
   call process_write (process, 90)
end subroutine process_test4

```

13.4 Decays

Particles can be marked as unstable, so during event generation (cascade) decays are applied to them. For each decay mode, we temporarily use the corresponding process entry in the process store, which is filled and evaluated and connected to the mother process.

```
<decays.f90>≡  
  <File header>  
  
  module decays  
  
    <Use kinds>  
    use kinds, only: double !NODEP!  
    <Use strings>  
    <Use file utils>  
    use diagnostics !NODEP!  
    use lorentz !NODEP!  
    use tao_random_numbers !NODEP!  
    use flavors  
    use quantum_numbers  
    use processes  
    use interactions  
    use evaluators  
  
    <Standard module head>  
  
    <Decays: public>  
  
    <Decays: types>  
  
    <Decays: variables>  
  
    contains  
  
    <Decays: procedures>  
  
  end module decays
```

13.4.1 Decay configuration

We store the decay properties of a particular particle. First, we need an array of process pointers:

```
<Decays: types>≡  
  type :: decay_channel_t  
  private  
    type(process_t), pointer :: process => null ()  
    real(default) :: br = 0  
  end type decay_channel_t
```

Decay configurations are stored in a list:

```
<Decays: public>≡  
  public :: decay_configuration_t
```

```

<Decays: types>+≡
  type :: decay_configuration_t
  private
    type(flavor_t) :: flv
    real(default) :: width = 0
    type(decay_channel_t), dimension(:), allocatable :: channel
    type(string_t), dimension(:), allocatable :: process_id
    type(decay_configuration_t), pointer :: next => null ()
  end type decay_configuration_t

```

Allocate the array for a known number of decay channels.

```

<Decays: procedures>≡
  subroutine decay_configuration_init (conf, flv, width, n_channels)
    type(decay_configuration_t), intent(out) :: conf
    type(flavor_t), intent(in) :: flv
    real(default), intent(in) :: width
    integer, intent(in) :: n_channels
    conf%flv = flv
    conf%width = width
    allocate (conf%channel (n_channels))
    allocate (conf%process_id (n_channels))
  end subroutine decay_configuration_init

```

Set a single decay channel:

```

<Decays: public>+≡
  public :: decay_configuration_set_channel

<Decays: procedures>+≡
  subroutine decay_configuration_set_channel (conf, i, process, br)
    type(decay_configuration_t), intent(inout) :: conf
    integer, intent(in) :: i
    type(process_t), intent(in), target :: process
    real(default), intent(in) :: br
    conf%channel(i)%process => process
    conf%channel(i)%br = br
    conf%process_id(i) = process_get_id (process)
  end subroutine decay_configuration_set_channel

```

Output. Note that either no channel or all channels have to be defined.

```

<Decays: public>+≡
  public :: decay_configuration_write

<Decays: procedures>+≡
  subroutine decay_configuration_write (conf, unit)
    type(decay_configuration_t), intent(in) :: conf
    integer, intent(in), optional :: unit
    character(12) :: fmt
    integer :: n_channels, proc_id_len
    integer :: u, i
    u = output_unit (unit); if (u < 0) return
    write (u, "(A)") "Decay configuration of particle " &
      // char (flavor_get_name (conf%flv)) // ":"
    write (6, *) " Computed total width = ", conf%width, " GeV"

```

```

write (6, *) " Branching ratios:"
n_channels = decay_configuration_get_n_channels (conf)
if (n_channels /= 0) then
  proc_id_len = maxval (len (conf%process_id))
  do i = 1, n_channels
    write (fmt, "(A,I0,A)") "(4x,A", proc_id_len + 1, ")"
    write (6, fmt, advance="no") char (conf%process_id(i)) // ":"
    print *, 100 * conf%channel(i)%br, "%"
  end do
else
  write (6, *) " [undefined]"
end if
end subroutine decay_configuration_write

```

Return the number of decay channels:

```

<Decays: public>+≡
  public :: decay_configuration_get_n_channels

<Decays: procedures>+≡
  function decay_configuration_get_n_channels (conf) result (n)
    integer :: n
    type(decay_configuration_t), intent(in) :: conf
    if (allocated (conf%channel)) then
      n = size (conf%channel)
    else
      n = 0
    end if
  end function decay_configuration_get_n_channels

```

Select a decay channel, using the random-number generator. Return the process pointer. Note that the sum of branching ratios must be unity. (As a fallback, the last channel is selected if the sum of ratios is less than unity.)

```

<Decays: procedures>+≡
  function decay_configuration_select_channel (conf, rng) result (channel)
    integer :: channel
    type(decay_configuration_t), intent(in) :: conf
    type(tao_random_state), intent(inout) :: rng
    real(double) :: x
    real(default) :: x_sum
    call tao_random_number (rng, x)
    x_sum = 0
    do channel = 1, size (conf%channel)
      x_sum = x_sum + conf%channel(channel)%br
      if (x < x_sum) return
    end do
    channel = size (conf%channel)
  end function decay_configuration_select_channel

```

Return a pointer to a specified decay process.

```

<Decays: procedures>+≡
  function decay_configuration_get_process_ptr (conf, channel) &
    result (process)

```

```

    type(process_t), pointer :: process
    type(decay_configuration_t), intent(in) :: conf
    integer, intent(in) :: channel
    process => conf%channel(channel)%process
end function decay_configuration_get_process_ptr

```

13.4.2 List of decay configurations

Similar to the list of active processes (`process_store`), we maintain a list of unstable particles and their decay properties.

```

<Decays: types>+≡
    type :: decay_store_t
    private
    integer :: n = 0
    type(decay_configuration_t), pointer :: first => null ()
    type(decay_configuration_t), pointer :: last => null ()
end type decay_store_t

<Decays: variables>≡
    type(decay_store_t), save :: store

```

Finalize.

```

<Decays: public>+≡
    public :: decay_store_final

<Decays: procedures>+≡
    subroutine decay_store_final ()
    type(decay_configuration_t), pointer :: current
    store%last => null ()
    do while (associated (store%first))
        current => store%first
        store%first => current%next
        deallocate (current)
    end do
    store%n = 0
end subroutine decay_store_final

```

Output.

```

<Decays: public>+≡
    public :: decay_store_write

<Decays: procedures>+≡
    subroutine decay_store_write (unit)
    integer, intent(in), optional :: unit
    type(decay_configuration_t), pointer :: decay
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write (u, "(A)") "Decay configuration for unstable particles:"
    decay => store%first
    do while (associated (decay))
        if (.not. flavor_is_stable (decay%flv)) &

```

```

        call decay_configuration_write (decay, unit)
    decay => decay%next
end do
end subroutine decay_store_write

```

Append a new entry for an unstable particle. If a decay exists already, it is overwritten. Return a pointer to the new decay configuration.

```

<Decays: public>+≡
    public :: decay_store_append_decay
<Decays: procedures>+≡
    subroutine decay_store_append_decay (flv, width, n_channels, decay)
        type(flavor_t), intent(in) :: flv
        real(default), intent(in) :: width
        integer, intent(in) :: n_channels
        type(decay_configuration_t), pointer :: decay
        decay => store%first
        do while (associated (decay))
            if (decay%flv == flv) then
                call decay_configuration_init (decay, flv, width, n_channels)
                return
            end if
            decay => decay%next
        end do
        allocate (decay)
        call decay_configuration_init (decay, flv, width, n_channels)
        if (associated (store%first)) then
            store%last%next => decay
        else
            store%first => decay
        end if
        store%last => decay
    end subroutine decay_store_append_decay

```

Return a pointer to the decay configuration for a particular unstable particle.

```

<Decays: procedures>+≡
    function decay_store_get_decay_configuration_ptr (flv) result (config)
        type(decay_configuration_t), pointer :: config
        type(flavor_t), intent(in) :: flv
        config => store%first
        SCAN_PARTICLES: do while (associated (config))
            if (config%flv == flv) exit SCAN_PARTICLES
            config => config%next
        end do SCAN_PARTICLES
    end function decay_store_get_decay_configuration_ptr

```

13.4.3 Decays

The decay object contains a pointer to the decay process, evaluators that hold the product of production and decay, and a pointer to the next decay node (which holds all possible subsequent decays).

```

<Decays: types>+≡

```

```

type :: decay_t
  private
  logical :: initialized = .false.
  type(process_t), pointer :: process => null ()
  type(evaluator_t) :: eval_sqme
  type(evaluator_t) :: eval_flows
  type(decay_node_t), pointer :: next_node => null ()
end type decay_t

```

Initialize the decay with a certain process, and use this together with the production evaluators to initialize product evaluators.

(Decays: procedures)+≡

```

subroutine decay_init (decay, process, eval_sqme, eval_flows, i)
  type(decay_t), intent(out), target :: decay
  type(process_t), intent(inout), target :: process
  type(evaluator_t), intent(in), target :: eval_sqme, eval_flows
  integer, intent(in) :: i
  type(interaction_t), pointer :: prc_int
  type(evaluator_t), pointer :: prc_eval_sqme, prc_eval_flows
  integer :: n_tot
  logical, dimension(:), allocatable :: ignore_hel
  type(quantum_numbers_mask_t), dimension(:), allocatable :: &
    mask_hel, mask_sqme, mask_flows
  type(quantum_numbers_mask_t) :: mask_conn
  call process_request_copy (process, decay%process)
  prc_int => process_get_hi_int_ptr (decay%process)
  prc_eval_sqme => process_get_hi_eval_sqme_ptr (decay%process)
  prc_eval_flows => process_get_hi_eval_flows_ptr (decay%process)
  n_tot = evaluator_get_n_tot (prc_eval_sqme)
  allocate (ignore_hel (n_tot))
  ignore_hel(1) = .true.
  ignore_hel(2:) = .false.
  allocate (mask_hel (n_tot), mask_sqme (n_tot), mask_flows (n_tot))
  call quantum_numbers_mask_set_helicity (mask_hel, ignore_hel)
  mask_sqme = evaluator_get_mask (prc_eval_sqme) .or. mask_hel
  mask_flows = evaluator_get_mask (prc_eval_flows) .or. mask_hel
  mask_conn = new_quantum_numbers_mask (.false., .false., .true.)
  call evaluator_set_source_link (prc_eval_sqme, 1, eval_sqme, i)
  call evaluator_set_source_link (prc_eval_flows, 1, eval_flows, i)
  call evaluator_init_product (decay%eval_sqme, &
    eval_sqme, prc_eval_sqme, mask_conn, &
    connections_are_resonant=.true.)
  call evaluator_init_product (decay%eval_flows, &
    eval_flows, prc_eval_flows, mask_conn, &
    connections_are_resonant=.true.)
  call evaluator_set_source_link (prc_eval_sqme, 1, prc_int, 1)
  call evaluator_set_source_link (prc_eval_flows, 1, prc_int, 1)
  allocate (decay%next_node)
  decay%initialized = .true.
end subroutine decay_init

```

Finalizer: Delete the evaluators. Do not delete the process copy, just mark it as free.

```

<Decays: procedures>+≡
recursive subroutine decay_final (decay)
  type(decay_t), intent(inout) :: decay
  if (decay%initialized) then
    if (associated (decay%next_node)) &
      call decay_node_final (decay%next_node)
    call process_copy_free (decay%process)
    call evaluator_final (decay%eval_sqme)
    call evaluator_final (decay%eval_flows)
  end if
end subroutine decay_final

```

Output.

```

<Decays: procedures>+≡
subroutine decay_write (decay, unit)
  type(decay_t), intent(in) :: decay
  integer, intent(in), optional :: unit
  integer :: u
  u = output_unit (unit); if (u < 0) return
  write (u, "(A)") repeat ("%", 72)
  write (u, "(A)") "Decay record:"
  write (u, "(A)") repeat ("=", 72)
  write (u, "(A)") "Decay process:"
  call process_write (decay%process, unit)
  write (u, "(A)") repeat ("=", 72)
  write (u, "(A)") "Combined sqme including color factors " &
    // "(process + decay):"
  call evaluator_write (decay%eval_sqme, unit)
  write (u, "(A)") repeat ("=", 72)
  write (u, "(A)") "Combined color flow coefficients " &
    // "(process + decay):"
  call evaluator_write (decay%eval_flows, unit)
end subroutine decay_write

```

Given preconfigured evaluators, generate an event.

TODO: Any excess weight is collected (to avoid VAMP warnings) but not recorded anywhere.

```

<Decays: procedures>+≡
subroutine decay_generate (decay, rng, flv, p)
  type(decay_t), intent(inout) :: decay
  type(tao_random_state), intent(inout) :: rng
  type(flavor_t), intent(in) :: flv
  type(vector4_t), intent(in) :: p
  type(process_t), pointer :: process
  real(default) :: excess
  call process_set_beam_momenta (decay%process, (/ p /))
  call process_generate_unweighted_event (decay%process, rng, excess=excess)
  call evaluator_receive_momenta (decay%eval_sqme)
  call evaluator_receive_momenta (decay%eval_flows)
  call evaluator_evaluate (decay%eval_sqme)
  call evaluator_evaluate (decay%eval_flows)
end subroutine decay_generate

```

13.4.4 Decay trees

A decay tree is created during event generation. Each node holds the possible decays as branches, together with the decay configuration which is used to select a branch for a particular event. Whenever a branch is selected for the first time, it is initialized with the appropriate evaluators, which are then kept for later use.

```

<Decays: types>+≡
    type :: decay_node_t
    private
        type(decay_configuration_t), pointer :: configuration => null ()
        type(decay_t), dimension(:), allocatable :: decay
    end type decay_node_t

```

Initializer:

```

<Decays: procedures>+≡
    subroutine decay_node_init (node, flv)
        type(decay_node_t), intent(out) :: node
        type(flavor_t), intent(in) :: flv
        node%configuration => decay_store_get_decay_configuration_ptr (flv)
        if (associated (node%configuration)) then
            allocate (node%decay &
                (decay_configuration_get_n_channels (node%configuration)))
        else
            call msg_bug ("Particle '" // char (flavor_get_name (flv)) &
                // "': Missing decay configuration")
        end if
    end subroutine decay_node_init

```

Recursive finalizer:

```

<Decays: procedures>+≡
    recursive subroutine decay_node_final (node)
        type(decay_node_t), intent(inout) :: node
        integer :: i
        if (allocated (node%decay)) then
            do i = 1, size (node%decay)
                call decay_final (node%decay(i))
            end do
            deallocate (node%decay)
        end if
    end subroutine decay_node_final

```

The decay tree holds references to the production process as well as pointers to the final evaluators.

```

<Decays: public>+≡
    public :: decay_tree_t

<Decays: types>+≡
    type :: decay_tree_t
    private
        type(process_t), pointer :: hard_process => null ()
        type(evaluator_t), pointer :: eval_sqme_in => null ()

```

```

    type(evaluator_t), pointer :: eval_flows_in => null ()
    type(decay_node_t), pointer :: root => null ()
    type(evaluator_t), pointer :: eval_sqme => null ()
    type(decay_node_t), pointer :: eval_flows => null ()
end type decay_tree_t

```

Initialize the decay tree with a particular process and allocate the root node.

```

<Decays: public>+≡
    public :: decay_tree_init

<Decays: procedures>+≡
    subroutine decay_tree_init (decay_tree, process)
        type(decay_tree_t), intent(out) :: decay_tree
        type(process_t), intent(in), target :: process
        decay_tree%hard_process => process
        decay_tree%eval_sqme_in => process_get_eval_sqme_ptr (process)
        decay_tree%eval_flows_in => process_get_eval_flows_ptr (process)
        allocate (decay_tree%root)
    end subroutine decay_tree_init

```

```

<Decays: public>+≡
    public :: decay_tree_final

<Decays: procedures>+≡
    subroutine decay_tree_final (decay_tree)
        type(decay_tree_t), intent(inout) :: decay_tree
        if (associated (decay_tree%root)) then
            call decay_node_final (decay_tree%root)
            deallocate (decay_tree%root)
        end if
    end subroutine decay_tree_final

```

Generate a decay chain; construct the decay tree as far as necessary, otherwise reuse it.

```

<Decays: public>+≡
    public :: decay_tree_generate_event

<Decays: procedures>+≡
    subroutine decay_tree_generate_event (decay_tree, rng)
        type(decay_tree_t), intent(inout) :: decay_tree
        type(tao_random_state), intent(inout) :: rng
        decay_tree%eval_sqme => decay_tree%eval_sqme_in
        decay_tree%eval_flows => decay_tree%eval_flows_in
        call decay_node_generate_event (decay_tree%root)
    contains
        recursive subroutine decay_node_generate_event (node)
            type(decay_node_t), intent(inout), target :: node
            type(flavor_t) :: flv
            type(vector4_t) :: p
            integer :: i, channel
            type(process_t), pointer :: process
            call evaluator_get_unstable_particle (decay_tree%eval_sqme, flv, p, i)
            if (flavor_is_defined (flv)) then
                if (.not. associated (node%configuration)) &

```

```

        call decay_node_init (node, flv)
        channel = decay_configuration_select_channel (node%configuration, rng)
        if (.not. node%decay(channel)%initialized) then
            process => decay_configuration_get_process_ptr &
                (node%configuration, channel)
            call decay_init (node%decay(channel), &
                process, decay_tree%eval_sqme, decay_tree%eval_flows, i)
        end if
        call decay_generate (node%decay(channel), rng, flv, p)
        decay_tree%eval_sqme => node%decay(channel)%eval_sqme
        decay_tree%eval_flows => node%decay(channel)%eval_flows
        call decay_node_generate_event (node%decay(channel)%next_node)
    end if
end subroutine decay_node_generate_event
end subroutine decay_tree_generate_event

```

Return pointers to the final evaluators:

```

<Decays: public>+≡
    public :: decay_tree_get_eval_sqme_ptr
    public :: decay_tree_get_eval_flows_ptr

<Decays: procedures>+≡
    function decay_tree_get_eval_sqme_ptr (decay_tree) result (eval)
        type(evaluator_t), pointer :: eval
        type(decay_tree_t), intent(in), target :: decay_tree
        eval => decay_tree%eval_sqme
    end function decay_tree_get_eval_sqme_ptr

    function decay_tree_get_eval_flows_ptr (decay_tree) result (eval)
        type(evaluator_t), pointer :: eval
        type(decay_tree_t), intent(in), target :: decay_tree
        eval => decay_tree%eval_flows
    end function decay_tree_get_eval_flows_ptr

```

13.5 Events

The event record becomes relevant only after cross sections have been integrated. It gets filled by some signal process (including beam/structure functions) if an event has been successfully generated (passing rejection).

If requested, particles in the event are subject to decay and/or showering. This is not implemented yet.

```

<events.f90>≡
<File header>

module events

<Use kinds>
    use kinds, only: double !NODEP!
<Use strings>
    use limits, only: RAW_EVENT_FILE_VERSION !NODEP!
<Use file utils>

```

```

use diagnostics !NODEP!
use tao_random_numbers !NODEP!
use os_interface
use lexers
use parser
use expressions
use models
use flavors
use state_matrices
use polarizations
use les_houches_events
use hepmc_interface
use particles
use interactions
use evaluators
use process_libraries
use beams
use sf_lhapdf
use mappings
use phs_forests
use cascades
use processes
use decays

```

⟨Standard module head⟩

⟨Events: public⟩

⟨Events: types⟩

contains

⟨Events: procedures⟩

end module events

13.5.1 The event type

⟨Events: public⟩≡

```
public :: event_t
```

⟨Events: types⟩≡

```

type :: event_t
  type(process_t), pointer :: process => null ()
  logical :: particle_set_exists = .false.
  type(particle_set_t) :: particle_set
  real(default) :: weight = 0
  real(default) :: excess = 0
end type event_t

```

The event record is initialized with a pointer to a specific “signal” process. The particle set is not (yet) initialized, this is done for each event.

⟨Events: public⟩+≡

```
public :: event_init
```

```

<Events: procedures>+=
  subroutine event_init (event, process)
    type(event_t), intent(out) :: event
    type(process_t), intent(in), target :: process
    event%process => process
  end subroutine event_init

```

Finalize the event: delete the particle set.

```

<Events: public>+=
  public :: event_final

<Events: procedures>+=
  subroutine event_final (event)
    type(event_t), intent(inout) :: event
    call particle_set_final (event%particle_set)
  end subroutine event_final

```

Output: Only the particle set is printed explicitly, unless verbose format is selected.

```

<Events: public>+=
  public :: event_write

<Events: procedures>+=
  subroutine event_write (event, unit, verbose)
    type(event_t), intent(in) :: event
    integer, intent(in), optional :: unit
    logical, intent(in), optional :: verbose
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write (u, *) repeat ("=", 72)
    write (u, *) "Event record:"
    if (associated (event%process)) then
      if (present (verbose)) then
        if (verbose) then
          call process_write (event%process, unit)
          write (u, *)
        end if
      end if
    else
      write (u, *) " [empty]"
    end if
    write (u, *) repeat ("=", 72)
    write (u, *) " [Process: ", char (process_get_id (event%process)), "]"
    write (u, *)
    call particle_set_write (event%particle_set, unit)
    write (u, *)
    write (u, *) "Event weight =", event%weight
    write (u, *) "Excess weight =", event%excess
    write (u, *) repeat ("=", 72)
  end subroutine event_write

```

13.5.2 Event generation

Generate a new event and transfer the resulting data to the event record.

(Events: public)+≡

```
public :: event_generate_weighted
public :: event_generate_unweighted
```

(Events: procedures)+≡

```
subroutine event_generate_weighted (event, decay_tree, rng, &
    factorization_mode, keep_correlations, keep_virtual)
    type(event_t), intent(inout), target :: event
    type(decay_tree_t), intent(inout), target :: decay_tree
    type(tao_random_state), intent(inout) :: rng
    integer, intent(in) :: factorization_mode
    logical, intent(in) :: keep_correlations, keep_virtual
    integer :: channel
    real(double) :: r
    call event_discard_particle_set (event)
    call tao_random_number (rng, r)
    channel = 1 + r * process_get_n_channels (event%process)
    call process_generate_weighted_event &
        (event%process, rng, channel, event%weight)
    ! call decay_tree_generate_event (decay_tree, rng)
    call event_factorize_process (event, decay_tree, rng, &
        factorization_mode, keep_correlations, keep_virtual)
end subroutine event_generate_weighted

subroutine event_generate_unweighted (event, decay_tree, rng, &
    factorization_mode, keep_correlations, keep_virtual)
    type(event_t), intent(inout), target :: event
    type(decay_tree_t), intent(inout), target :: decay_tree
    type(tao_random_state), intent(inout) :: rng
    integer, intent(in) :: factorization_mode
    logical, intent(in) :: keep_correlations, keep_virtual
    call event_discard_particle_set (event)
    call process_generate_unweighted_event (event%process, rng, event%excess)
    event%weight = 1
    call decay_tree_generate_event (decay_tree, rng)
    call event_factorize_process (event, decay_tree, rng, &
        factorization_mode, keep_correlations, keep_virtual)
end subroutine event_generate_unweighted
```

Transfer event data from the process record (if a decay has happened: the decay chain) to the event record, factorizing the correlated quantum-number state. We use both the colorless and the colored evaluators to determine the particle set. The factorization of the correlated state is done in one of three modes (unpolarized, definite helicity, generic one-particle density matrices); optionally, the fully correlated density matrix can also be transferred to the particle set.

(Events: procedures)+≡

```
subroutine event_factorize_process (event, decay_tree, rng, &
    factorization_mode, keep_correlations, keep_virtual)
    type(event_t), intent(inout), target :: event
    type(decay_tree_t), intent(in), target :: decay_tree
    type(tao_random_state), intent(inout) :: rng
```

```

integer, intent(in) :: factorization_mode
logical, intent(in) :: keep_correlations, keep_virtual
type(interaction_t), pointer :: int_sqme, int_flows
real(double), dimension(2) :: r
int_sqme => evaluator_get_int_ptr &
    (decay_tree_get_eval_sqme_ptr (decay_tree))
int_flows => evaluator_get_int_ptr &
    (decay_tree_get_eval_flows_ptr (decay_tree))
call tao_random_number (rng, r)
if (interaction_get_n_in (int_sqme) /= 0) then
    call particle_set_init (event%particle_set, &
        int_sqme, int_flows, factorization_mode, r, &
        keep_correlations, keep_virtual)
else
    call particle_set_init (event%particle_set, &
        int_sqme, int_flows, factorization_mode, r, &
        keep_correlations, keep_virtual, &
        n_incoming = process_get_n_in (event%process))
end if
event%particle_set_exists = .true.
end subroutine event_factorize_process

```

Analyze an event (only if the event has been created by other means than ordinary event generation). The analysis results are stored as side-effect operations.

(Events: public)+≡

```
public :: event_do_analysis
```

(Events: procedures)+≡

```

subroutine event_do_analysis (event)
    type(event_t), intent(inout), target :: event
    if (associated (event%process)) then
        call process_do_analysis (event%process)
    end if
end subroutine event_do_analysis

```

Delete any previous contents of the particle set.

(Events: procedures)+≡

```

subroutine event_discard_particle_set (event)
    type(event_t), intent(inout), target :: event
    if (event%particle_set_exists) then
        call particle_set_final (event%particle_set)
        event%particle_set_exists = .false.
    end if
end subroutine event_discard_particle_set

```

13.5.3 Binary I/O

Read/write the particle set including the associated state matrix from/to an unformatted file. This can be used to re-read events generated in a previous run.

(Limits: public parameters)+≡

```
integer, parameter, public :: RAW_EVENT_FILE_VERSION = 1
```

```

<Events: public>+≡
    public :: raw_event_file_write_header
    public :: raw_event_file_read_header

<Events: procedures>+≡
    subroutine raw_event_file_write_header (unit, &
        md5sum_process, md5sum_parameters, md5sum_results)
        integer, intent(in) :: unit
        character(32), dimension(:), intent(in) :: md5sum_process
        character(32), dimension(:), intent(in) :: md5sum_parameters
        character(32), dimension(:), intent(in) :: md5sum_results
        write (unit) RAW_EVENT_FILE_VERSION
        write (unit) size (md5sum_process)
        write (unit) md5sum_process
        write (unit) md5sum_parameters
        write (unit) md5sum_results
    end subroutine raw_event_file_write_header

    subroutine raw_event_file_read_header (unit, &
        md5sum_process, md5sum_parameters, md5sum_results, &
        ok, iostat)
        integer, intent(in) :: unit
        character(32), dimension(:), intent(in) :: md5sum_process
        character(32), dimension(:), intent(in) :: md5sum_parameters
        character(32), dimension(:), intent(in) :: md5sum_results
        logical, intent(out) :: ok
        integer, intent(out), optional :: iostat
        integer :: version, n
        character(32), dimension(:), allocatable :: md5sum_array
        ok = .false.
        read (unit, iostat=iostat) version
        if (version /= RAW_EVENT_FILE_VERSION) then
            call msg_message &
                ("Event-file format version has changed, discarding old event file")
            return
        end if
        read (unit, iostat=iostat) n
        if (n /= size (md5sum_process)) then
            call msg_message &
                ("Process number has changed, discarding old event file")
            return
        end if
        allocate (md5sum_array (n))
        read (unit, iostat=iostat) md5sum_array
        if (any (md5sum_process /= md5sum_array)) then
            call msg_message &
                ("Process configuration has changed, discarding old event file")
            return
        end if
        read (unit, iostat=iostat) md5sum_array
        if (any (md5sum_parameters /= md5sum_array)) then
            call msg_message &
                ("Model parameters have changed, discarding old event file")
            return
        end if

```

```

    read (unit, iostat=iostat) md5sum_array
    if (any (md5sum_results /= md5sum_array)) then
        call msg_message &
            ("Integration results have changed, skipping event file")
        return
    end if
    ok = .true.
end subroutine raw_event_file_read_header

```

<Events: public>+≡

```

    public :: event_write_raw
    public :: event_read_raw

```

<Events: procedures>+≡

```

subroutine event_write_raw (event, unit)
    type(event_t), intent(in) :: event
    integer, intent(in) :: unit
    if (associated (event%process)) then
        write (unit) process_get_store_index (event%process)
        write (unit) process_get_scale (event%process)
        write (unit) process_get_alpha_s (event%process)
        write (unit) process_get_sqme (event%process)
    else
        write (unit) 0
        write (unit) 0._default
        write (unit) 0._default
        write (unit) 0._default
    end if
    call particle_set_write_raw (event%particle_set, unit)
    write (unit) event%weight, event%excess
end subroutine event_write_raw

subroutine event_read_raw (event, unit, iostat)
    type(event_t), intent(out) :: event
    integer, intent(in) :: unit
    integer, intent(out), optional :: iostat
    integer :: index
    real(default) :: scale, alpha_s, sqme
    read (unit, iostat=iostat) index
    if (iostat /= 0) return
    read (unit, iostat=iostat) scale
    read (unit, iostat=iostat) alpha_s
    read (unit, iostat=iostat) sqme
    event%process => process_store_get_process_ptr (index)
    call particle_set_read_raw (event%particle_set, unit, iostat=iostat)
    event%particle_set_exists = .true.
    if (associated (event%process)) then
        call process_set_particles (event%process, event%particle_set)
        call process_set_scale (event%process, scale)
        call process_set_alpha_s (event%process, alpha_s)
        call process_set_sqme (event%process, sqme)
    end if
    read (unit, iostat=iostat) event%weight, event%excess
end subroutine event_read_raw

```

13.5.4 HepMC interface

Read/write the particle set from/to a HepMC event record. This accesses only the particle set; process data are not modified.

The polarization mode must be known when reading from HepMC because the HepMC event record does not specify it.

```
<Events: public>+≡
  public :: event_read_from_hepmc
  public :: event_write_to_hepmc

<Events: procedures>+≡
  subroutine event_read_from_hepmc (event, hepmc_event, polarization_mode)
    type(event_t), intent(inout) :: event
    type(hepmc_event_t), intent(in) :: hepmc_event
    integer, intent(in) :: polarization_mode
    call event_discard_particle_set (event)
    call particle_set_init (event%particle_set, hepmc_event, &
      process_get_model_ptr (event%process), polarization_mode)
    event%particle_set_exists = .true.
  end subroutine event_read_from_hepmc

  subroutine event_write_to_hepmc (event, hepmc_event)
    type(event_t), intent(in) :: event
    type(hepmc_event_t), intent(inout) :: hepmc_event
    call particle_set_fill_hepmc_event (event%particle_set, hepmc_event)
  end subroutine event_write_to_hepmc
```

13.5.5 LHEF interface

Fill the HEPEUP (event) common block:

```
<Events: public>+≡
  public :: event_write_to_hepeup

<Events: procedures>+≡
  subroutine event_write_to_hepeup (event)
    type(event_t), intent(in) :: event
    integer :: proc_id
    real(default) :: scale, alpha_qcd
    call particle_set_fill_hepeup (event%particle_set)
    if (associated (event%process)) then
      proc_id = process_get_store_index (event%process)
      call hepeup_set_event_parameters (proc_id = proc_id)
      scale = process_get_scale (event%process)
      if (scale /= 0) call hepeup_set_event_parameters (scale = scale)
      alpha_qcd = process_get_alpha_s (event%process)
      if (alpha_qcd /= 0) &
        call hepeup_set_event_parameters (alpha_qcd = alpha_qcd)
    end if
  end subroutine event_write_to_hepeup
```

13.5.6 Test

<Events: public>+≡

public :: event_test

<Events: procedures>+≡

```
subroutine event_test ()
  type(os_data_t) :: os_data
  type(process_library_t) :: prc_lib
  type(event_t), target :: event
  type(model_t), pointer :: model
  print *, "*** Read model file"
  call syntax_model_file_init ()
  call model_list_read_model &
    (var_str("QCD"), var_str("test.mdl"), os_data, model)
  call syntax_pexpr_init ()
  call syntax_phs_forest_init ()
  print *
  print *, "*** Load process library"
  call process_library_init (prc_lib, var_str("proc"), os_data)
  call process_library_load (prc_lib, os_data)
  print *
  call event_test1 (prc_lib, model)
  print *
  print *, "* Cleanup"
  call event_final (event)
  call process_store_final ()
  call syntax_pexpr_final ()
  call syntax_phs_forest_final ()
  call syntax_model_file_final ()
end subroutine event_test
```

<Events: procedures>+≡

```
subroutine event_test1 (prc_lib, model)
  type(process_library_t), intent(in) :: prc_lib
  type(model_t), intent(in), target :: model
  type(lhapdf_status_t) :: lhpdf_status
  type(process_t), pointer :: process
  type(phs_parameters_t) :: phs_par
  type(mapping_defaults_t) :: mapping_defaults
  type(flavor_t), dimension(2) :: flv
  type(polarization_t), dimension(2) :: pol
  type(beam_data_t) :: beam_data
  type(stream_t) :: stream
  type(parse_tree_t) :: parse_tree
  type(grid_parameters_t) :: grid_parameters
  integer :: i
  type(tao_random_state) :: rng
  type(event_t), target :: event
  type(decay_tree_t), target :: decay_tree
  logical :: rebuild_phs = .true.
  print *, "*** Test process setup"
  print *
  print *, "* Initialization"
  call tao_random_create (rng, 0)
```

```

call process_store_init_process &
  (process, prc_lib, var_str ("qq"), model, lhpdf_status)
print *, " Process ID = ", char (process_get_id (process))
print *
print *, "* Beam setup"
print *
call flavor_init (flv, (/ 21, 21 /), model)
call polarization_init_unpolarized (pol(1), flv(1))
call polarization_init_unpolarized (pol(2), flv(2))
call beam_data_init_sqrts (beam_data, 1000._default, flv, pol)
call process_setup_beams (process, beam_data, 0, 0)
call process_connect_strfun (process)
print *
print *, "* Phase space setup"
call process_setup_phase_space (process, rebuild_phs, &
  phs_par, mapping_defaults, filename_out=var_str("qq.phs"))
print *
print *, "* Cuts setup"
call stream_init (stream, var_str ("all Pt > 200 GeV (outgoing u:d:U:D)"))
call parse_tree_init_lexpr (parse_tree, stream, .true.)
call process_setup_cuts (process, parse_tree_get_root_ptr (parse_tree))
call parse_tree_final (parse_tree)
call stream_final (stream)
print *
print *, "*** Integration"
print *, "* Grids setup"
call process_setup_grids (process, grid_parameters, calls=10000)
print *
print *, "* 5 + 3 iterations"
call process_results_write_header (process)
do i = 1, 5
  call process_integrate (process, rng, grid_parameters, &
    1, 1, 1, 5000, i==1, .true., i>2, .true.)
end do
call process_results_write_current_average (process)
call process_integrate (process, rng, grid_parameters, &
  2, 1, 3, 5000, .true., .false., .true., .true.)
call process_results_write_footer (process)
print *
print *, "*** Event generation"
call process_setup_event_generation (process)
call event_init (event, process)
call decay_tree_init (decay_tree, process)
print *
print *, "* Weighted event"
call event_generate_weighted &
  (event, decay_tree, rng, FM_IGNORE_HELICITY, .false., .false.)
call event_write (event)
print *
print *, "* Unweighted event"
call event_generate_unweighted &
  (event, decay_tree, rng, FM_SELECT_HELICITY, .false., .true.)
call event_write (event)
print *, " Process data written to fort.81"

```

```
    call process_write (process, 81)
    call event_final (event)
end subroutine event_test1
```

Chapter 14

External modules

The modules in this chapter provide the interface to external libraries which have to be linked to the main program. If the libraries are not present, there are replacement modules which provide dummy functions without the external calls.

These modules have not (yet) been reactivated in the WHIZARD2 context. They need revision or should be deleted.

stdhep Interface to the STDHEP library for portable I/O of binary event data.

pdflib Interface to the PDFLIB library of parton distribution functions.

jetset Interface to the PYTHIA and JETSET libraries used for background event generation, fragmentation and hadronization.

hepevt Provides the HEPEVT common block definition and a routine to fill this block, which is accessed by external libraries including PYTHIA/JETSET

14.1 STDHEP interface

The first module is needed if the STDHEP library cannot be linked, in order to provide dummy routines. The second module contains calls to the actual stdhep routines.

```
<stdhep_dummy.f90>≡  
<File header>  
  
module stdhep_interface  
  
    use kinds, only: i64 !NODEP!  
    use diagnostics !NODEP!  
  
<Standard module head>  
  
    public :: stdhep_init, stdhep_write, stdhep_end  
  
    integer, parameter, public :: &  
        STDHEP_HEPEVT = 1, STDHEP_HEPEUP = 11, STDHEP_HEPRUP = 12
```

contains

```
subroutine stdhep_init (file, title, nevt)
  character(len=*), intent(in) :: file, title
  integer(i64), intent(in) :: nevt
  call msg_error (" STDHEP output is not available.")
  call msg_message (" To enable STDHEP, rerun configure and recompile WHIZARD.")
end subroutine stdhep_init
```

```
subroutine stdhep_write (dummy)
  integer, intent(in) :: dummy
end subroutine stdhep_write
```

```
subroutine stdhep_end
end subroutine stdhep_end
```

end module stdhep_interface

The number of expected events is not really important. It is a 32-bit number, so if the actual number gets larger, insert the maximal possible 32-bit number.

When writing events, the flag `ilbl` determines the common block to write: 1 for HEPEVT, 11 for HEPEUP, 12 for HEPRUP

(stdhep_interface.f90)≡
 File header

module stdhep_interface

```
use kinds, only: i32, i64 !NODEP!
```

Standard module head

```
public :: stdhep_init, stdhep_write, stdhep_end
```

```
integer, parameter, public :: &
  STDHEP_HEPEVT = 1, STDHEP_HEPEUP = 11, STDHEP_HEPRUP = 12
```

```
integer, save :: istr, lok
```

contains

```
subroutine stdhep_init (file, title, nevt)
  character(len=*), intent(in) :: file, title
  integer(i64), intent(in) :: nevt
  integer(i32) :: nevt32
  external stdxwinit, stdxwrt

  nevt32 = min (nevt, int (huge (1_i32), i64))
  call stdxwinit (file, title, nevt32, istr, lok)
  call stdxwrt (100, istr, lok)
end subroutine stdhep_init
```

```
subroutine stdhep_write (ilbl)
  integer, intent(in) :: ilbl
```

```

        external stdxwrt
        call stdxwrt (ilbl, istr, lok)
    end subroutine stdhep_write

    subroutine stdhep_end
        external stdxend
        call stdxend (istr)
    end subroutine stdhep_end

end module stdhep_interface

```

14.2 PDFLIB interface

The first module is needed if the PDFLIB cannot be linked, in order to provide dummy routines. The second module contains calls to the actual pdflib routines. Note that the PDF structure functions will be taken from the USER module if the parameter PDF_ngroup is negative.

<pdflib_dummy.f90>≡
<File header>

```

module pdflib_interface

<Use kinds>
    use diagnostics !NODEP!
    use kinds, only: double !NODEP!
    use user, only: PDF_user_init => PDF_init
    use user, only: PDF_user_strfun_array => PDF_strfun_array

<Standard module head>

    public :: pdflib_init, pdflib_strfun_array

    integer, parameter :: TQUARK = 6
    integer, parameter :: PROTON = 2212, ANTIPROTON = -PROTON, PHOTON = 22

    logical, save :: pdf_invert = .false.
    logical, save :: pdf_user = .false.

contains

    subroutine pdflib_init &
        & (pdg_code_in, ngroup, nset, nfl, lo, QCDL4, top_mass, first)
        integer, intent(in) :: pdg_code_in, ngroup, nset, nfl, lo
        real(default), intent(in) :: QCDL4, top_mass
        logical, intent(in), optional :: first
        integer :: nptype
        select case (pdg_code_in)
        case (PROTON)
            nptype = 1
            pdf_invert = .false.
        case (ANTIPROTON)
            nptype = 1

```

```

        pdf_invert = .true.
    case (PHOTON)
        nptype = 3
        pdf_invert = .false.
    case default
        call msg_fatal &
            & (" PDFlib called for beam different from (anti)proton or photon")
    end select
    if (ngroup < 0) then
        pdf_user = .true.
        call PDF_user_init &
            & (pdg_code_in, abs(ngroup), nset, nfl, lo, &
            & real(QCDL4,kind=double), real(top_mass,kind=double))
    else
        pdf_user = .false.
        call msg_fatal &
            & (" PDF library not linked.  No standard structure functions available.")
    end if
end subroutine pdflib_init

subroutine pdflib_strfun_array (x, scale, rho)
    real(default), intent(in) :: x, scale
    real(default), dimension(-TQUARK:TQUARK), intent(out) :: rho
    real(kind=double), dimension(-TQUARK:TQUARK) :: dxpdf
    real(kind=double) :: xd
    xd = min (max (real (x, kind=double), tiny(xd)), 1.0_double - epsilon(xd))
    if (pdf_user) then
        call PDF_user_strfun_array &
            & (real(x,kind=double), real(scale,kind=double), dxpdf)
    else
        dxpdf = 0
    end if
    if (.not.pdf_invert) then
        rho = dxpdf / xd
    else
        rho = dxpdf(TQUARK:-TQUARK:-1) / xd
    end if
end subroutine pdflib_strfun_array

end module pdflib_interface

```

The incoming particle code may be negative (antiproton), in case which the codes of the quarks are inverted. This is stored in a module variable. The group and set indices may be zero, in which case they are not transferred. The library will then take the default values.

<Limits: public parameters>+≡

<pdflib_interface.f90>≡
<File header>

```

module pdflib_interface

<Use kinds>
    use kinds, only: double !NODEP!

```

```

use diagnostics !NODEP!
use user, only: PDF_user_init => PDF_init
use user, only: PDF_user_strfun_array => PDF_strfun_array

<Standard module head>

public :: pdflib_init, pdflib_strfun_array

integer, parameter :: TQUARK = 6, GLUON1 = 9, GLUON2 = 21
integer, parameter :: PROTON = 2212, ANTIPROTON = -PROTON, PHOTON = 22

integer, parameter, public :: PDFSET_ARRAY_SIZE = 20
integer, parameter, public :: PDFSET_CHAR_LEN = 20

logical, save :: pdf_invert = .false.
logical, save :: pdf_user = .false.

contains

subroutine pdflib_init &
    & (pdg_code_in, ngroup, nset, nfl, lo, QCDL4, top_mass, first)
    integer, intent(in) :: pdg_code_in, ngroup, nset, nfl, lo
    real(default), intent(in) :: QCDL4, top_mass
    logical, intent(in), optional :: first
    integer :: nptype, i
    character (len=PDFSET_CHAR_LEN), dimension(PDFSET_ARRAY_SIZE) :: parm
    real(kind=double), dimension(PDFSET_ARRAY_SIZE) :: value
    real(kind=double), parameter :: x_dummy = 0.5_double
    real(kind=double), parameter :: scale_dummy = 100._double
    real(kind=double), dimension(-TQUARK:TQUARK) :: dxpdf_dummy
    external pdfset, pftopdg
    select case (pdg_code_in)
    case (PROTON)
        nptype = 1
        pdf_invert = .false.
    case (ANTIPROTON)
        nptype = 1
        pdf_invert = .true.
    case (PHOTON)
        nptype = 3
        pdf_invert = .false.
    case default
        call msg_fatal &
            & (" PDFlib called for beam different from (anti)proton or photon")
    end select
    if (ngroup < 0) then
        pdf_user = .true.
        call PDF_user_init &
            & (pdg_code_in, abs(ngroup), nset, nfl, lo, &
            & real(QCDL4,kind=double), real(top_mass,kind=double))
    else
        pdf_user = .false.
        parm = " "
        value = 0
    end if
end subroutine pdflib_init

```

```

i = 1
if (nptype > 0) then
  parm (i) = "NPTYPE"; value(i) = nptype; i = i+1
end if
if (ngroup > 0) then
  parm (i) = "NGROUP"; value(i) = ngroup; i = i+1
end if
if (nset > 0) then
  parm (i) = "NSET"; value(i) = nset; i = i+1
end if
if (nfl > 0) then
  parm (i) = "NFL"; value(i) = nfl; i = i+1
end if
if (lo > 0) then
  parm (i) = "LO"; value(i) = lo; i = i+1
end if
if (QCDL4 > 0) then
  parm (i) = "QCDL4"; value(i) = QCDL4; i = i+1
end if
if (top_mass > 0) then
  parm (i) = "TMAS"; value(i) = top_mass; i = i+1
end if
call pdfset (parm, value)
if (present(first)) then
  if (first) call pftopdg (x_dummy, scale_dummy, dxpdf_dummy)
end if
end if
end subroutine pdfplib_init

subroutine pdfplib_strfun_array (x, scale, rho)
  real(default), intent(in) :: x, scale
  real(default), dimension(-TQUARK:TQUARK), intent(out) :: rho
  real(kind=double), dimension(-TQUARK:TQUARK) :: dxpdf
  external pftopdg
  if (pdf_user) then
    call PDF_user_strfun_array &
      & (real(x,kind=double), real(scale,kind=double), dxpdf)
  else
    call pftopdg (real(x,kind=double), real(scale,kind=double), dxpdf)
  end if
  if (.not.pdf_invert) then
    rho = dxpdf / x
  else
    rho = dxpdf(TQUARK:-TQUARK:-1) / x
  end if
end subroutine pdfplib_strfun_array

end module pdfplib_interface

```

14.2.1 PDFLIB replacement routines

These routines are there and have to be compiled into a separate library because they may be called by PYTHIA even if PDFLIB is absent, and the dummy

replacements may not be compiled into the PYTHIA library. The code is taken from PYTHIA, but simplified.

```

<pdfset_dummy.f90>≡
! PDFSET dummy routine, to be removed when PDFLIB is to be linked.
subroutine pdfset (parm,value)
  implicit double precision(a-h, o-z)
  implicit integer(i-n)
  character*20 parm(20)
  double precision value(20)
  stop " Can't happen: PDFSET dummy routine called"
end

<structp_dummy.f90>≡
! STRUCTP dummy routine, to be removed when PDFLIB is to be linked.
subroutine structp (xx,qq2,p2,ip2,upv,dnv,usea,dsea,str,chm,bot,top,glu)
  implicit double precision(a-h, o-z)
  implicit integer(i-n)
  stop " Can't happen: STRUCTP dummy routine called"
end subroutine structp

<structm_dummy.f90>≡
! STRUCTM dummy routine, to be removed when PDFLIB is to be linked.
subroutine structm (xx,qq,upv,dnv,usea,dsea,str,chm,bot,top,glu)
  implicit double precision(a-h, o-z)
  implicit integer(i-n)
  stop " Can't happen: STRUCTM dummy routine called"
end subroutine structm

```

14.3 PYTHIA interface

The first module is a replacement if PYTHIA is not available. The second one is the actual implementation in the pre-6.2 version. The third module implements the new Les Houches user process standard, supported from PYTHIA6.2 on. Calling the first two versions JETSET makes the distinction easier, although it is not quite appropriate.

14.3.1 Dummy module

```

<jetset_dummy.f90>≡
<File header>

module jetset_interface

  <Use kinds>
  use kinds, only: double !NODEP!
  use diagnostics !NODEP!
  use limits, only: BUFFER_SIZE, PYTHIA_PARAMETERS_LEN !NODEP!

  <Standard module head>

  <Jetset interface: public parameters>

  <Jetset interface: public types>

```

```

<Jetset interface: public routines>

<Jetset interface: module variables (dummy case)>

contains

<Jetset interface: dummy routines>

end module jetset_interface

```

14.3.2 The old interface

There is one routine PYUPEV which must be visible from PYTHIA, so we cannot enclose it in the module.

```

<jetset_interface.f90>≡
<File header>

module jetset_interface

<Use kinds>
  use kinds, only: double !NODEP!
  use file_utils, only: free_unit !NODEP!
  use diagnostics !NODEP!
  use limits, only: PYTHIA_EXTERNAL_PROCESS, MB_PER_FB_EXPONENT !NODEP!
  use limits, only: BUFFER_SIZE !NODEP!
  use limits, only: PYTHIA_PARAMETERS_LEN !NODEP!
  use lexers, only: lex_clear
  use parser, only: get_integer

<Standard module head>

<Jetset interface: public parameters>

<Jetset interface: public types>

<Jetset interface: public routines>

<Jetset interface: module variables>
<Pythia old interface: module variables>
  save

contains

<Jetset interface: subroutines>

<Pythia old interface: subroutines>

end module jetset_interface

<Pythia old interface: external routines>

```

14.3.3 The new interface

```
<pythia_interface.f90>≡  
<File header>  
  
module jetset_interface  
  
  <Use kinds>  
    use kinds, only: double !NODEP!  
    use file_utils, only: free_unit !NODEP!  
    use diagnostics !NODEP!  
    use limits, only: BUFFER_SIZE, PYTHIA_PARAMETERS_LEN !NODEP!  
    use parser, only: get_integer  
    use lexers, only: lex_clear  
  
  <Standard module head>  
  
  <Jetset interface: public parameters>  
  
  <Jetset interface: public types>  
  
  <Jetset interface: public routines>  
  
  <Jetset interface: module variables>  
  
  save  
  
contains  
  
  <Jetset interface: subroutines>  
  
  <Pythia new interface: subroutines>  
  
end module jetset_interface  
  
  <Pythia new interface: external routines>
```

14.3.4 Initialization: dummy routines

```
<Jetset interface: public routines>≡  
  public :: jetset_init, pythia_init  
  
<Jetset interface: dummy routines>≡  
  subroutine jetset_init (dummy)  
    character(len=*), intent(in) :: dummy  
    call msg_error (" JETSET fragmentation is not available.")  
    call msg_message &  
      & (" To enable JETSET/PYTHIA, rerun configure and recompile WHIZARD.")  
  end subroutine jetset_init  
  
  subroutine pythia_init (dummy)  
    type(pythia_init_data), intent(in) :: dummy  
    call msg_error (" PYTHIA fragmentation is not available.")  
    call msg_message &  
      & (" To enable PYTHIA, rerun configure and recompile WHIZARD.")  
  end subroutine pythia_init
```

```
end subroutine pythia_init
```

<Limits: public parameters>+≡

```
integer, parameter, public :: PYTHIA_EXTERNAL_PROCESS = 199
integer, parameter, public :: MB_PER_FB_EXPONENT = 12
integer, parameter, public :: PB_PER_FB_EXPONENT = 3
```

14.3.5 Fragmentation: JETSET

In the JETSET case, we should need no initialization at all except for letting the user control the behavior of the program. Unfortunately, without a collider-specific pyinit call, in PYTHIA6.2 some initializations are missing. Therefore, we initialize PYTHIA for a definite (arbitrary) collider, but hide this from the user to avoid confusion.

<Jetset interface: subroutines>≡

```
subroutine jetset_init (chin)
  character(len=*), intent(in) :: chin
  <Jetset interface: parameter common block>
  call msg_message (" Initializing PYTHIA ...")
  call pyinit ("NONE", "", "", 0._double)
  mstp(122)=0      ! Second pyinit call silent
  call pyinit ("CMS", "e+", "e-", 5000._double)
  mstp(122)=1      ! Now print it again
  if (chin /= ' ') then
    call call_pygive (chin)
  end if
end subroutine jetset_init
```

This is JETSET fragmentation: Only the final state is treated. We translate the HEPEVT common block into the PYJETS format, insert color flow information (if available), do the fragmentation, and translate back. Currently, all PYTHIA variables retain their default values. This fragmentation call does not include showering, which would require a call to pyshow before pyexec.

<Jetset interface: public routines>+≡

```
public :: jetset_fragment
```

<Jetset interface: dummy routines>+≡

```
subroutine jetset_fragment (color_flow_dummy, anticolor_flow_dummy)
  integer, dimension(:), intent(in) :: color_flow_dummy, anticolor_flow_dummy
end subroutine jetset_fragment
```

<Jetset interface: subroutines>+≡

```
subroutine jetset_fragment (color_flow, anticolor_flow)
  integer, dimension(:), intent(in) :: color_flow, anticolor_flow
  integer, dimension(size(color_flow)) :: cflow, aflow
  integer :: i
  call pyhepc (2)
  <jetset_fragment: Handle color flow>
  call pyexec ()
  call pyhepc (1)
contains
<jetset_fragment: internal subroutines>
```

```
end subroutine jetset_fragment
```

The color flow information has to be transformed into `pyjoin` calls. First, we check all quarks and follow the color string they initiate. Next, follow the antiquarks. Finally, treat the remaining gluons (which necessarily make up closed strings).

```
(jetset_fragment: Handle color flow)≡
  cflow = color_flow
  aflow = anticolor_flow
  do i=1, size(cflow)
    if (cflow(i)/=0 .and. aflow(i)==0) then
      call make_color_string (i, cflow, aflow)
    end if
  end do
  do i=1, size(cflow)
    if (aflow(i)/=0 .and. cflow(i)==0) then
      call make_color_string (i, aflow, cflow)
    end if
  end do
  do i=1, size(cflow)
    if (cflow(i)/=0 .and. aflow(i)/=0) then
      call make_color_string (i, cflow, aflow)
    end if
  end do
```

When the color string is followed, we zero out all entries we encounter in `flow1` and `flow2`, so they cannot be treated twice. No parton can be member of more than one string. When an initial parton is encountered, the string is broken there since JETSET fragmentation applies to the final state only (in WHIZARD). For the same reason, we have to subtract 2 from the particle indices when inserting them into `ijoin`. Finally, for strings containing more than one member `pyjoin` is called.

```
(jetset_fragment: internal subroutines)≡
  subroutine make_color_string (i0, flow1, flow2)
    integer, intent(in) :: i0
    integer, dimension(:), intent(inout) :: flow1, flow2
    integer, dimension(size(flow1)) :: ijoin
    integer :: njoin
    integer :: i1, i2, j
    i1 = i0
    ijoin = 0
    njoin = 0
    do j=1, size(ijoin)
      if (i1 <= 2) exit
      ijoin(j) = i1 - 2
      njoin = njoin + 1
      i2 = i1
      i1 = flow1(i2)
      flow1(i2) = 0
      flow2(i2) = 0
    end do
    if (njoin > 1) call pyjoin (njoin, ijoin)
  end subroutine make_color_string
```

14.3.6 Fragmentation: PYTHIA (old version)

For the PYTHIA interface, the crucial point is whether to include showering. The PYTHIA external process interface needs pairings of partons to develop showers, which are not easy to figure out. One may pair partons along with color strings, but they may consist of more than two partons and they could contain initial-state partons. PYTHIA 6.1 contains some more routines to handle showering, in particular 4-fermion and *qqgg* configurations, but many cases are not treated.

In principle, WHIZARD is able to calculate multi-jet configurations directly, when suitable cuts are introduced. These cuts should set the upper scales for parton showering, while the lower scales are given by fragmentation (again within PYTHIA). So the missing piece, currently, is gluon (and photon) radiation between these two scales. One should note that WHIZARD uses a fixed α_s value (strict fixed-order QCD) which also underestimates radiation at lower scales.

Temporarily, we switch off showering completely. This is done by resetting the parameters inside `pythia_up_fill` which is called by the external routine `pyupev` we provide below. After PYTHIA has returned, we reset the showering parameters.

PYTHIA initialization needs beam information; to avoid cross-dependencies of modules, we let the appropriate character constants be determined in the caller routine. The WHIZARD process will be declared as user process in PYTHIA. Furthermore, parameters to be modified by `pygive` are transferred.

To simplify things, we collect all PYTHIA initialization information in a record. Most of this information is used by the old PYTHIA interface only, while the new interface relies on the HEPRUP common block which is not accessed here.

```
<Jetset interface: public types>≡
type, public :: pythia_init_data
  integer :: n_external
  character(len=BUFFER_SIZE) :: process_id, pyproc, beam, target
  logical :: fixed_energy, show_pymaxi
  real(default) :: sqrts, integral, error
  character(len=PYTHIA_PARAMETERS_LEN) :: chin
end type pythia_init_data
```

Apparently, not all initialization is done in the `pyinit` call. To force initialization of resonance decays (?), a single *ZH* event is generated and discarded before the actual initialization is performed. This is done silently, to not confuse the user.

The result for the integral is used both as maximum and as current event weight, so no events get rejected by PYTHIA. Note that PYTHIA counts cross sections in millibarns, so a conversion is in order (or it would be necessary if more PYTHIA processes could be generated in parallel; be prepared for that).

```
<Pythia old interface: subroutines>≡
subroutine pythia_init (pydat)
  type(pythia_init_data), intent(in) :: pydat
  character(len=len(pydat%beam)) :: beam_test1, beam_test2
  character(len=BUFFER_SIZE) :: buffer
  integer :: isub_test
```

```

<Jetset interface: parameter common block>
<Jetset interface: subprocess common block>
call msg_message
call msg_message (" Initializing PYTHIA ...")
msel=0          ! No extra processes
isub_test = 24   ! ZH subprocess
msub(isub_test)=1
mstp(122)=0      ! First pyinit call silent
beam_test1="e+"
beam_test2="e-"
call pyinit ("CMS", beam_test1, beam_test2, 5000._double)
call pyevnt
msub(isub_test)=0
mstp(122)=1      ! Now print it again
if (pydat%n_external > 20) then
    write (msg_buffer, "(A,1x,I5)") &
        & " Number of external particles:", pydat%n_external
    call msg_message
    call msg_fatal &
        & (" PYTHIA fragmentation is possible for max. 20 particles.")
end if
pythia_nup = pydat%n_external
pythia_isub = PYTHIA_EXTERNAL_PROCESS
pythia_sqrts = pydat%sqrts
pythia_integral = pydat%integral / 10._double**MB_PER_FB_EXPONENT
pythia_error = pydat%error / 10._double**MB_PER_FB_EXPONENT
call set_processes (pydat%pyproc)
call pyupin (pythia_isub, trim(pydat%process_id), pythia_integral)
if (.not. pydat%fixed_energy) then
    pythia_sqrts = pythia_sqrts &
        & * 1.00000000001_double      ! suppress x=1 warnings
end if
call pygive ("MSTP(11)=0; MSTP(61)=0; MSTP(71)=0") ! Suppress ISR/FSR
if (pydat%chin /= ' ') call call_pygive (pydat%chin) ! User intervention
buffer = " "
write (buffer, "(I3)") pythia_isub
call pygive ("MSEL=0; MSUB("//trim(buffer)//")=1") ! select user process
if (.not.pydat%show_pymaxi) call pygive ("MSTP(122)=0")
call pyinit ("CMS", pydat%beam, pydat%target, pythia_sqrts)
new_event_needed_pythia = .true.
number_events_whizard = 0
number_events_pythia = 0
end subroutine pythia_init

```

When fragmentation is enabled, we allow for additional processes generated by PYTHIA. Those are specified in the input file in the string `pythia_processes`, part of the `simulation_input` block. Here, we parse this string and set the PYTHIA parameters accordingly.

```

<Jetset interface: subroutines>+≡
subroutine set_processes (pyproc)
character(len=*), intent(in) :: pyproc
integer :: u, iostat, process
character(len=BUFFER_SIZE) :: buffer

```

```

u = free_unit ()
open (u, status="scratch")
write (u, "(A)") pyproc
rewind (u)
SCAN_TOKENS: do
  process = get_integer (u, iostat=iostat)
  if (iostat /= 0) exit SCAN_TOKENS
  buffer = " "
  write (buffer, "(I4)") process
  call pygive ("MSUB("//trim(buffer)//") = 1")
end do SCAN_TOKENS
close (u, status="delete")
call lex_clear
end subroutine set_processes

```

PYTHIA fragmentation is more complicated. First, we transfer the event information to the `jetset_interface` module, filling a set of module variables. Then we are ready to call `PYEVNT` which in turn (within PYTHIA) calls `PYUPEV`, the routine we provide separately. This routine makes use of `pythia_up_fill`, another part of the `jetset` interface module which transfers module variables into the appropriate common block. After `pyevnt` has completed, the results are finally moved to the `HEPEVT` common block.

(Jetset interface: public routines)+≡

```
public :: pythia_fragment
```

(Jetset interface: dummy routines)+≡

```

subroutine pythia_fragment (m_dummy, p_dummy, code_dummy, &
  & color_flow_dummy, anticolor_flow_dummy)
  real(default), dimension(:), intent(in) :: m_dummy
  real(default), dimension(:,0:), intent(in) :: p_dummy
  integer, dimension(:), intent(in) :: code_dummy
  integer, dimension(:), intent(in) :: color_flow_dummy, anticolor_flow_dummy
end subroutine pythia_fragment

```

Assume that all arrays have the same length (the number of particles is set in `pythia_init`), and that the first two entries are the incoming particles for which color has to be inverted.

Since showering is turned off, we do not take care of the variables which control parton pairing.

(Pythia old interface: subroutines)+≡

```

subroutine pythia_fragment (m, p, code, color_flow, anticolor_flow)
  real(default), dimension(:), intent(in) :: m
  real(default), dimension(:,0:), intent(in) :: p
  integer, dimension(:), intent(in) :: code, color_flow, anticolor_flow
  integer :: n

```

(Jetset interface: parameter common block)

```

!   mstp(61) = mstp61
!   mstp(71) = mstp71
if (new_event_needed_pythia) then
  n = pythia_nup
  pythia_kup (:n,1) = 1
  pythia_kup (:n,2) = code (:n)
  pythia_kup (:n,3) = 0

```

```

        pythia_kup (:2,4) = 0
        pythia_kup (3:n,4) = color_flow (3:n)
        pythia_kup (1:2,5) = 0
        pythia_kup (3:n,5) = anticolor_flow (3:n)
        pythia_kup (1:2,6) = anticolor_flow (1:2)
        pythia_kup (3:n,6) = 0
        pythia_kup (1:2,7) = color_flow (1:2)
        pythia_kup (3:n,7) = 0
        pythia_pup (1:n,1:3) = p(1:n,1:3)
        pythia_pup (1:n,4) = p(1:n,0)
        pythia_pup (1:n,5) = m(1:n)
        new_event_needed_pythia = .false.
    end if
    call pyevnt ()
    call pyhepc (1)
    if (new_event_needed_pythia) then
        number_events_whizard = number_events_whizard + 1
    else
        number_events_pythia = number_events_pythia + 1
    end if
end subroutine pythia_fragment

```

This variable tells whether the user process has actually been called by PYTHIA. If not, it may mean that PYTHIA has generated a different process (if allowed) and we should rather retain the event. This flag will be set false when PYTHIA is called and set to true again when the user process has been called. So, if the user process has not been called by PYTHIA, the flag will stay false after `pythia_fragment` is finished. In the dummy routine, it is always kept true.

<Jetset interface: module variables>≡

<Jetset interface: module variables (dummy case)>

<Jetset interface: module variables (dummy case)>≡

```
logical, public :: new_event_needed_pythia = .true.
```

Count the WHIZARD events fragmented by PYTHIA vs. the events *generated* by PYTHIA

<Jetset interface: module variables (dummy case)>+≡

```
integer, public :: number_events_whizard = 0
```

```
integer, public :: number_events_pythia = 0
```

This counter is needed if fragmentation is turned off but we nevertheless use PYTHIA for writing events. We have two counters, one for screen output and one for file output.

<Jetset interface: module variables (dummy case)>+≡

```
integer, dimension(2), public :: number_events_written = 0
```

The showering parameters:

<Jetset interface: parameter common block>≡

```
common /PYPARS/ mstp(200),parp(200),msti(200),pari(200)
```

```
integer :: mstp, msti
```

```
real(kind=double) :: parp, pari
```

The subprocess data:

<Jetset interface: subprocess common block>≡

```
common /PYSUBS/ msel,mselpd,msub(500),kfin(2,-40:40),ckin(200)
```

```
integer :: msel, mselpd, msub, kfin
real(kind=double) :: ckin
```

<Jetset interface: module variables>+≡
! integer :: mstp61, mstp71

Module variables which are static but needed by PYTHIA. Making these double precision makes conversion automatic, if necessary.

<Pythia old interface: module variables>≡
integer :: pythia_isub
real(kind=double) :: pythia_sqrts, pythia_integral, pythia_error

These module variables parallel the contents of the PYUPPR common block. The showering parameters are disabled.

<Pythia old interface: module variables>+≡
integer :: pythia_nup
integer, dimension(20,7) :: pythia_kup
real(kind=double), dimension(20,5) :: pythia_pup
! integer :: pythia_nfup
! integer, dimension(10,2) :: pythia_ifup
! real(kind=double) :: pythia_q2up

This routine has to return the event in a special common block. Since it is already there (contained in the `jetset_interface` module variables), we just have to transfer it. This side-effect programming is appropriate since neither `pyevnt` nor `pyupev` can take further arguments (and since it is not excluded by the documentation that `pyevnt` modifies the common block before calling `pyupev`); the argument lists are hard-coded in PYTHIA.

<Pythia old interface: external routines>≡
subroutine pyupev (isub_dummy, sigev)
use kinds, only: double !NODEP!
use jetset_interface, only: pythia_up_fill, new_event_needed_pythia !NODEP!
implicit none
integer, intent(in) :: isub_dummy
real(kind=double), intent(out) :: sigev
real(kind=double) :: integral
call pythia_up_fill (integral)
sigev = integral
new_event_needed_pythia = .true.
end subroutine pyupev

Fill the PYTHIA user-process common block from module variables. Return the integral since it is needed explicitly by `pyupev`. Disable showering/ISR/FSR (temporarily) so that WHIZARD events do not get showered.

<Jetset interface: public routines>+≡
public :: pythia_up_fill

<Jetset interface: dummy routines>+≡
subroutine pythia_up_fill
end subroutine pythia_up_fill

<Pythia old interface: subroutines>+≡
subroutine pythia_up_fill (integral)
real(kind=double), intent(out) :: integral

```

      <PYUPPR common block>
      <Jetset interface: parameter common block>
!      mstp(61) = 0
!      mstp(71) = 0
      nup = pythia_nup
      kup = pythia_kup
      pup = pythia_pup
      integral = pythia_integral
!      nfup = pythia_nfup
!      ifup = pythia_ifup
!      q2up = pythia_q2up
      end subroutine pythia_up_fill

<Pythia new interface: subroutines>≡
      subroutine pythia_up_fill
      end subroutine pythia_up_fill

```

The ordering of this common block has changed in PYTHIA 6.1. In PYTHIA 6.2, it has been abandoned.

```

<PYUPPR common block>≡
      integer :: nup, kup, nfup, ifup
      real(kind=double) :: pup, q2up
      common /PYUPPR/ nup, kup(20,7), nfup, ifup(10,2), pup(20,5), q2up(0:10)
      save /PYUPPR/

```

14.3.7 Fragmentation: PYTHIA (new version)

In the new version, the standard initialization of PYTHIA is skipped and transferred to a call of `upinit` instead. This can only be done after the HEPRUP common block has been filled, which is done by a call to `heprup_fill`.

```

<Pythia new interface: subroutines>+≡
      subroutine pythia_init (pydat)
      type(pythia_init_data), intent(in) :: pydat
      call msg_message
      call msg_message (" Initializing PYTHIA ...")
      call set_processes (pydat%pyproc)
      call pyinit ("USER", "", "", 0._double)
      call pygive ("MSTP(11)=0; MSTP(61)=0; MSTP(71)=0") ! Suppress ISR/FSR
      if (pydat%chin /= ' ') call call_pygive (pydat%chin) ! User intervention
      new_event_needed_pythia = .true.
      number_events_whizard = 0
      number_events_pythia = 0
      end subroutine pythia_init

```

The new version of the fragmentation call is much simpler since we assume that the HEPEUP common block has already been filled by `hepeup_fill`. Therefore, the arguments are actually thrown away. Nevertheless, the program flow is similar: `pythia_fragment` calls `pyevnt` which in turn may call the external subroutine `upevnt`, or generate an event on its own if this is allowed. The `upevnt` subroutine does nothing but record the fact that the WHIZARD event has

been read by PYTHIA, and a new one will be needed. In any case, the result is transferred to the HEPEVT common block.

```

(Pythia new interface: subroutines)+≡
subroutine pythia_fragment &
    & (m_dummy, p_dummy, code_dummy, color_flow_dummy, anticolor_flow_dummy)
    real(default), dimension(:), intent(in) :: m_dummy
    real(default), dimension(:,0:), intent(in) :: p_dummy
    integer, dimension(:), intent(in) :: code_dummy
    integer, dimension(:), intent(in) :: color_flow_dummy, anticolor_flow_dummy
    new_event_needed_pythia = .false.
    call pyevnt ()
    call pyhepc (1)
    if (new_event_needed_pythia) then
        number_events_whizard = number_events_whizard + 1
    else
        number_events_pythia = number_events_pythia + 1
    end if
end subroutine pythia_fragment

```

This is outside the module, to be called as an independent subroutine by pyevnt:

```

(Pythia new interface: external routines)≡
subroutine upevnt
    use jetset_interface, only: new_event_needed_pythia !NODEP!
    new_event_needed_pythia = .true.
end subroutine upevnt

```

14.3.8 Event listings

Use the F77 routines (below) to open and close files. Here is the interface. (The unit, in fact, is irrelevant to the F90 code)

```

(Jetset interface: public routines)+≡
public :: jetset_open_write, jetset_close

(Jetset interface: dummy routines)+≡
subroutine jetset_open_write (unit, file)
    integer, intent(in) :: unit
    character (len=*), intent(in) :: file
end subroutine jetset_open_write

subroutine jetset_close (unit)
    integer, intent(in) :: unit
end subroutine jetset_close

(Jetset interface: subroutines)+≡
subroutine jetset_open_write (unit, file)
    integer, intent(in) :: unit
    character (len=*), intent(in) :: file
    external F77OPN
    call F77OPN (unit, trim(file))
    number_events_written = 0
end subroutine jetset_open_write

```

```

subroutine jetset_close (unit)
  integer, intent(in) :: unit
  external F77CLS
  call F77CLS (unit)
end subroutine jetset_close

```

The PYJETS block is probably filled already, but to be sure, we refill it from the HEPEVT block. The output is to be sent to standard output (screen). We would like to alternatively send it to the event file, but there is no way to associate the logical unit within JETSET to a file opened within the Fortran90 driver program.

```

<Jetset interface: public routines>+≡
  public :: jetset_write

```

```

<Jetset interface: dummy routines>+≡
  subroutine jetset_write (dummy1, dummy2)
    integer, intent(in) :: dummy1, dummy2
    call msg_error (" PYTHIA event listing format is not available.")
    call msg_message (" To enable PYTHIA, rerun configure and recompile WHIZARD.")
  end subroutine jetset_write

```

Temporarily reset the output unit such that we can write events to file. In addition, we do not want to have a banner page here.

```

<Jetset interface: subroutines>+≡
  subroutine jetset_write (unit, mlist)
    integer, intent(in) :: unit, mlist
    <Jetset interface: COMMON block>
    integer :: mstu11, nev
    character(len=BUFFER_SIZE) :: buffer
    external F77WCH
    call pyhepc (2)
    mstu11 = mstu(11)
    mstu(11) = unit
    buffer = " "
    if (unit==6) then
      number_events_written(1) = number_events_written(1) + 1
      nev = number_events_written(1)
    else
      number_events_written(2) = number_events_written(2) + 1
      nev = number_events_written(2)
    end if
    if (new_event_needed_pythia) then
      write (buffer, "(1x,A,1x,I12,3x,A)") "*** Event #", nev, "(WHIZARD):"
    else
      write (buffer, "(1x,A,1x,I12,3x,A)") "*** Event #", nev, "(PYTHIA):"
    end if
    call F77WCH (unit, " ")
    call F77WCH (unit, " ")
    call F77WCH (unit, " ")
    call F77WCH (unit, trim(buffer))
    call jetset_suppress_banner
    call pylist (mlist)
    mstu(11) = mstu11
  end subroutine jetset_write

```

14.3.9 Manipulating PYTHIA behavior directly

The PYDATA COMMON block, in case we wish to address it directly.

```
<Jetset interface: COMMON block>≡  
  common /PYDAT1/ mstu(200), paru(200), mstj(200), parj(200)  
  integer :: mstu, mstj  
  real(kind=double) :: paru, parj
```

This should be called before any other routine, if desired

```
<Jetset interface: public routines>+≡  
  public :: jetset_suppress_banner  
  
<Jetset interface: dummy routines>+≡  
  subroutine jetset_suppress_banner  
  end subroutine jetset_suppress_banner  
  
<Jetset interface: subroutines>+≡  
  subroutine jetset_suppress_banner  
    <Jetset interface: COMMON block>  
    mstu(12) = 0  
  end subroutine jetset_suppress_banner
```

14.3.10 Setting PYTHIA parameters

It is possible to set PYTHIA parameters using the `pygive` call. However, this call is limited to 100 characters. Therefore, split the string at semicolons and transfer the parameters one-by-one.

```
<Limits: public parameters>+≡  
  integer, parameter, public :: PYTHIA_PARAMETERS_LEN = 1000  
  
<Jetset interface: public parameters>≡  
  integer, parameter, public :: PYGIVE_LEN = 100  
  
<Jetset interface: subroutines>+≡  
  subroutine call_pygive (string)  
    character(len=*), intent(in) :: string  
    character(len=PYGIVE_LEN) :: chin  
    integer :: pos1, pos2  
    pos1 = 1  
    do  
      pos2 = scan (string(pos1:), ";")  
      if (pos2 == 0) then  
        chin = string(pos1:)  
        call pygive (chin)  
      else if (pos2 > PYGIVE_LEN) then  
        write (msg_buffer, "(1x,A)" ) '''//string(pos1:pos2)//'''  
        call msg_message  
        call msg_error &  
          & (" Substring of pythia_parameters too long, will be ignored")  
        chin = ""  
        pos1 = pos1 + pos2 + 1  
      else  
        pos1 = pos1 + pos2 + 1  
      end if  
    end do
```

```

        chin = string(pos1:pos1+pos2-2)
        call pygive (chin)
        pos1 = pos1 + pos2 + 1
    end if
    if (pos2 == 0) exit
end do
end subroutine call_pygive

```

14.3.11 Statistics

This function prints the PYTHIA statistics.

```

<Jetset interface: public routines>+≡
    public :: pythia_print_statistics

<Jetset interface: dummy routines>+≡
    subroutine pythia_print_statistics
    end subroutine pythia_print_statistics

<Jetset interface: subroutines>+≡
    subroutine pythia_print_statistics
        call pystat (1)
    end subroutine pythia_print_statistics

```

14.3.12 F77 file handling

PYTHIA may need an open file to write to. This has to be done by the native F77 compiler, if PYTHIA is linked as a precompiled library.

```

<f77_files.f>≡
    SUBROUTINE F77OPN (UNIT, FILE)
    INTEGER UNIT
    CHARACTER*(*) FILE
    OPEN (UNIT, FILE=FILE)
    RETURN
    END

    SUBROUTINE F77CLS (UNIT)
    INTEGER UNIT
    CLOSE (UNIT)
    RETURN
    END

    SUBROUTINE F77WCH (UNIT, STRING)
    INTEGER UNIT
    CHARACTER*(*) STRING
    WRITE (UNIT, FMT='(A)') STRING
    RETURN
    END

```

14.4 HERWIG interface

The first module is a replacement if **HERWIG** is not available. The second module interfaces **HERWIG**, using the Les Houches user process standard supported from **HERWIG6.5** on.

14.4.1 Dummy module

```
<herwig_dummy.f90>≡  
  <File header>  
  
  module herwig_interface  
  
    <Use kinds>  
    use kinds, only: double !NODEP!  
    use diagnostics !NODEP!  
    ! use limits, only: BUFFER_SIZE, HERWIG_PARAMETERS_LEN !NODEP!  
  
    <Standard module head>  
  
    <Herwig interface: public parameters>  
  
    <Herwig interface: public types>  
  
    <Herwig interface: public routines>  
  
    <Herwig interface: module variables (dummy case)>  
  
    contains  
  
    <Herwig interface: dummy routines>  
  
  end module herwig_interface
```

14.4.2 The HERWIG interface

```
<herwig_interface.f90>≡  
  <File header>  
  
  module herwig_interface  
  
    <Use kinds>  
    use kinds, only: double !NODEP!  
    ! use file_utils, only: free_unit  
    use diagnostics !NODEP!  
    ! use limits, only: BUFFER_SIZE, HERWIG_PARAMETERS_LEN !NODEP!  
    ! use parser, only: get_integer, lex_clear  
  
    <Standard module head>  
  
    <Herwig interface: public parameters>  
  
    <Herwig interface: public types>
```

```

    <Herwig interface: public routines>

    <Herwig interface: module variables>

    <Herwig interface: common blocks>

    save

contains

    <Herwig interface: subroutines>

    <Herwig new interface: subroutines>

end module herwig_interface

    <Herwig new interface: external routines>

```

14.4.3 Initialization: dummy routines

```

    <Herwig interface: public routines>≡
        public :: herwig_init, herwig_init

    <Herwig interface: dummy routines>≡
        subroutine herwig_init (dummy)
            character(len=*), intent(in) :: dummy
            call msg_error (" HERWIG fragmentation is not available.")
            call msg_message &
                & (" To enable HERWIG/HERWIG, rerun configure and recompile WHIZARD.")
        end subroutine herwig_init

        subroutine herwig_init (dummy)
            type(herwig_init_data), intent(in) :: dummy
            call msg_error (" HERWIG fragmentation is not available.")
            call msg_message &
                & (" To enable HERWIG, rerun configure and recompile WHIZARD.")
        end subroutine herwig_init

    <Limits: public parameters>+≡
        ! integer, parameter, public :: HERWIG_EXTERNAL_PROCESS = 199

```

14.4.4 COMMON blocks

We need only access a few variables directly, therefore we may hardcode this here, in the hope that the common blocks do not change drastically:

```

    <Herwig interface: common blocks>≡
        double precision :: ebeam1, ebeam2, pbeam1, pbeam2
        integer :: iproc, maxev
        common /HWPROC/ ebeam1,ebeam2,pbeam1,pbeam2,iproc,maxev

```

The block will be filled by HERWIG using the Les Houches interface, if `iproc` is negative.

```
<Herwig interface: initialize common blocks>≡
  ebeam1 = 0
  ebeam2 = 0
  pbeam1 = 0
  pbeam2 = 0
  iproc = -1
  maxev = 0
```

14.4.5 Fragmentation: HERWIG

In the Les Houches Accord implementation, the standard initialization of HERWIG is skipped and transferred to a call of `upinit` instead. This routine is empty in our case, since the filling of the COMMON block has already been done by a call to `heprup_fill`.

```
<Herwig new interface: subroutines>≡
  subroutine herwig_init ()
    external hwigin, hwuinc
    call msg_message
    call msg_message (" Initializing HERWIG ...")
    <Herwig interface: initialize common blocks>
    call hwigin          ! initialize generic parameters to default
    ! Here, we could reset HERWIG parameters
    call hwuinc          ! call UPINIT and finish initialization
    !   call hwusta('PIO  ') ! call this to make any particle stable
    !   call hwabeg          ! User initial calculations (empty)
    call hweini          ! Initialise elementary process
  end subroutine herwig_init
```

This is called to fragment an event by HERWIG. The program flow follows the sample main program of HERWIG. We can assume that the `HEPEUP` common block has already been filled by `hepeup_fill`. `herwig_fragment` calls `hwepro` which in turn may call the external subroutine `upegvt`. The `upegvt` subroutine does nothing. After the remaining HERWIG calls In any case, the result is transferred to the `HEPEVT` common block.

```
<Herwig new interface: subroutines>+≡
  subroutine herwig_fragment &
    & (m_dummy, p_dummy, code_dummy, color_flow_dummy, anticolor_flow_dummy)
    real(default), dimension(:), intent(in) :: m_dummy
    real(default), dimension(:,0:), intent(in) :: p_dummy
    integer, dimension(:), intent(in) :: code_dummy
    integer, dimension(:), intent(in) :: color_flow_dummy, anticolor_flow_dummy
    new_event_needed_herwig = .false.
    call pyevnt ()
    call pyhepc (1)
    if (new_event_needed_herwig) then
      number_events_whizard = number_events_whizard + 1
    else
      number_events_herwig = number_events_herwig + 1
    end if
  end subroutine herwig_fragment
```

This is outside the module, to be called as an independent subroutine by pyevnt:

(Herwig new interface: external routines)≡

```
subroutine upevnt
  use herwig_interface, only: new_event_needed_herwig !NODEP!
  new_event_needed_herwig = .true.
end subroutine upevnt
```

The PYJETS block is probably filled already, but to be sure, we refill it from the HEPEVT block. The output is to be sent to standard output (screen). We would like to alternatively send it to the event file, but there is no way to associate the logical unit within HERWIG to a file opened within the Fortran90 driver program.

(Herwig interface: public routines)+≡

```
public :: herwig_write
```

(Herwig interface: dummy routines)+≡

```
subroutine herwig_write (dummy1, dummy2)
  integer, intent(in) :: dummy1, dummy2
  call msg_error (" HERWIG event listing format is not available.")
  call msg_message (" To enable HERWIG, rerun configure and recompile WHIZARD.")
end subroutine herwig_write
```

Temporarily reset the output unit such that we can write events to file. In addition, we do not want to have a banner page here.

(Herwig interface: subroutines)≡

```
subroutine herwig_write (unit, mlist)
  integer, intent(in) :: unit, mlist
  (Herwig interface: COMMON block)
  integer :: mstu11, nev
  character(len=BUFFER_SIZE) :: buffer
  external F77WCH
  call pyhepc (2)
  mstu11 = mstu(11)
  mstu(11) = unit
  buffer = " "
  if (unit==6) then
    number_events_written(1) = number_events_written(1) + 1
    nev = number_events_written(1)
  else
    number_events_written(2) = number_events_written(2) + 1
    nev = number_events_written(2)
  end if
  if (new_event_needed_herwig) then
    write (buffer, "(1x,A,1x,I12,3x,A)") "*** Event #", nev, "(WHIZARD):"
  else
    write (buffer, "(1x,A,1x,I12,3x,A)") "*** Event #", nev, "(HERWIG):"
  end if
  call F77WCH (unit, " ")
  call F77WCH (unit, " ")
  call F77WCH (unit, " ")
  call F77WCH (unit, trim(buffer))
  call herwig_suppress_banner
  call pylist (mlist)
```

```

        mstu(11) = mstu11
    end subroutine herwig_write

```

14.4.6 Manipulating HERWIG behavior directly

The PYDATA COMMON block, in case we wish to address it directly.

```

<Herwig interface: COMMON block>≡
    common /PYDAT1/ mstu(200), paru(200), mstj(200), parj(200)
    integer :: mstu, mstj
    real(kind=double) :: paru, parj

```

This should be called before any other routine, if desired

```

<Herwig interface: public routines>+≡
    public :: herwig_suppress_banner

<Herwig interface: dummy routines>+≡
    subroutine herwig_suppress_banner
    end subroutine herwig_suppress_banner

<Herwig interface: subroutines>+≡
    subroutine herwig_suppress_banner
        <Herwig interface: COMMON block>
        mstu(12) = 0
    end subroutine herwig_suppress_banner

```

14.4.7 Setting HERWIG parameters

It is possible to set HERWIG parameters using the `pygive` call. However, this call is limited to 100 characters. Therefore, split the string at semicolons and transfer the parameters one-by-one.

```

<Limits: public parameters>+≡
    integer, parameter, public :: HERWIG_PARAMETERS_LEN = 1000

<Herwig interface: public parameters>≡
    integer, parameter, public :: PYGIVE_LEN = 100

<Herwig interface: subroutines>+≡
    subroutine call_pygive (string)
        character(len=*), intent(in) :: string
        character(len=PYGIVE_LEN) :: chin
        integer :: pos1, pos2
        pos1 = 1
        do
            pos2 = scan (string(pos1:), ";")
            if (pos2 == 0) then
                chin = string(pos1:)
                call pygive (chin)
            else if (pos2 > PYGIVE_LEN) then
                write (msg_buffer, "(1x,A)") ' '//string(pos1:pos2)//' '
                call msg_message
                call msg_error &
                    & (" Substring of herwig_parameters too long, will be ignored")
                chin = ""
            end if
            pos1 = pos2 + 1
        end do
    end subroutine call_pygive

```

```

        pos1 = pos1 + pos2 + 1
    else
        chin = string(pos1:pos1+pos2-2)
        call pygive (chin)
        pos1 = pos1 + pos2 + 1
    end if
    if (pos2 == 0) exit
end do
end subroutine call_pygive

```

14.4.8 Statistics

This function prints the HERWIG statistics.

```

<Herwig interface: public routines>+≡
    public :: herwig_print_statistics

<Herwig interface: dummy routines>+≡
    subroutine herwig_print_statistics
    end subroutine herwig_print_statistics

<Herwig interface: subroutines>+≡
    subroutine herwig_print_statistics
        call pystat (1)
    end subroutine herwig_print_statistics

```

14.5 Common blocks for external program interfaces

We would like to provide a standard interface. The HEPEVT standard uses a common block, which is bad practice in Fortran90. Nevertheless, we provide it, placing the common block and subroutines for handling it in a separate module. In this module everything is **public** by default, since we cannot hide the common block anyway. Fortran90 may access the HEPEVT variables directly by **USE**ing the module, while F77 procedures need a copy of the common block specification.

On the Les Houches workshop 2001, it was agreed to provide two additional common blocks as a portable interface between Monte Carlo event generators and shower/hadronization programs, one for initialization and one for event transfer. These common blocks are also defined and filled here. The corresponding routines are only called when fragmentation is switched on.

```

<hepevt_common.f90>≡
    <File header>

    <HEPEVT: documentation>

    module hepevt_common

    <Use kinds>
        use kinds, only: double, i32, i64 !NODEP!
        use diagnostics !NODEP!

```

```

use limits, only: PB_PER_FB_EXPONENT !NODEP!
use lorentz !NODEP!
use particles
use events
use jetset_interface !NODEP!
use stdhep_interface !NODEP!

implicit none
public

<HEPEVT: public routines>

<HEPEVT: common block>

<HEPEVT: interfaces>

contains

<HEPEVT: subroutines>

end module hepevt_common

```

14.5.1 The HEPEVT common block

```

<HEPEVT: documentation>≡
! For the LEP Monte Carlos, a standard common block has been proposed
! in AKV89. We strongly recommend its use. (The description is an
! abbreviated transcription of AKV89, Vol. 3, pp. 327-330).
!
!
! NMXHEP is the maximum number of entries:
!
!
! NEVHEP is normally the event number, but may take special
! values as follows:
!
!   0   the program does not keep track of event numbers.
!  -1   a special initialization record.
!  -2   a special final record.
!
!
! NHEP holds the number of entries for this event.
!
!
! The entry ISTHEP(N) gives the status code for the Nth entry,
! with the following semantics:
!   0      a null entry.
!   1      an existing entry, which has not decayed or fragmented.
!   2      a decayed or fragmented entry, which is retained for
!           event history information.
!   3      documentation line.
!   4- 10  reserved for future standards.
!  11-200  at the disposal of each model builder.
! 201-     at the disposal of users.

```

```

!
!
! The Particle Data Group has proposed standard particle codes,
! which are to be stored in IDHEP(N).
!
!
! JMOHEP(1,N) points to the mother of the Nth entry, if any.
! It is set to zero for initial entries.
! JMOHEP(2,N) points to the second mother, if any.
!
!
! JDAHEP(1,N) and JDAHEP(2,N) point to the first and last daughter
! of the Nth entry, if any. These are zero for entries which have not
! yet decayed. The other daughters are stored in between these two.
!
!
! In PHEP we store the momentum of the particle, more specifically
! this means that PHEP(1,N), PHEP(2,N), and PHEP(3,N) contain the
! momentum in the x, y, and z direction (as defined by the machine
! people), measured in GeV/c. PHEP(4,N) contains the energy in GeV
! and PHEP(5,N) the mass in GeV/c**2. The latter may be negative for
! spacelike partons.
!
!
! Finally VHEP is the place to store the position of the production
! vertex. VHEP(1,N), VHEP(2,N), and VHEP(3,N) contain the x, y,
! and z coordinate (as defined by the machine people), measured in mm.
! VHEP(4,N) contains the production time in mm/c.
!
!
! As an amendment to the proposed standard common block HEPEVT, we
! also have a polarisation common block HEPSPN, as described in
! AKV89. SHEP(1,N), SHEP(2,N), and SHEP(3,N) give the x, y, and z
! component of the spinvector s of a fermion in the fermions
! restframe.
!
! By convention, SHEP(4,N) is always 1.

```

This is taken from StdHep 4.06 manual and written using Fortran90 conventions:

<HEPEVT: common block>≡

```

integer, parameter :: nmxhep = 4000
integer :: nevhep, nhep
integer, dimension(nmxhep) :: isthep, idhep
integer, dimension(2, nmxhep) :: jmohep, jdahep
real(kind=double), dimension(5, nmxhep) :: phep
real(kind=double), dimension(4, nmxhep) :: vhep
common /HEPEVT/ nevhep, nhep, isthep, idhep, &
& jmohep, jdahep, phep, vhep

```

Filling HEPEVT: If the event count is not provided, set `nevhep` to zero. If the event count is -1 or -2, the record corresponds to initialization and finalization, and the event is irrelevant.

Note that the event count may be larger than 2^{31} (2 GEvents). In that case, cut off the upper bits since `nevhep` is probably limited to default integer.

```

<HEPEVT: public routines>≡
  public :: hepevt_fill

<HEPEVT: subroutines>≡
  subroutine hepevt_fill (evt)
    type(event), intent(in) :: evt
    integer :: i, j, offset
    integer(i32), parameter :: huge32 = huge (0_i32)
    real(kind=double), dimension(0:3) :: p
    nevhep = mod (evt%count, int (huge32, i64))
    offset = 0
    nhep = event_n_entries (evt)
    if (evt%keep_initials) then
      do j = 1, evt%n_in
        i = offset + j
        isthep(i) = 2
        idhep(i) = particle_get_code(evt%beam_particle(j))
        jmohep(:, i) = 0
        jdahep(1, i) = evt%n_in + 1
        jdahep(2, i) = 2*evt%n_in + evt%n_beam_remnants
        p = array(particle_get_momentum(evt%beam_particle(j)))
        phep(1:3, i) = p(1:3)
        phep(4, i) = p(0)
        phep(5, i) = particle_get_mass(evt%beam_particle(j))
        vhep(:, i) = 0
      end do
      offset = offset + evt%n_in
      do j = 1, evt%n_in
        i = offset + j
        isthep(i) = 2
        idhep(i) = particle_get_code(evt%prt(-j))
        jmohep(1, i) = 1
        jmohep(2, i) = evt%n_in
        jdahep(1, i) = 2*evt%n_in + evt%n_beam_remnants + 1
        jdahep(2, i) = evt%n_in + evt%n_tot + evt%n_beam_remnants
        p = array(particle_get_momentum(evt%prt(-j)))
        phep(1:3, i) = p(1:3)
        phep(4, i) = p(0)
        phep(5, i) = particle_get_mass(evt%prt(-j))
        vhep(:, i) = 0
      end do
      offset = offset + evt%n_in
    end if
    do j = 1, evt%n_beam_remnants
      i = offset + j
      isthep(i) = 1
      idhep(i) = particle_get_code(evt%beam_remnant(j))
      if (evt%keep_initials) then
        jmohep(1, i) = 1
        jmohep(2, i) = evt%n_in
      else
        jmohep(:, i) = 0
      end if
      jdahep(:, i) = 0
      p = array(particle_get_momentum(evt%beam_remnant(j)))
    end do
  end subroutine hepevt_fill

```

```

        phep(1:3, i) = p(1:3)
        phep(4, i) = p(0)
        phep(5, i) = particle_get_mass(evt%beam_remnant(j))
        vhep(:, i) = 0
    end do
    offset = offset + evt%n_beam_remnants
    do j = 1, evt%n_out
        i = offset + j
        isthep(i) = 1
        idhep(i) = particle_get_code(evt%prt(j))
        if (evt%keep_initials) then
            jmohep(1, i) = evt%n_in + 1
            jmohep(2, i) = 2*evt%n_in
        else
            jmohep(:, i) = 0
        end if
        jdahep(:, i) = 0
        p = array(particle_get_momentum(evt%prt(j)))
        phep(1:3, i) = p(1:3)
        phep(4, i) = p(0)
        phep(5, i) = particle_get_mass(evt%prt(j))
        vhep(:, i) = 0
    end do
end subroutine hepevt_fill

```

This writes the event common block contents. While HEPEVT_FMT and STDHEP_FMT/STDHEP_UP_FMT are sent to file, the various human-readable JETSET_FMTs are sent to screen. The SCREEN_FMT is not available here.

The LHA and STDHEP_UP formats actually write the HEPEUP common block instead, which contains the event before fragmentation.

```

<HEPEVT: public routines>+≡
    public :: hepevt_write

<HEPEVT: interfaces>≡
    interface hepevt_write
        module procedure hepevt_write_unit
    end interface

<HEPEVT: subroutines>+≡
    subroutine hepevt_write_unit (u, fmt)
        integer, intent(in) :: u
        integer, intent(in), optional :: fmt
        integer :: mode, i, j
        mode = HEPEVT_FMT; if (present(fmt)) mode = fmt
        if (nevhep < 0) return
        select case(mode)
        case (HEPEVT_FMT)
            <Write HEPEVT in generator output format>
        case(SHORT_FMT)
            <Write HEPEVT in short generator output format>
        case (STDHEP_FMT)
            <Write HEPEVT in STDHEP format>
        case (STDHEP_UP_FMT)
            <Write HEPEUP in STDHEP format>
        end select
    end subroutine

```

```

    case (JETSET_FMT1, JETSET_FMT2, JETSET_FMT3)
        <Write HEPEVT in JETSET format>
    case(ATHENA_FMT)
        <Write HEPEVT in ATHENA (ATLAS) input format>
    case(LHA_FMT)
        <Write HEPEUP in Les Houches Accord (MadEvent) output format>
    case default
        call msg_fatal (" Invalid format selected for HEPEVT contents output")
    end select
    <Generator format specifications>
end subroutine hepevt_write_unit

<Write HEPEVT in generator output format>≡
write(u,11) nhep
do i=1, nhep
    write (u,13) isthep(i), idhep(i), &
        & (jmohep(j,i), j=1,2), (jdahep(j,i), j=1,2)
    write (u,12) (phep(j,i), j=1,5)
    write (u,12) (vhhep(j,i), j=1,5)
end do

<Write HEPEVT in short generator output format>≡
write(u,11) nhep
do i=1, nhep
    write (u,13) idhep(i)
    write (u,12) (phep(j,i), j=1,5)
end do

<Write HEPEVT in STDHEP format>≡
call stdhep_write (STDHEP_HEPEVT)

<Write HEPEUP in STDHEP format>≡
call stdhep_write (STDHEP_HEPEUP)

<Write HEPEVT in JETSET format>≡
call jetset_write (u,mode-10)

<Write HEPEVT in ATHENA (ATLAS) input format>≡
write(u,11) nevhep, nhep
do i=1, nhep
    write (u,13) i, isthep(i), idhep(i), jmohep(1,i), &
        & jmohep(2,i), jdahep(1,i), jdahep(2,i)
    write (u,12) phep(1,i), phep(2,i), &
        & phep(3,i), phep(4,i), phep(5,i)
    write (u,*) vhep(1,i), vhep(2,i), &
        & vhep(3,i), vhep(4,i)
end do

<Write HEPEUP in Les Houches Accord (MadEvent) output format>≡
write (u,16) nup, idprup, xwgtup, scalup, aqedup, aqcdup
write (u,17) idup(:nup)
write (u,17) mothup(1,:nup)
write (u,17) mothup(2,:nup)
write (u,17) icolup(1,:nup)
write (u,17) icolup(2,:nup)
write (u,17) istup(:nup)
write (u,17) ispinup(:nup)

```

```

do i=1, nup
  write (u,18) i, pup((/4,1,2,3/),i)
end do

```

14.5.2 The Les Houches common blocks

The HEPRUP common block (the user process run common block) is used for initialization. In short, the contents are as follows:

idbmup: PDG codes of beam particles

ebmup: beam energy in GeV for both beams

pdfgup: PDF library author groups used for beam structure functions

pdfsup: PDF library structure function set ID

idwtup: Master switch which determines the interpretation of event weights. For WHIZARD, this is set to +2, meaning that events are weighted and could be rejected by the hadronization program. However, when unweighted event generation is requested, WHIZARD will set the event weight to 1, so events are always accepted.

nprup: Number of different user processes. WHIZARD will set this to 1 and mix its processes internally.

xsecup: Total cross section in pb. WHIZARD will sum up all processes.

xerrup: Statistical error of the cross section in pb.

xmaxup: Maximum weight. This is set to 1.

lprup: Array of process IDs. Not used by WHIZARD.

```

<HEPEVT: common block>+≡
  integer, parameter :: MAXPUP=100
  integer, dimension(2) :: idbmup, pdfgup, pdfsup
  integer :: idwtup, nprup
  integer, dimension(MAXPUP) :: lprup
  real(kind=double), dimension(2) :: ebmup
  real(kind=double), dimension(MAXPUP) :: xsecup, xerrup, xmaxup
  common /HEPRUP/ idbmup, ebmup, pdfgup, pdfsup, &
    & idwtup, nprup, xsecup, xerrup, xmaxup, lprup

```

Filling the initialization common block:

```

<HEPEVT: public routines>+≡
  public :: heprup_fill

<HEPEVT: subroutines>+≡
  subroutine heprup_fill &
    & (beam_code, beam_energy, PDF_ngroup, PDF_nset, integral, error)
    integer, dimension(2), intent(in) :: beam_code
    real(default), dimension(2), intent(in) :: beam_energy
    integer, dimension(2), intent(in) :: PDF_ngroup, PDF_nset
    real(default), intent(in) :: integral, error

```

```

idbmup = beam_code
ebmup = beam_energy
if (any (PDF_ngroup == 0 .or. PDF_nset == 0)) then
    pdfgup = -1
    pdfsup = -1
else
    pdfgup = PDF_ngroup
    pdfsup = PDF_nset
end if
idwtup = 2
nprup = 1
xsecup(1) = integral / 10._double**PB_PER_FB_EXPONENT
xerrup(1) = error / 10._double**PB_PER_FB_EXPONENT
xmaxup(1) = 1
lprup(1) = 1
xsecup(2:) = 0
xerrup(2:) = 0
xmaxup(2:) = 0
lprup(2:) = 0
end subroutine heprup_fill

```

Write this common block in human-readable form (debugging)

```

<HEPEVT: public routines>+≡
    public :: heprup_write

<HEPEVT: interfaces>+≡
    interface heprup_write
        module procedure heprup_write_unit
    end interface

<HEPEVT: subroutines>+≡
    subroutine heprup_write_unit (u)
        integer, intent(in) :: u
        write(u,*) "HEPRUP contents:"
        write(u,*) " IDBMUP =", idbmup
        write(u,*) " EBMUP  =", ebmup
        write(u,*) " PDFGUP =", pdfgup
        write(u,*) " PDFSUP =", pdfsup
        write(u,*) " IDWTUP =", idwtup
        write(u,*) " NPRUP  =", nprup
        write(u,*) " XSECUP =", xsecup(1)
        write(u,*) " XERRUP =", xerrup(1)
        write(u,*) " XMAXUP =", xmaxup(1)
        write(u,*) " LPRUP  =", lprup(1)
    end subroutine heprup_write_unit

```

The HEPEUP common block contains the complete event information, some of which is not contained in HEPEVT. This common block should be used when interfacing fragmentation.

nup: Number of particle entries

idprup: Process ID. For WHIZARD, this is always 1.

xwgtup: Event weight. Equal to 1 for unweighted events, which is currently the only option for fragmentation.

scalup: Scale of the event in GeV. This is not (yet) provided by WHIZARD, and set -1 .

aqedup: α_{QED} . Not set and not used by PYTHIA, therefore -1 .

aqcdup: α_{QCD} . Not set and not used by PYTHIA, therefore -1 .

idup: PDG codes of particles

istup: Status code of particles. We use only -1 for incoming particles and $+1$ for outgoing particles.

mothup: Index of first and last mother. Zero for incoming particles, 1, 2 for outgoing particles.

icolup: Color flow line index passing through the color/anticolor of the particle. The standard recommends using large numbers; we start from MAXNUP+1.

pup: Event momenta, energies and masses

vtimup: Invariant lifetime from production to decay in mm. Zero for WHIZARD events.

spinup: Cosine of the angle between the spin-vector of the particle and of the direction of flight of its decay mother, calculated in the lab frame. This does not apply for general spin, and in general the decay mother is not well-defined. Therefore, we do not transfer the helicity information which in principle is available and insert 9 here.

```

<HEPEVT: common block>+≡
  integer, parameter :: MAXNUP = 500
  integer :: nup, idprup
  integer, dimension(MAXNUP) :: idup, istup
  integer, dimension(2,MAXNUP) :: mothup, icolup
  real(kind=double) :: xwgtup, scalup, aqedup, aqcdup
  real(kind=double), dimension(5,MAXNUP) :: pup
  real(kind=double), dimension(MAXNUP) :: vtimup, spinup
  integer, dimension(MAXNUP) :: ispinup
  common /HEPEUP/ nup, idprup, xwgtup, scalup, aqedup, aqcdup, &
    & idup, istup, mothup, icolup, pup, vtimup, spinup

```

Fill the HEPEUP common block from the information available for the current event.

```

<HEPEVT: public routines>+≡
  public :: hepeup_fill

```

```

<HEPEVT: subroutines>+=
subroutine hepeup_fill (evt)
  type(event), intent(in) :: evt
  integer, dimension(evt%n_tot) :: color_index, anticolor_index
  integer :: i, j
  nup = evt%n_tot
  idprup = 1
  call translate_color_info &
    & (color_index, anticolor_index, evt%color_flow, evt%anticolor_flow)
  do i = 1, 2
    j = -i
    idup(i) = particle_get_code (evt%prt(j))
    istup(i) = -1
    mothup(:,i) = 0
    icolup(1,i) = anticolor_index (i)
    icolup(2,i) = color_index (i)
    pup((/4,1,2,3/),i) = array (particle_get_momentum (evt%prt(j)))
    pup(5,i) = particle_get_mass (evt%prt(j))
    vtimup(i) = 0
    ispinup(i) = 9
    spinup(i) = ispinup(i)
  end do
  do i = 3, nup
    j = i - 2
    idup(i) = particle_get_code (evt%prt(j))
    istup(i) = 1
    mothup(:,i) = (/ 1, 2 /)
    icolup(1,i) = color_index (i)
    icolup(2,i) = anticolor_index (i)
    pup((/4,1,2,3/),i) = array (particle_get_momentum (evt%prt(j)))
    pup(5,i) = particle_get_mass (evt%prt(j))
    vtimup(i) = 0
    if (associated (evt%hel_out)) then
      ispinup(i) = evt%hel_out(j)
    else
      ispinup(i) = 9
    end if
    spinup(i) = ispinup(i)
  end do
  xwgtup = 1
  scalup = evt%energy_scale
  aqedup = -1
  aqcdup = -1
contains
  <Internal subroutine: translate color info>
end subroutine hepeup_fill

```

The color information has to be translated according to the Les Houches standard. The color flow array as used by whizard defines, for each particle, the index where its color comes from. In-particles are replaced by their outgoing antiparticles. Conversely, the anticolor flow array defines, for each particle, the index where its anticolor goes to. By contrast, in the Les Houches standard it is required that the color flow lines are given indices, and for each particle the

two indices of its color flow and anticolor flow line are stored. The translation is done within this subroutine. Since the standard defines color and anticolor according to the time-ordering of the process, one still has to exchange color and anticolor for incoming particles after this subroutine has been called.

```

<Internal subroutine: translate_color_info>≡
subroutine translate_color_info &
    & (color_index, anticolor_index, color_flow, anticolor_flow)
    integer, dimension(:), intent(out) :: color_index, anticolor_index
    integer, dimension(:), intent(in) :: color_flow, anticolor_flow
    integer :: i, cl
    cl = MAXNUP
    color_index = 0
    anticolor_index = 0
    do i = 1, size (color_flow)
        if (color_index(i) == 0) then
            if (color_flow(i) /= 0) then
                cl = cl + 1
                color_index(i) = cl
                anticolor_index(color_flow(i)) = cl
            end if
        end if
        if (anticolor_index(i) == 0) then
            if (anticolor_flow(i) /= 0) then
                cl = cl + 1
                anticolor_index(i) = cl
                color_index(anticolor_flow(i)) = cl
            end if
        end if
    end do
end subroutine translate_color_info

```

Write the HEPEUP common block in human-readable form (debugging)

```

<HEPEVT: public routines>+≡
public :: hepeup_write

<HEPEVT: interfaces>+≡
interface hepeup_write
    module procedure hepeup_write_unit
end interface

<HEPEVT: subroutines>+≡
subroutine hepeup_write_unit (u)
    integer, intent(in) :: u
    integer :: i
    write(u,*) "HEPEUP contents:"
    write(u,*) " NUP      =", nup
    write(u,*) " IDPRUP =", idprup
    write(u,*) " XWGTUP =", xwgtup
    write(u,*) " SCALUP =", scalup
    write(u,*) " AQEDUP =", aqedup
    write(u,*) " AQCDUP =", aqcdup
    do i = 1, nup
        write(u,*) " Particle", i
        write(u,*) " IDUP      =", idup(i)
    end do
end subroutine hepeup_write_unit

```

```

        write(u,*) "    ISTUP    =", istup(i)
        write(u,*) "    MOTHUP   =", mothup(:,i)
        write(u,*) "    ICOLUP   =", icolup(:,i)
        write(u,*) "    PUP(1:3) =", pup(1:3,i)
        write(u,*) "    PUP(4,5) =", pup(4:5,i)
        write(u,*) "    VTIMUP   =", vtimup(i)
        write(u,*) "    SPINUP   =", spinup(i)
    end do
end subroutine hepeup_write_unit

```

Chapter 15

Custom code

This module provides the hook for inserting user code.

```
<user.f90.default>≡
!=====
! File: user.f90.default
!
! This is a template for user-defined functions to be called by WHIZARD.
! Copy this code to 'user.f90' and modify it according to your needs.
! The code will automatically be compiled and included in the WHIZARD
! executable.
!
! There are four places where user code can be inserted:
! 1) User-defined beam spectra
! 2) User-defined structure functions
! 3) User-defined cut algorithms
! 4) User-defined reweighting functions for the squared matrix element
! 5) User-defined fragmentation
!=====

module user

  <Use kinds>
    use kinds, only: double !NODEP!
    use kinds, only: i64 !NODEP!
    use lorentz !NODEP!
    use particles

  <Standard module head>

    public :: spectrum_single, spectrum_double
    public :: spectrum_prt_out, spectrum_beam_remnant

    public :: strfun_single, strfun_double
    public :: strfun_prt_out, strfun_beam_remnant

    public :: pdf_init, pdf_strfun_array

    public :: cut
    public :: weight
```

```

public :: fragment_init, fragment_call, fragment_end

! module variables used by the structure function part
integer :: pdf_code_in, pdf_ngroup, pdf_nset, pdf_nfl, pdf_lo
real(kind=double) :: pdf_QCDL4, pdf_top_mass

contains

!=====

! While the physical meaning of a 'spectrum' and a 'structure function'
! is different, the implementation is exactly analogous.
! The difference is that a user spectrum will be applied BEFORE all built-in
! spectra and structure functions (if any), while a user structure functions
! will be applied AFTER all built-ins.
!
! Four functions have to be coded by the user:
!   spectrum_single, spectrum_double, spectrum_prt_out, spectrum_beam_remnant
! Except for 'spectrum_single', the templates below can be left unchanged,
! if the default behavior is appropriate.
!
! The user spectrum functions take two parameters which can be set in
! the WHIZARD input file:
!   sqrts : default real (if not set, the total c.m. energy of the process)
!   mode   : integer      (to distinguish among different user spectra)
! In the input file, these are called USER_spectrum_sqrts and
! USER_spectrum_mode, resp. USER_strfun_sqrts and USER_strfun_mode

!-----
! Return the outgoing particle PDG code, given the incoming particle code
! and the mode. Note that named constants for PDG codes are defined in the
! 'particles.f90' module and are available here.
! For a beam spectrum, this is usually trivial.

function spectrum_prt_out (prt_in, mode) result (prt_out)
integer, intent(in) :: prt_in, mode
integer :: prt_out
select case (mode)
case default
prt_out = prt_in
end select
end function spectrum_prt_out

!-----
! Return the PDG code of the beam remnant, given the incoming particle code
! and the mode.
! For a beam spectrum, normally there is no beam remnant, and we return
! UNDEFINED (=0)

function spectrum_beam_remnant (prt_in, mode) result (prt_out)
integer, intent(in) :: prt_in, mode
integer :: prt_out
select case (mode)

```

```

        case default
!           prt_out = UNDEFINED
        end select
    end function spectrum_beam_remnant

!-----
! The correlated spectrum for a beam pair.
! Given the two input parameters x(1), x(2), which are uniformly distributed
! between 0 and 1, the spectrum function returns output x values together
! with 'factor', which is the spectrum times the Jacobian of the x mapping,
! if any.
!
! The numbers returned may also depend on the helicities of the incoming
! and outgoing particles. These are specified in the form of complex density
! matrices rho_in(:, :, i) and rho_out(:, :, i), where i is the beam index.
!
! Each density matrix is a two-dimensional array, where the diagonal elements
! should be real, and the trace should be normalized to unity. For states
! with definite helicity, only the diagonal elements are set. Off-diagonal
! elements refer to superpositions of helicity states, e.g., transversal
! polarization of fermions.
! The norm of the spectrum, i.e., the spectrum averaged over initial
! helicities and summed over outgoing helicities, should be returned
! as the overall 'factor'.
! The non-zero entries in the density matrices are defined as +-1 for fermions,
! +-1 for massless vector bosons, +-1 and 0 for massive vector bosons, and 0
! for scalars. Note that the correct assignment is not checked.
!
! If the spectrum does not depend on polarization, one should set
!   rho_out = rho_in   if the in- and out-particles are identical, resp.
!   rho_out = unpolarized_density_matrix (prt_out)   if they are not.
! The function 'unpolarized_density_matrix' is defined in the module
! 'particles', as are the PDG codes of the particles.
!
! For factorized spectra, the code below is appropriate. Modify it if
! spectra are correlated, or if you want to improve the performance by
! mapping the unit square onto itself.

subroutine spectrum_double (factor, x, prt_in, sqrts, rho_in, rho_out, mode)
    real(default), intent(out) :: factor
    real(default), dimension(2), intent(inout) :: x
    integer, dimension(2), intent(in) :: prt_in
    real(default), dimension(2), intent(in) :: sqrts
    complex(default), dimension(-1:1,-1:1,2), intent(in) :: rho_in
    complex(default), dimension(-1:1,-1:1,2), intent(out) :: rho_out
    integer, dimension(2), intent(in) :: mode
    real(default), dimension(2) :: f
    integer :: i
    factor = 1
    do i = 1, 2
        call spectrum_single (f(i), x(i), prt_in(i), sqrts(i), &
            & rho_in(:, :, i), rho_out(:, :, i), mode(i))
        factor = factor * f(i)
    end do

```

```

end subroutine spectrum_double

!-----
! The spectrum for a single beam
! Given the input parameter x, which is initially uniformly distributed
! between 0 and 1, the spectrum function returns an output x value together
! with 'factor', which is the unpolarized spectrum times the Jacobian of the
! x mapping, if any.
! The outgoing density matrix must also be set. See the comment for
! spectrum_double.
!
! The code below describes a trivial spectrum which is unity over the
! whole kinematical range. Modify this according to your needs.
! For correlated spectra, leave the code below as is and modify the subroutine
! spectrum_double instead.

subroutine spectrum_single (factor, x, prt_in, sqrts, rho_in, rho_out, mode)
  real(default), intent(out) :: factor
  real(default), intent(inout) :: x
  integer, intent(in) :: prt_in
  real(default), intent(in) :: sqrts
  complex(default), dimension(-1:1,-1:1), intent(in) :: rho_in
  complex(default), dimension(-1:1,-1:1), intent(out) :: rho_out
  integer, intent(in) :: mode
  integer :: prt_out
  prt_out = spectrum_prt_out (prt_in, mode)
  select case (mode)
    case default
      ! Trivial spectrum without polarization dependence
      factor = 1
      if (prt_in == prt_out) then
        rho_out = rho_in
      else
!        rho_out = unpolarized_density_matrix (prt_out)
      end if
    end select
end subroutine spectrum_single

!=====

! The structure function definitions are analogous to spectrum definitions
!
! Four functions have to be coded by the user:
!   strfun_single, strfun_double, strfun_prt_out, strfun_beam_remnant
! Except for 'strfun_single', the templates below can be left unchanged,
! if the default behavior is appropriate.
!
! The user functions take two parameters which can be set in
! the WHIZARD input file:
!   sqrts : default real (if not set, the total c.m. energy of the process)
!   mode  : integer      (to distinguish among different user spectra)
! In the input file, these are called USER_strfun_sqrts and
! USER_strfun_mode, resp. USER_strfun_sqrts and USER_strfun_mode

!-----

```

```

! Return the outgoing particle PDG code, given the incoming particle code
! and the mode. Note that named constants for PDG codes are defined in the
! 'particles.f90' module and are available here.
! Default: incoming=outgoing (like, e.g., ISR)

```

```

function strfun_prt_out (prt_in, mode) result (prt_out)
  integer, intent(in) :: prt_in, mode
  integer :: prt_out
  select case (mode)
  case default
    prt_out = prt_in
  end select
end function strfun_prt_out

```

```

!-----
! Return the PDG code of the beam remnant, given the incoming particle code
! and the mode.
! Insert something sensible here if you want to have it in the event record.

```

```

function strfun_beam_remnant (prt_in, mode) result (prt_out)
  integer, intent(in) :: prt_in, mode
  integer :: prt_out
  select case (mode)
  case default
    prt_out = UNDEFINED
  end select
end function strfun_beam_remnant

```

```

!-----
! The correlated structure functions for a beam pair.
! Given the two input parameters x(1), x(2), which are uniformly distributed
! between 0 and 1, the strfun function returns output x values together
! with 'factor', which is the strfun times the Jacobian of the x mapping,
! if any.
! For the helicity treatment, see the comments for spectrum_double above.
!
! Given the fact that structure functions are normally factorized, this may
! be left as is. However, you can improve the performance by
! mapping the unit square. Mapping should take place only if the last
! argument 'map' is .true. If 'map' is .false., this function should return
! the structure-function f(x) without modifying the x values

```

```

subroutine strfun_double &
  & (factor, x, prt_in, sqrts, rho_in, rho_out, mode, map)
  real(default), intent(out) :: factor
  real(default), dimension(2), intent(inout) :: x
  integer, dimension(2), intent(in) :: prt_in
  real(default), dimension(2), intent(in) :: sqrts
  complex(default), dimension(-1:1,-1:1,2), intent(in) :: rho_in
  complex(default), dimension(-1:1,-1:1,2), intent(out) :: rho_out
  integer, dimension(2), intent(in) :: mode
  logical, intent(in) :: map
  real(default), dimension(2) :: f
  integer :: i

```

```

factor = 1
do i = 1, 2
    call strfun_single (f(i), x(i), prt_in(i), sqrts(i), &
        & rho_in(:, :, i), rho_out(:, :, i), mode(i), map)
    factor = factor * f(i)
end do
end subroutine strfun_double

!-----
! The structure function for a single beam/parton
! Given the input parameter x, which is initially uniformly distributed
! between 0 and 1, the strfun function returns an output x value together
! with 'factor', which is the strfun times the Jacobian of the x mapping,
! if any.
!
! The code below describes a trivial structure function which is unity over the
! whole kinematical range. Modify this according to your needs.
!
! If the structure function is strongly peaked (normally at x=0 or x=1) or
! even infinite there (it still has to be integrable), you may apply a mapping,
! so the input and output values of x differ. Mapping should take place only
! if the last argument 'map' is .true. If 'map' is .false., this function
! should return the structure-function f(x) without modifying the x value

subroutine strfun_single &
    & (factor, x, prt_in, sqrts, rho_in, rho_out, mode, map)
    real(default), intent(out) :: factor
    real(default), intent(inout) :: x
    integer, intent(in) :: prt_in
    real(default), intent(in) :: sqrts
    complex(default), dimension(-1:1,-1:1), intent(in) :: rho_in
    complex(default), dimension(-1:1,-1:1), intent(out) :: rho_out
    integer, intent(in) :: mode
    logical, intent(in) :: map
    integer :: prt_out
    prt_out = spectrum_prt_out (prt_in, mode)
    select case (mode)
    case default
        ! Trivial function without polarization dependence
        factor = 1
        if (prt_in == prt_out) then
            rho_out = rho_in
        else
            rho_out = unpolarized_density_matrix (prt_out)
        end if
    end select
end subroutine strfun_single

!=====
! This interface allow for inserting user-defined parton distribution
! functions or PDFs which are not (yet) contained in the standard PDFlib

! This interface will be selected if PDF_ngroup is negative in the
! WHIZARD input file, while a positive value will select the corresponding
! PDFLIB structure functions.

```

```

! Available parameters and module variables:
!   code_in      : PDG code of the beam particle (e.g., PROTON)
!   ngroup       : Absolute value of PDF_ngroup
!   nset         : Value of PDF_nset
!   nfl          : Number of active flavors (PDF_nfl)
!   lo           : QCD order (PDF_lo)
!   QC DL4       : Value of Lambda(QCD)_4 (PDF_QC DL4)
!   top_mass     : Top mass value to be used

! Initialization call:
subroutine pdf_init (pdg_code_in, ngroup, nset, nfl, lo, QC DL4, top_mass)
  integer, intent(in) :: pdg_code_in, ngroup, nset, nfl, lo
  real(kind=double), intent(in) :: QC DL4, top_mass
  pdf_code_in = pdg_code_in
  pdf_ngroup = ngroup
  pdf_nset = nset
  pdf_nfl = nfl
  pdf_lo = lo
  pdf_QC DL4 = QC DL4
  pdf_top_mass = top_mass
  ! More initialization here
end subroutine pdf_init

! Structure function call:
! Input parameters:
!   x             : Bjorken x value
!   scale         : Q scale (set by PDF_running_scale or PDF_scale)
! Output:
!   dxpdf         : array of PDF values [x*f(x)]
!                 : (tbar,bbar,cbar,sbar,ubar,dbar,g,d,u,s,c,b,t)
!                 :   -6  -5  -4  -3  -2  -1  0  1  2  3  4  5  6
subroutine pdf_strfun_array (x, scale, dxpdf)
  real(kind=double), intent(in) :: x, scale
  real(kind=double), dimension(-6:6), intent(out) :: dxpdf
  dxpdf = 0 ! Modify this as needed
end subroutine pdf_strfun_array

=====

! This minimal cut function accepts everything

function cut (p, code, mode) result (accept)
  type(vector4_t), dimension(:), intent(in) :: p
  integer, dimension(:), intent(in) :: code
  integer, intent(in) :: mode
  logical :: accept
  select case (mode)
  case default
    accept = .true.
  end select
end function cut

! ! This is an example of a cut function which simulates a 'trigger' at

```

```

!! a hadron collider detector. It may be adapted to your special needs,
!! placed instead of the no-op routine above, and activated by setting
!! user_cut_mode nonzero in the input file. The value of user_cut_mode
!! is transferred as the mode argument of the cut function.
!! The routine is written such that it scans the particle codes, therefore
!! it applies to any process. This is recommended practice, although it
!! is possible to write process-dependent code by explicitly addressing
!! particle indices.
!! In this sample cut function, the event is accepted if
!! (1) all partons are 0.4 units in eta-phi space apart from each other
!! (2) There is at least
!!     - a lepton with pT > 20 or
!!     - missing pT > 50
!!     - a b quark with pT > 80 or
!!     - a jet (quark/gluon) with pT > 100 GeV
!! Note that kinematical functions are available in the module lorentz.f90
!! while the PDG codes E_LEPTON etc. and functions such as [[visible]]
!! are defined in particles.f90

! function cut (p, code, mode) result (accept)
!   ! function arguments and result
!   type(vector4_t), dimension(:), intent(in) :: p
!   integer, dimension(:), intent(in) :: code
!   integer, intent(in) :: mode
!   logical :: accept
!   ! local variables
!   integer :: n, i, j
!   logical, dimension (size(code)) :: is_visible
!   ! number of particles
!   n = size (code)
!   ! flag the visible particles in a logical array
!   is_visible = particle_is_visible (code)
!   ! There is one nontrivial set of cuts for mode=1
!   select case (mode)
!   case (1)
!     ! check if all particles (except invisible ones) are separated
!     accept = .true.
!     do i=1, n
!       if (is_visible(i)) then
!         do j=i+1, n
!           if (is_visible(j) .and. eta_phi_distance (p(i), p(j)) < 0.4) &
!             & accept = .false.
!         end do
!       end if
!     end do
!     if (.not.accept) return ! No need to check further
!     ! Check for particles with minimum pT
!     accept = .false.
!     do i=1, n
!       ! Do not distinguish particle/antiparticle
!       select case (abs(code(i)))
!       case (E_LEPTON,MU_LEPTON,TAU_LEPTON)
!         if (transverse_part (p(i)) > 20) accept = .true.
!       case (B_QUARK)

```

```

!           if (transverse_part (p(i)) > 80) accept = .true.
!           case (GLUON, GLUON2, U_QUARK, D_QUARK, S_QUARK, C_QUARK)
!             if (transverse_part (p(i)) > 100) accept = .true.
!           end select
!         end do
!         if (accept) return          ! No need to check further
!         ! Check the total visible and invisible tranverse momentum
!         if (transverse_part (sum (p, mask=is_visible)) > 50) then
!           accept = .true.
!         !       else if (transverse_part (sum (p, mask=.not.is_visible)) > 80) then
!         !         accept = .true.
!       end if
!     case default
!       ! No operation for other modes
!       accept = .true.
!     end select
!   end function cut

```

!=====

```

! This weight function returns unity, i.e. no reweighting.
! Change this code if you need to reweight the matrix element according
! to a known (positive-semidefinite) function of the particle momenta
! and activate it by setting user_weight_mode nonzero (the mode) in the
! input file.
! You may use the kinematical functions, operators and particle codes from the
! lorentz.f90 and particles.f90 modules for that purpose.

```

```

function weight (p, code, mode)
  type(vector4_t), dimension(:), intent(in) :: p
  integer, dimension(:), intent(in) :: code
  integer, intent(in) :: mode
  real(default) :: weight
  select case (mode)
  case default
    weight = 1
  end select
end function weight

```

!=====

```

! A standard interface for fragmentation has been defined in
! E. Boos et al., Proc. Les Houches 2001, hep-ph/0109068
! The interface consists of two common blocks, HEPRUP and HEPEUP
! which are used to transfer all relevant information from the
! Monte Carlo generator to the fragmentation program.

```

```

! This subroutine can be modified for initializing user fragmentation.
! The fragmentation method is determined by the input variable
! user_fragmentation_mode. It can be used to select among different versions
! of user fragmentation.
! For convenience, the process energy and the random generator seed are given.
! The PYTHIA parameters string is also made accessible here and can thus be

```

```

! abused for transferring any further information if PYTHIA is not invoked
! otherwise.
! You can assume that the common block HEPRUP has been filled.
! Use HEPRUP to access all relevant information.

subroutine fragment_init (mode, sqrts, seed, pythia_parameters)
  integer, intent(in) :: mode
  real(default), intent(in) :: sqrts
  integer, intent(in) :: seed
  character(*), intent(in) :: pythia_parameters
  select case (mode)
  case default
    ! (insert code here)
  end select
end subroutine fragment_init

! This subroutine can be modified for executing user fragmentation of
! a generated event.
! You may access the event counter as a 64-bit integer.
! You can assume that the common block HEPEUP has been filled.
! Use HEPEUP to access all relevant information.
! The result of fragmentation should be stored in the standard HEPEVT common
! block.

subroutine fragment_call (mode, event_count)
  integer, intent(in) :: mode
  integer(i64), intent(in) :: event_count
  select case (mode)
  case default
    ! (insert code here)
  end select
end subroutine fragment_call

! This subroutine can be modified for finalizing user fragmentation.
! You may access the event counter (64-bit integer) and the integral.

subroutine fragment_end (mode, event_count, integral)
  integer, intent(in) :: mode
  integer(i64), intent(in) :: event_count
  real(default), intent(in) :: integral
  select case (mode)
  case default
    ! (insert code here)
  end select
end subroutine fragment_end

!=====

end module user

```

Chapter 16

The SUSY Les Houches Accord

The SUSY Les Houches Accord defines a standard interfaces for storing the physics data of SUSY models. Here, we provide the means for reading, storing, and writing such data.

`<slha_interface.f90>`≡
<File header>

```
module slha_interface
```

```
<Use kinds>
```

```
<Use strings>
```

```
  use limits, only: EOF, VERSION_STRING !NODEP!
```

```
  use constants !NODEP!
```

```
<Use file utils>
```

```
  use diagnostics !NODEP!
```

```
  use os_interface
```

```
  use ifiles
```

```
  use lexers
```

```
  use syntax_rules
```

```
  use parser
```

```
  use variables
```

```
  use expressions
```

```
  use models
```

```
<Standard module head>
```

```
<SLHA: public>
```

```
<SLHA: parameters>
```

```
<SLHA: variables>
```

```
  save
```

```
contains
```

<SLHA: procedures>

```
end module slha_interface
```

16.0.3 Preprocessor

SLHA is a mixed-format standard. It should be read in assuming free format (but line-oriented), but it has some fixed-format elements.

To overcome this difficulty, we implement a preprocessing step which transforms the SLHA into a format that can be swallowed by our generic free-format lexer and parser. Each line with a blank first character is assumed to be a data line. We prepend a 'DATA' keyword to these lines. Furthermore, to enforce line-orientation, each line is appended a '\$' key which is recognized by the parser. To do this properly, we first remove trailing comments, and skip lines consisting only of comments.

The preprocessor reads from a stream and puts out an `ifile`. Blocks that are not recognized are skipped. For some blocks, data items are quoted, so they can be read as strings if necessary.

<SLHA: parameters>≡

```
integer, parameter :: MODE_SKIP = 0, MODE_DATA = 1, MODE_INFO = 2
```

<SLHA: procedures>≡

```
subroutine slha_preprocess (stream, ifile)
  type(stream_t), intent(inout) :: stream
  type(ifile_t), intent(out) :: ifile
  type(string_t) :: buffer, line, item
  integer :: iostat
  integer :: mode
  mode = MODE
  SCAN_FILE: do
    call stream_get_record (stream, buffer, iostat)
    select case (iostat)
    case (0)
      call split (buffer, line, "#")
      if (len_trim (line) == 0) cycle SCAN_FILE
      select case (char (extract (line, 1, 1)))
      case ("B", "b")
        mode = check_block_handling (line)
        call ifile_append (ifile, line // "$")
      case ("D", "d")
        mode = MODE_DATA
        call ifile_append (ifile, line // "$")
      case (" ")
        select case (mode)
        case (MODE_DATA)
          call ifile_append (ifile, "DATA" // line // "$")
        case (MODE_INFO)
          line = adjustl (line)
          call split (line, item, " ")
          call ifile_append (ifile, "INFO" // " " // item // " " &
            // ' ' // trim (adjustl (line)) // ' ' '$')
        end select
      end select
```

```

        case default
            call msg_message (char (line))
            call msg_fatal ("SLHA: Incomprehensible line")
        end select
    case (EOF)
        exit SCAN_FILE
    case default
        call msg_fatal ("SLHA: I/O error occured while reading SLHA input")
    end select
end do SCAN_FILE
end subroutine slha_preprocess

```

Return the mode that we should treat this block with. We need to recognize only those blocks that we actually use.

```

⟨SLHA: procedures⟩+≡
function check_block_handling (line) result (mode)
    integer :: mode
    type(string_t), intent(in) :: line
    type(string_t) :: buffer, key, block_name
    buffer = trim (line)
    call split (buffer, key, " ")
    buffer = adjustl (buffer)
    call split (buffer, block_name, " ")
    block_name = trim (adjustl (upper_case (block_name)))
    select case (char (block_name))
    case ("MODSEL", "MINPAR", "SMINPUTS")
        mode = MODE_DATA
    case ("MASS")
        mode = MODE_DATA
    case ("NMIX", "UMIX", "VMIX", "STOPMIX", "SBOTMIX", "STAUMIX")
        mode = MODE_DATA
    case ("ALPHA", "HMIX")
        mode = MODE_DATA
    case ("AU", "AD", "AE")
        mode = MODE_DATA
    case ("SPINFO", "DCINFO")
        mode = MODE_INFO
    case default
        mode = MODE_SKIP
    end select
end function check_block_handling

```

16.0.4 Lexer and syntax

```

⟨SLHA: variables⟩≡
type(syntax_t), target :: syntax_slha

```

```

⟨SLHA: public⟩≡
public :: syntax_slha_init

```

```

⟨SLHA: procedures⟩+≡
subroutine syntax_slha_init ()

```

```

        type(ifile_t) :: ifile
        call define_slha_syntax (ifile)
        call syntax_init (syntax_slha, ifile)
        call ifile_final (ifile)
    end subroutine syntax_slha_init

<SLHA: public>+=
    public :: syntax_slha_final

<SLHA: procedures>+=
    subroutine syntax_slha_final ()
        call syntax_final (syntax_slha)
    end subroutine syntax_slha_final

<SLHA: procedures>+=
    subroutine define_slha_syntax (ifile)
        type(ifile_t), intent(inout) :: ifile
        call ifile_append (ifile, "SEQ slha = chunk*")
        call ifile_append (ifile, "ALT chunk = block_def | decay_def")
        call ifile_append (ifile, "SEQ block_def = " &
            // "BLOCK block_spec '$' block_line*")
        call ifile_append (ifile, "KEY BLOCK")
        call ifile_append (ifile, "SEQ block_spec = block_name qvalue?")
        call ifile_append (ifile, "IDE block_name")
        call ifile_append (ifile, "SEQ qvalue = qname '=' real")
        call ifile_append (ifile, "IDE qname")
        call ifile_append (ifile, "KEY '='")
        call ifile_append (ifile, "REA real")
        call ifile_append (ifile, "KEY '$'")
        call ifile_append (ifile, "ALT block_line = block_data | block_info")
        call ifile_append (ifile, "SEQ block_data = DATA data_line '$'")
        call ifile_append (ifile, "KEY DATA")
        call ifile_append (ifile, "SEQ data_line = data_item+")
        call ifile_append (ifile, "ALT data_item = signed_number | number")
        call ifile_append (ifile, "SEQ signed_number = sign number")
        call ifile_append (ifile, "ALT sign = '+' | '-'")
        call ifile_append (ifile, "ALT number = integer | real")
        call ifile_append (ifile, "INT integer")
        call ifile_append (ifile, "KEY '-'")
        call ifile_append (ifile, "KEY '+'")
        call ifile_append (ifile, "SEQ block_info = INFO info_line '$'")
        call ifile_append (ifile, "KEY INFO")
        call ifile_append (ifile, "SEQ info_line = integer string_literal")
        call ifile_append (ifile, "QUO string_literal = '... '")
        call ifile_append (ifile, "SEQ decay_def = " &
            // "DECAY decay_spec '$' decay_data*")
        call ifile_append (ifile, "KEY DECAY")
        call ifile_append (ifile, "SEQ decay_spec = pdg_code data_item")
        call ifile_append (ifile, "ALT pdg_code = signed_integer | integer")
        call ifile_append (ifile, "SEQ signed_integer = sign integer")
        call ifile_append (ifile, "SEQ decay_data = DATA decay_line '$'")
        call ifile_append (ifile, "SEQ decay_line = data_item integer pdg_code+")
    end subroutine define_slha_syntax

```

The SLHA specification allows for string data items in certain places. Currently, we do not interpret them, but the strings, which are not quoted, must be parsed somehow. The hack for this problem is to allow essentially all characters as special characters, so the string can be read before it is discarded.

```

<SLHA: public>+=
    public :: lexer_init_slha

<SLHA: procedures>+=
    subroutine lexer_init_slha (lexer)
        type(lexer_t), intent(out) :: lexer
        call lexer_init (lexer, &
            comment_chars = "#", &
            quote_chars = "'", &
            quote_match = "'", &
            single_chars = "+-=$", &
            special_class = (/ " " /), &
            keyword_list = syntax_get_keyword_list_ptr (syntax_slha), &
            upper_case_keywords = .true.) ! $
    end subroutine lexer_init_slha

```

16.0.5 Interpreter

Find blocks

From the parse tree, find the node that represents a particular block. If `required` is true, issue an error if not found. Since `block_name` is always invoked with capital letters, we have to capitalize `pn_block_name`.

```

<SLHA: procedures>+=
    function slha_get_block_ptr &
        (parse_tree, block_name, required) result (pn_block)
        type(parse_node_t), pointer :: pn_block
        type(parse_tree_t), intent(in) :: parse_tree
        type(string_t), intent(in) :: block_name
        logical, intent(in) :: required
        type(parse_node_t), pointer :: pn_root, pn_block_spec, pn_block_name
        pn_root => parse_tree_get_root_ptr (parse_tree)
        pn_block => parse_node_get_sub_ptr (pn_root)
        do while (associated (pn_block))
            select case (char (parse_node_get_rule_key (pn_block)))
            case ("block_def")
                pn_block_spec => parse_node_get_sub_ptr (pn_block, 2)
                pn_block_name => parse_node_get_sub_ptr (pn_block_spec)
                if (trim (adjustl (upper_case (parse_node_get_string &
                    (pn_block_name)))) == block_name) then
                    return
                end if
            end select
            pn_block => parse_node_get_next_ptr (pn_block)
        end do
        if (required) then
            call msg_fatal ("SLHA: block '" // char (block_name) // "' not found")
        end if
    end function

```

```
end function slha_get_block_ptr
```

Scan the file for the first/next DECAY block.

(SLHA: procedures)+≡

```
function slha_get_first_decay_ptr (parse_tree) result (pn_decay)
  type(parse_node_t), pointer :: pn_decay
  type(parse_tree_t), intent(in) :: parse_tree
  type(parse_node_t), pointer :: pn_root
  pn_root => parse_tree_get_root_ptr (parse_tree)
  pn_decay => parse_node_get_sub_ptr (pn_root)
  do while (associated (pn_decay))
    select case (char (parse_node_get_rule_key (pn_decay)))
      case ("decay_def")
        return
    end select
    pn_decay => parse_node_get_next_ptr (pn_decay)
  end do
end function slha_get_first_decay_ptr
```

```
function slha_get_next_decay_ptr (pn_block) result (pn_decay)
  type(parse_node_t), pointer :: pn_decay
  type(parse_node_t), intent(in), target :: pn_block
  pn_decay => parse_node_get_next_ptr (pn_block)
  do while (associated (pn_decay))
    select case (char (parse_node_get_rule_key (pn_decay)))
      case ("decay_def")
        return
    end select
    pn_decay => parse_node_get_next_ptr (pn_decay)
  end do
end function slha_get_next_decay_ptr
```

Extract and transfer data from blocks

Given the parse node of a block, find the parse node of a particular switch or data line. Return this node and the node of the data item following the integer code.

(SLHA: procedures)+≡

```
subroutine slha_find_index_ptr (pn_block, pn_data, pn_item, code)
  type(parse_node_t), intent(in), target :: pn_block
  ! type(parse_node_t), intent(out), pointer :: pn_data
  ! type(parse_node_t), intent(out), pointer :: pn_item
  type(parse_node_t), pointer :: pn_data
  type(parse_node_t), pointer :: pn_item
  integer, intent(in) :: code
  pn_data => parse_node_get_sub_ptr (pn_block, 4)
  call slha_next_index_ptr (pn_data, pn_item, code)
end subroutine slha_find_index_ptr

subroutine slha_find_index_pair_ptr (pn_block, pn_data, pn_item, code1, code2)
  type(parse_node_t), intent(in), target :: pn_block
  ! type(parse_node_t), intent(out), pointer :: pn_data
```

```

!   type(parse_node_t), intent(out), pointer :: pn_item
      type(parse_node_t), pointer :: pn_data
      type(parse_node_t), pointer :: pn_item
      integer, intent(in) :: code1, code2
      pn_data => parse_node_get_sub_ptr (pn_block, 4)
      call slha_next_index_pair_ptr (pn_data, pn_item, code1, code2)
end subroutine slha_find_index_pair_ptr

```

Starting from the pointer to a data line, find a data line with the given integer code.

(SLHA: procedures)+≡

```

subroutine slha_next_index_ptr (pn_data, pn_item, code)
  type(parse_node_t), intent(inout), pointer :: pn_data
  integer, intent(in) :: code
!   type(parse_node_t), intent(out), pointer :: pn_item
      type(parse_node_t), pointer :: pn_item
      type(parse_node_t), pointer :: pn_line, pn_code
      do while (associated (pn_data))
        pn_line => parse_node_get_sub_ptr (pn_data, 2)
        pn_code => parse_node_get_sub_ptr (pn_line)
        select case (char (parse_node_get_rule_key (pn_code)))
          case ("integer")
            if (parse_node_get_integer (pn_code) == code) then
              pn_item => parse_node_get_next_ptr (pn_code)
              return
            end if
          end select
        pn_data => parse_node_get_next_ptr (pn_data)
      end do
      pn_item => null ()
end subroutine slha_next_index_ptr

```

Starting from the pointer to a data line, find a data line with the given integer code pair.

(SLHA: procedures)+≡

```

subroutine slha_next_index_pair_ptr (pn_data, pn_item, code1, code2)
  type(parse_node_t), intent(inout), pointer :: pn_data
  integer, intent(in) :: code1, code2
!   type(parse_node_t), intent(out), pointer :: pn_item
      type(parse_node_t), pointer :: pn_item
      type(parse_node_t), pointer :: pn_line, pn_code1, pn_code2
      do while (associated (pn_data))
        pn_line => parse_node_get_sub_ptr (pn_data, 2)
        pn_code1 => parse_node_get_sub_ptr (pn_line)
        select case (char (parse_node_get_rule_key (pn_code1)))
          case ("integer")
            if (parse_node_get_integer (pn_code1) == code1) then
              pn_code2 => parse_node_get_next_ptr (pn_code1)
              if (associated (pn_code2)) then
                select case (char (parse_node_get_rule_key (pn_code2)))
                  case ("integer")
                    if (parse_node_get_integer (pn_code2) == code2) then
                      pn_item => parse_node_get_next_ptr (pn_code2)

```

```

        return
    end if
end select
end if
end if
end select
pn_data => parse_node_get_next_ptr (pn_data)
end do
pn_item => null ()
end subroutine slha_next_index_pair_ptr

```

Handle info data

Return all strings with index i. The result is an allocated string array. Since we do not know the number of matching entries in advance, we build an intermediate list which is transferred to the final array and deleted before exiting.

(*SLHA: procedures*)+≡

```

subroutine retrieve_strings_in_block (pn_block, code, str_array)
  type(parse_node_t), intent(in), target :: pn_block
  integer, intent(in) :: code
  type(string_t), dimension(:), allocatable, intent(out) :: str_array
  type(parse_node_t), pointer :: pn_data, pn_item
  type :: str_entry_t
    type(string_t) :: str
    type(str_entry_t), pointer :: next => null ()
  end type str_entry_t
  type(str_entry_t), pointer :: first => null ()
  type(str_entry_t), pointer :: current => null ()
  integer :: n
  n = 0
  call slha_find_index_ptr (pn_block, pn_data, pn_item, code)
  if (associated (pn_item)) then
    n = n + 1
    allocate (first)
    first%str = parse_node_get_string (pn_item)
    current => first
    do while (associated (pn_data))
      pn_data => parse_node_get_next_ptr (pn_data)
      call slha_next_index_ptr (pn_data, pn_item, code)
      if (associated (pn_item)) then
        n = n + 1
        allocate (current%next)
        current => current%next
        current%str = parse_node_get_string (pn_item)
      end if
    end do
    allocate (str_array (n))
    n = 0
    do while (associated (first))
      n = n + 1
      current => first
      str_array(n) = current%str
    end do
  end if
end subroutine

```

```

        first => first%next
        deallocate (current)
    end do
else
    allocate (str_array (0))
end if
end subroutine retrieve_strings_in_block

```

Transfer data from SLHA to variables

Extract real parameter with index *i*. If it does not exist, retrieve it from the variable list, using the given name.

(SLHA: procedures)+≡

```

function get_parameter_in_block (pn_block, code, name, var_list) result (var)
    real(default) :: var
    type(parse_node_t), intent(in), target :: pn_block
    integer, intent(in) :: code
    type(string_t), intent(in) :: name
    type(var_list_t), intent(in), target :: var_list
    type(parse_node_t), pointer :: pn_data, pn_item
    call slha_find_index_ptr (pn_block, pn_data, pn_item, code)
    if (associated (pn_item)) then
        var = get_real_parameter (pn_item)
    else
        var = var_list_get_rval (var_list, name)
    end if
end function get_parameter_in_block

```

Extract a real data item with index *i*. If it does exist, set it in the variable list, using the given name. If the variable is not present in the variable list, ignore it.

(SLHA: procedures)+≡

```

subroutine set_data_item (pn_block, code, name, var_list)
    type(parse_node_t), intent(in), target :: pn_block
    integer, intent(in) :: code
    type(string_t), intent(in) :: name
    type(var_list_t), intent(inout), target :: var_list
    type(parse_node_t), pointer :: pn_data, pn_item
    call slha_find_index_ptr (pn_block, pn_data, pn_item, code)
    if (associated (pn_item)) then
        call var_list_set_real &
            (var_list, name, get_real_parameter (pn_item), &
             is_known=.true., ignore=.true.)
    end if
end subroutine set_data_item

```

Extract a real matrix element with index *i, j*. If it does exist, set it in the variable list, using the given name. If the variable is not present in the variable list, ignore it.

(SLHA: procedures)+≡

```

subroutine set_matrix_element (pn_block, code1, code2, name, var_list)

```

```

type(parse_node_t), intent(in), target :: pn_block
integer, intent(in) :: code1, code2
type(string_t), intent(in) :: name
type(var_list_t), intent(inout), target :: var_list
type(parse_node_t), pointer :: pn_data, pn_item
call slha_find_index_pair_ptr (pn_block, pn_data, pn_item, code1, code2)
if (associated (pn_item)) then
    call var_list_set_real &
        (var_list, name, get_real_parameter (pn_item), &
         is_known=.true., ignore=.true.)
end if
end subroutine set_matrix_element

```

Transfer data from variables to SLHA

Get a real/integer parameter with index *i* from the variable list and write it to the current output file. In the integer case, we account for the fact that the variable is type real. If it does not exist, do nothing.

(SLHA: procedures)+≡

```

subroutine write_integer_data_item (u, code, name, var_list, comment)
    integer, intent(in) :: u
    integer, intent(in) :: code
    type(string_t), intent(in) :: name
    type(var_list_t), intent(in) :: var_list
    character(*), intent(in) :: comment
    integer :: item
    if (var_list_exists (var_list, name)) then
        item = nint (var_list_get_rval (var_list, name))
        call write_integer_parameter (u, code, item, comment)
    end if
end subroutine write_integer_data_item

subroutine write_real_data_item (u, code, name, var_list, comment)
    integer, intent(in) :: u
    integer, intent(in) :: code
    type(string_t), intent(in) :: name
    type(var_list_t), intent(in) :: var_list
    character(*), intent(in) :: comment
    real(default) :: item
    if (var_list_exists (var_list, name)) then
        item = var_list_get_rval (var_list, name)
        call write_real_parameter (u, code, item, comment)
    end if
end subroutine write_real_data_item

```

Get a real data item with two integer indices from the variable list and write it to the current output file. If it does not exist, do nothing.

(SLHA: procedures)+≡

```

subroutine write_matrix_element (u, code1, code2, name, var_list, comment)
    integer, intent(in) :: u
    integer, intent(in) :: code1, code2
    type(string_t), intent(in) :: name

```

```

type(var_list_t), intent(in) :: var_list
character(*), intent(in) :: comment
real(default) :: item
if (var_list_exists (var_list, name)) then
    item = var_list_get_rval (var_list, name)
    call write_real_matrix_element (u, code1, code2, item, comment)
end if
end subroutine write_matrix_element

```

16.0.6 Auxiliary function

Write a block header.

(SLHA: procedures)+≡

```

subroutine write_block_header (u, name, comment)
    integer, intent(in) :: u
    character(*), intent(in) :: name, comment
    write (u, "(A,1x,A,3x,'#',1x,A)") "BLOCK", name, comment
end subroutine write_block_header

```

Extract a real parameter that may be defined real or integer, signed or unsigned.

(SLHA: procedures)+≡

```

function get_real_parameter (pn_item) result (var)
    real(default) :: var
    type(parse_node_t), intent(in), target :: pn_item
    type(parse_node_t), pointer :: pn_sign, pn_var
    integer :: sign
    select case (char (parse_node_get_rule_key (pn_item)))
    case ("signed_number")
        pn_sign => parse_node_get_sub_ptr (pn_item)
        pn_var => parse_node_get_next_ptr (pn_sign)
        select case (char (parse_node_get_key (pn_sign)))
        case ("+"); sign = +1
        case ("-"); sign = -1
        end select
    case default
        sign = +1
        pn_var => pn_item
    end select
    select case (char (parse_node_get_rule_key (pn_var)))
    case ("integer"); var = sign * parse_node_get_integer (pn_var)
    case ("real"); var = sign * parse_node_get_real (pn_var)
    end select
end function get_real_parameter

```

Auxiliary: Extract an integer parameter that may be defined signed or unsigned.
A real value is an error.

(SLHA: procedures)+≡

```

function get_integer_parameter (pn_item) result (var)
    integer :: var
    type(parse_node_t), intent(in), target :: pn_item
    type(parse_node_t), pointer :: pn_sign, pn_var

```

```

integer :: sign
select case (char (parse_node_get_rule_key (pn_item)))
case ("signed_integer")
    pn_sign => parse_node_get_sub_ptr (pn_item)
    pn_var => parse_node_get_next_ptr (pn_sign)
    select case (char (parse_node_get_key (pn_sign)))
    case ("+"); sign = +1
    case ("-"); sign = -1
    end select
case ("integer")
    sign = +1
    pn_var => pn_item
case default
    call parse_node_write (pn_var)
    call msg_error ("SLHA: Integer parameter expected")
    var = 0
    return
end select
var = sign * parse_node_get_integer (pn_var)
end function get_integer_parameter

```

Write an integer parameter with a single index directly to file, using the required output format.

```

<SLHA: procedures>+≡
subroutine write_integer_parameter (u, code, item, comment)
    integer, intent(in) :: u
    integer, intent(in) :: code
    integer, intent(in) :: item
    character(*), intent(in) :: comment
1   format (1x, I9, 3x, 3x, I9, 4x, 3x, '#', 1x, A)
    write (u, 1) code, item, comment
end subroutine write_integer_parameter

```

Write a real parameter with two indices directly to file, using the required output format.

```

<SLHA: procedures>+≡
subroutine write_real_parameter (u, code, item, comment)
    integer, intent(in) :: u
    integer, intent(in) :: code
    real(default), intent(in) :: item
    character(*), intent(in) :: comment
1   format (1x, I9, 3x, 1P, E16.8, 0P, 3x, '#', 1x, A)
    write (u, 1) code, item, comment
end subroutine write_real_parameter

```

Write a real parameter with a single index directly to file, using the required output format.

```

<SLHA: procedures>+≡
subroutine write_real_matrix_element (u, code1, code2, item, comment)
    integer, intent(in) :: u
    integer, intent(in) :: code1, code2
    real(default), intent(in) :: item

```

```

character(*), intent(in) :: comment
1 format (1x, I2, 1x, I2, 3x, 1P, E16.8, 0P, 3x, '#', 1x, A)
write (u, 1) code1, code2, item, comment
end subroutine write_real_matrix_element

```

The concrete SLHA interpreter

SLHA codes for particular physics models

<SLHA: parameters>+≡

```

integer, parameter :: MDL_MSSM = 0
integer, parameter :: MDL_NMSSM = 1

```

Take the parse tree and extract relevant data. Select the correct model and store all data that is present in the appropriate variable list. Finally, update the variable record.

<SLHA: procedures>+≡

```

subroutine slha_interpret_parse_tree &
    (parse_tree, os_data, model, input, spectrum, decays)
type(parse_tree_t), intent(in) :: parse_tree
type(os_data_t), intent(in) :: os_data
! type(model_t), pointer, intent(out) :: model
type(model_t), pointer, intent(inout) :: model
logical, intent(in) :: input, spectrum, decays
logical :: errors
integer :: mssm_type
call slha_handle_MODELSEL (parse_tree, os_data, model, mssm_type)
if (associated(model)) then
    if (input) then
        call slha_handle_SMINPUTS (parse_tree, model)
        call slha_handle_MINPAR (parse_tree, model, mssm_type)
    end if
    if (spectrum) then
        call slha_handle_info_block (parse_tree, "SPINFO", errors)
        if (errors) return
        call slha_handle_MASS (parse_tree, model)
        call slha_handle_matrix_block (parse_tree, "NMIX", "mn_", 4, model)
        call slha_handle_matrix_block (parse_tree, "UMIX", "mu_", 2, model)
        call slha_handle_matrix_block (parse_tree, "VMIX", "mv_", 2, model)
        call slha_handle_matrix_block (parse_tree, "STOPMIX", "mt_", 2, model)
        call slha_handle_matrix_block (parse_tree, "SBOTMIX", "mb_", 2, model)
        call slha_handle_matrix_block (parse_tree, "STAUMIX", "ml_", 2, model)
        call slha_handle_ALPHA (parse_tree, model)
        call slha_handle_HMIX (parse_tree, model)
        call slha_handle_matrix_block (parse_tree, "AU", "Au_", 3, model)
        call slha_handle_matrix_block (parse_tree, "AD", "Ad_", 3, model)
        call slha_handle_matrix_block (parse_tree, "AE", "Ae_", 3, model)
    end if
    if (decays) then
        call slha_handle_info_block (parse_tree, "DCINFO", errors)
        if (errors) return
        call slha_handle_decays (parse_tree, model)
    end if
end if

```

```
end subroutine slha_interpret_parse_tree
```

Info blocks

Handle the informational blocks SPINFO and DCINFO. The first two items are program name and version. Items with index 3 are warnings. Items with index 4 are errors. We reproduce these as WHIZARD warnings and errors.

(SLHA: procedures) +=

```
subroutine slha_handle_info_block (parse_tree, block_name, errors)
  type(parse_tree_t), intent(in) :: parse_tree
  character(*), intent(in) :: block_name
  logical, intent(out) :: errors
  type(parse_node_t), pointer :: pn_block
  type(string_t), dimension(:), allocatable :: msg
  integer :: i
  pn_block => slha_get_block_ptr &
    (parse_tree, var_str (block_name), required=.true.)
  if (.not. associated (pn_block)) then
    call msg_error ("SLHA: Missing info block '" &
      // trim (block_name) // "'; ignored.")
    errors = .true.
    return
  end if
  select case (block_name)
  case ("SPINFO")
    call msg_message ("SLHA: SUSY spectrum program info:")
  case ("DCINFO")
    call msg_message ("SLHA: SUSY decay program info:")
  end select
  call retrieve_strings_in_block (pn_block, 1, msg)
  do i = 1, size (msg)
    call msg_message ("SLHA: " // char (msg(i)))
  end do
  call retrieve_strings_in_block (pn_block, 2, msg)
  do i = 1, size (msg)
    call msg_message ("SLHA: " // char (msg(i)))
  end do
  call retrieve_strings_in_block (pn_block, 3, msg)
  do i = 1, size (msg)
    call msg_warning ("SLHA: " // char (msg(i)))
  end do
  call retrieve_strings_in_block (pn_block, 4, msg)
  do i = 1, size (msg)
    call msg_error ("SLHA: " // char (msg(i)))
  end do
  errors = size (msg) > 0
end subroutine slha_handle_info_block
```

MODSEL

Handle the overall model definition. Only certain models are recognized. The soft-breaking model templates that determine the set of input parameters:

(SLHA: parameters)+≡

```
integer, parameter :: MSSM_GENERIC = 0
integer, parameter :: MSSM_SUGRA = 1
integer, parameter :: MSSM_GMSB = 2
integer, parameter :: MSSM_AMSB = 3
```

(SLHA: procedures)+≡

```
subroutine slha_handle_MODSEL (parse_tree, os_data, model, mssm_type)
  type(parse_tree_t), intent(in) :: parse_tree
  type(os_data_t), intent(in) :: os_data
  type(model_t), pointer, intent(inout) :: model
  integer, intent(out) :: mssm_type
  type(parse_node_t), pointer :: pn_block, pn_data, pn_item
  type(string_t) :: model_name
  type(string_t) :: filename
  pn_block => slha_get_block_ptr &
    (parse_tree, var_str ("MODSEL"), required=.true.)
  call slha_find_index_ptr (pn_block, pn_data, pn_item, 1)
  if (associated (pn_item)) then
    mssm_type = get_integer_parameter (pn_item)
  else
    mssm_type = MSSM_GENERIC
  end if
  call slha_find_index_ptr (pn_block, pn_data, pn_item, 3)
  if (associated (pn_item)) then
    select case (parse_node_get_integer (pn_item))
    case (MDL_MSSM); model_name = "MSSM"
    case (MDL_NMSSM); model_name = "NMSSM"
    case default
      call msg_fatal ("SLHA: unknown model code in MODSEL")
      return
    end select
  else
    model_name = "MSSM"
  end if
  select case (char (model_name))
  case ("MSSM")
    select case (char (model_get_name (model)))
    case ("MSSM","MSSM_CKM","MSSM_Grav")
      model_name = model_get_name (model)
    case default
      call msg_fatal (" User-defined model and model in SLHA input file do not match.")
    end select
  case ("NMSSM")
    select case (char (model_get_name (model)))
    case ("NMSSM","NMSSM_CKM")
      model_name = model_get_name (model)
    case default
      call msg_fatal (" User-defined model and model in SLHA input file do not match.")
    end select
  end select
```

```

        case default
            call msg_fatal (" SLHA model selection failure.")
        end select
        filename = model_name // ".mdl"
        model => null ()
        call model_list_read_model (model_name, filename, os_data, model)
        if (associated (model)) then
            call msg_message ("SLHA: Initializing model '" &
                // char (model_name) // "'")
        else
            call msg_fatal ("SLHA: Initialization failed for model '" &
                // char (model_name) // "'")
        end if
    end subroutine slha_handle_MODSEL

```

Write a MODSEL block, based on the contents of the current model.

(SLHA: procedures)+≡

```

subroutine slha_write_MODSEL (u, model, mssm_type)
    integer, intent(in) :: u
    type(model_t), intent(in), target :: model
    integer, intent(out) :: mssm_type
    type(var_list_t), pointer :: var_list
    integer :: model_id
    type(string_t) :: mtype_string
    var_list => model_get_var_list_ptr (model)
    if (var_list_exists (var_list, var_str ("mtype"))) then
        mssm_type = nint (var_list_get_rval (var_list, var_str ("mtype")))
    else
        call msg_error ("SLHA: parameter 'mtype' (SUSY breaking scheme) " &
            // "is unknown in current model, no SLHA output possible")
        mssm_type = -1
        return
    end if
    call write_block_header (u, "MODSEL", "SUSY model selection")
    select case (mssm_type)
    case (0); mtype_string = "Generic MSSM"
    case (1); mtype_string = "SUGRA"
    case (2); mtype_string = "GMSB"
    case (3); mtype_string = "AMSB"
    case default
        mtype_string = "unknown"
    end select
    call write_integer_parameter (u, 1, mssm_type, &
        "SUSY-breaking scheme: " // char (mtype_string))
    select case (char (model_get_name (model)))
    case ("MSSM"); model_id = MDL_MSSM
    case ("NMSSM"); model_id = MDL_NMSSM
    case default
        model_id = 0
    end select
    call write_integer_parameter (u, 3, model_id, &
        "SUSY model type: " // char (model_get_name (model)))
end subroutine slha_write_MODSEL

```

SMINPUTS

Read SM parameters and update the variable list accordingly. If a parameter is not defined in the block, we use the previous value from the model variable list. For the basic parameters we have to do a small recalculation, since SLHA uses the G_F - α - m_Z scheme, while WHIZARD derives them from G_F , m_W , and m_Z .

(SLHA: procedures)+≡

```

subroutine slha_handle_SMINPUTS (parse_tree, model)
  type(parse_tree_t), intent(in) :: parse_tree
  type(model_t), intent(inout), target :: model
  type(parse_node_t), pointer :: pn_block
  real(default) :: alpha_em_i, GF, alphas, mZ
  real(default) :: ee, vv, cw_sw, cw2, mW
  real(default) :: mb, mtop, mtau
  type(var_list_t), pointer :: var_list
  var_list => model_get_var_list_ptr (model)
  pn_block => slha_get_block_ptr &
    (parse_tree, var_str ("SMINPUTS"), required=.true.)
  if (.not. (associated (pn_block))) return
  alpha_em_i = &
    get_parameter_in_block (pn_block, 1, var_str ("alpha_em_i"), var_list)
  GF = get_parameter_in_block (pn_block, 2, var_str ("GF"), var_list)
  alphas = &
    get_parameter_in_block (pn_block, 3, var_str ("alphas"), var_list)
  mZ = get_parameter_in_block (pn_block, 4, var_str ("mZ"), var_list)
  mb = get_parameter_in_block (pn_block, 5, var_str ("mb"), var_list)
  mtop = get_parameter_in_block (pn_block, 6, var_str ("mtop"), var_list)
  mtau = get_parameter_in_block (pn_block, 7, var_str ("mtau"), var_list)
  ee = sqrt (4 * pi / alpha_em_i)
  vv = 1 / sqrt (sqrt (2._default) * GF)
  cw_sw = ee * vv / (2 * mZ)
  if (2*cw_sw <= 1) then
    cw2 = (1 + sqrt (1 - 4 * cw_sw**2)) / 2
    mW = mZ * sqrt (cw2)
    call var_list_set_real (var_list, var_str ("GF"), GF, .true.)
    call var_list_set_real (var_list, var_str ("mZ"), mZ, .true.)
    call var_list_set_real (var_list, var_str ("mW"), mW, .true.)
    call var_list_set_real (var_list, var_str ("mtau"), mtau, .true.)
    call var_list_set_real (var_list, var_str ("mb"), mb, .true.)
    call var_list_set_real (var_list, var_str ("mtop"), mtop, .true.)
    call var_list_set_real (var_list, var_str ("alphas"), alphas, .true.)
  else
    call msg_fatal ("SLHA: Unphysical SM parameter values")
    return
  end if
end subroutine slha_handle_SMINPUTS

```

Write a SMINPUTS block.

(SLHA: procedures)+≡

```

subroutine slha_write_SMINPUTS (u, model)
  integer, intent(in) :: u

```

```

type(model_t), intent(in), target :: model
type(var_list_t), pointer :: var_list
integer :: model_id
var_list => model_get_var_list_ptr (model)
call write_block_header (u, "SMINPUTS", "SM input parameters")
call write_real_data_item (u, 1, var_str ("alpha_em_i"), var_list, &
    "Inverse electromagnetic coupling alpha (Z pole)")
call write_real_data_item (u, 2, var_str ("GF"), var_list, &
    "Fermi constant")
call write_real_data_item (u, 3, var_str ("alphas"), var_list, &
    "Strong coupling alpha_s (Z pole)")
call write_real_data_item (u, 4, var_str ("mZ"), var_list, &
    "Z mass")
call write_real_data_item (u, 5, var_str ("mb"), var_list, &
    "b running mass (at mb)")
call write_real_data_item (u, 6, var_str ("mtop"), var_list, &
    "top mass")
call write_real_data_item (u, 7, var_str ("mtau"), var_list, &
    "tau mass")
end subroutine slha_write_SMINPUTS

```

MINPAR

The block of SUSY input parameters. They are accessible to WHIZARD, but they only get used when an external spectrum generator is invoked. The precise set of parameters depends on the type of SUSY breaking, which by itself is one of the parameters.

(*SLHA: procedures*) +=

```

subroutine slha_handle_MINPAR (parse_tree, model, mssm_type)
type(parse_tree_t), intent(in) :: parse_tree
type(model_t), intent(inout), target :: model
integer, intent(in) :: mssm_type
type(var_list_t), pointer :: var_list
type(parse_node_t), pointer :: pn_block
var_list => model_get_var_list_ptr (model)
call var_list_set_real (var_list, &
    var_str ("mtype"), real(mssm_type, default), is_known=.true.)
pn_block => slha_get_block_ptr &
    (parse_tree, var_str ("MINPAR"), required=.true.)
select case (mssm_type)
case (MSSM_SUGRA)
    call set_data_item (pn_block, 1, var_str ("m_zero"), var_list)
    call set_data_item (pn_block, 2, var_str ("m_half"), var_list)
    call set_data_item (pn_block, 3, var_str ("tanb"), var_list)
    call set_data_item (pn_block, 4, var_str ("sgn_mu"), var_list)
    call set_data_item (pn_block, 5, var_str ("A0"), var_list)
case (MSSM_GMSB)
    call set_data_item (pn_block, 1, var_str ("Lambda"), var_list)
    call set_data_item (pn_block, 2, var_str ("M_mes"), var_list)
    call set_data_item (pn_block, 3, var_str ("tanb"), var_list)
    call set_data_item (pn_block, 4, var_str ("sgn_mu"), var_list)
    call set_data_item (pn_block, 5, var_str ("N_5"), var_list)

```

```

        call set_data_item (pn_block, 6, var_str ("c_grav"), var_list)
    case (MSSM_AMSB)
        call set_data_item (pn_block, 1, var_str ("m_zero"), var_list)
        call set_data_item (pn_block, 2, var_str ("m_grav"), var_list)
        call set_data_item (pn_block, 3, var_str ("tanb"), var_list)
        call set_data_item (pn_block, 4, var_str ("sgn_mu"), var_list)
    case default
        call set_data_item (pn_block, 3, var_str ("tanb"), var_list)
    end select
end subroutine slha_handle_MINPAR

```

Write a MINPAR block as appropriate for the current model type.

(*SLHA: procedures*) +=

```

subroutine slha_write_MINPAR (u, model, mssm_type)
    integer, intent(in) :: u
    type(model_t), intent(in), target :: model
    integer, intent(in) :: mssm_type
    type(var_list_t), pointer :: var_list
    integer :: model_id
    var_list => model_get_var_list_ptr (model)
    call write_block_header (u, "MINPAR", "Basic SUSY input parameters")
    select case (mssm_type)
    case (MSSM_SUGRA)
        call write_real_data_item (u, 1, var_str ("m_zero"), var_list, &
            "Common scalar mass")
        call write_real_data_item (u, 2, var_str ("m_half"), var_list, &
            "Common gaugino mass")
        call write_real_data_item (u, 3, var_str ("tanb"), var_list, &
            "tan(beta)")
        call write_integer_data_item (u, 4, &
            var_str ("sgn_mu"), var_list, &
            "Sign of mu")
        call write_real_data_item (u, 5, var_str ("A0"), var_list, &
            "Common trilinear coupling")
    case (MSSM_GMSB)
        call write_real_data_item (u, 1, var_str ("Lambda"), var_list, &
            "Soft-breaking scale")
        call write_real_data_item (u, 2, var_str ("M_mes"), var_list, &
            "Messenger scale")
        call write_real_data_item (u, 3, var_str ("tanb"), var_list, &
            "tan(beta)")
        call write_integer_data_item (u, 4, &
            var_str ("sgn_mu"), var_list, &
            "Sign of mu")
        call write_integer_data_item (u, 5, var_str ("N_5"), var_list, &
            "Messenger index")
        call write_real_data_item (u, 6, var_str ("c_grav"), var_list, &
            "Gravitino mass factor")
    case (MSSM_AMSB)
        call write_real_data_item (u, 1, var_str ("m_zero"), var_list, &
            "Common scalar mass")
        call write_real_data_item (u, 2, var_str ("m_grav"), var_list, &
            "Gravitino mass")
        call write_real_data_item (u, 3, var_str ("tanb"), var_list, &

```

```

        "tan(beta)")
    call write_integer_data_item (u, 4, &
        var_str ("sgn_mu"), var_list, &
        "Sign of mu")
case default
    call write_real_data_item (u, 3, var_str ("tanb"), var_list, &
        "tan(beta)")
end select
end subroutine slha_write_MINPAR

```

Mass spectrum

Set masses. Since the particles are identified by PDG code, read the line and try to set the appropriate particle mass in the current model. At the end, update parameters, just in case the W or Z mass was included.

(SLHA: procedures)+≡

```

subroutine slha_handle_MASS (parse_tree, model)
    type(parse_tree_t), intent(in) :: parse_tree
    type(model_t), intent(inout), target :: model
    type(parse_node_t), pointer :: pn_block, pn_data, pn_line, pn_code
    type(parse_node_t), pointer :: pn_mass
    integer :: pdg
    real(default) :: mass
    pn_block => slha_get_block_ptr &
        (parse_tree, var_str ("MASS"), required=.true.)
    if (.not. (associated (pn_block))) return
    pn_data => parse_node_get_sub_ptr (pn_block, 4)
    do while (associated (pn_data))
        pn_line => parse_node_get_sub_ptr (pn_data, 2)
        pn_code => parse_node_get_sub_ptr (pn_line)
        if (associated (pn_code)) then
            pdg = get_integer_parameter (pn_code)
            pn_mass => parse_node_get_next_ptr (pn_code)
            if (associated (pn_mass)) then
                mass = get_real_parameter (pn_mass)
                call model_set_particle_mass (model, pdg, mass)
            else
                call msg_error ("SLHA: Block MASS: Missing mass value")
            end if
        else
            call msg_error ("SLHA: Block MASS: Missing PDG code")
        end if
        pn_data => parse_node_get_next_ptr (pn_data)
    end do
end subroutine slha_handle_MASS

```

Widths

Set widths. For each DECAY block, extract the header, read the PDG code and width, and try to set the appropriate particle width in the current model.

(SLHA: procedures)+≡

```

subroutine slha_handle_decays (parse_tree, model)
  type(parse_tree_t), intent(in) :: parse_tree
  type(model_t), intent(inout), target :: model
  type(parse_node_t), pointer :: pn_decay, pn_decay_spec, pn_code, pn_width
  integer :: pdg
  real(default) :: width
  pn_decay => slha_get_first_decay_ptr (parse_tree)
  do while (associated (pn_decay))
    pn_decay_spec => parse_node_get_sub_ptr (pn_decay, 2)
    pn_code => parse_node_get_sub_ptr (pn_decay_spec)
    pdg = get_integer_parameter (pn_code)
    pn_width => parse_node_get_next_ptr (pn_code)
    width = get_real_parameter (pn_width)
    call model_set_particle_width (model, pdg, width)
    pn_decay => slha_get_next_decay_ptr (pn_decay)
  end do
end subroutine slha_handle_decays

```

Mixing matrices

Read mixing matrices. We can treat all matrices by a single procedure if we just know the block name, variable prefix, and matrix dimension. The matrix dimension must be less than 10.

(SLHA: procedures) +=

```

subroutine slha_handle_matrix_block &
  (parse_tree, block_name, var_prefix, dim, model)
  type(parse_tree_t), intent(in) :: parse_tree
  character(*), intent(in) :: block_name, var_prefix
  integer, intent(in) :: dim
  type(model_t), intent(inout), target :: model
  type(parse_node_t), pointer :: pn_block
  type(var_list_t), pointer :: var_list
  integer :: i, j
  character(len=len(var_prefix)+2) :: var_name
  var_list => model_get_var_list_ptr (model)
  pn_block => slha_get_block_ptr &
    (parse_tree, var_str (block_name), required=.false.)
  if (.not. (associated (pn_block))) return
  do i = 1, dim
    do j = 1, dim
      write (var_name, "(A,I1,I1)") var_prefix, i, j
      call set_matrix_element (pn_block, i, j, var_str (var_name), var_list)
    end do
  end do
end subroutine slha_handle_matrix_block

```

Higgs data

Read the block ALPHA which holds just the Higgs mixing angle.

(SLHA: procedures) +=

```

subroutine slha_handle_ALPHA (parse_tree, model)

```

```

type(parse_tree_t), intent(in) :: parse_tree
type(model_t), intent(inout), target :: model
type(parse_node_t), pointer :: pn_block, pn_line, pn_data, pn_item
type(var_list_t), pointer :: var_list
real(default) :: al_h
var_list => model_get_var_list_ptr (model)
pn_block => slha_get_block_ptr &
    (parse_tree, var_str ("ALPHA"), required=.false.)
if (.not. (associated (pn_block))) return
pn_data => parse_node_get_sub_ptr (pn_block, 4)
pn_line => parse_node_get_sub_ptr (pn_data, 2)
pn_item => parse_node_get_sub_ptr (pn_line)
if (associated (pn_item)) then
    al_h = get_real_parameter (pn_item)
    call var_list_set_real (var_list, var_str ("al_h"), al_h, &
        is_known=.true., ignore=.true.)
end if
end subroutine slha_handle_ALPHA

```

Read the block HMX for the Higgs mixing parameters

(SLHA: procedures)+≡

```

subroutine slha_handle_HMX (parse_tree, model)
type(parse_tree_t), intent(in) :: parse_tree
type(model_t), intent(inout), target :: model
type(parse_node_t), pointer :: pn_block
type(var_list_t), pointer :: var_list
var_list => model_get_var_list_ptr (model)
pn_block => slha_get_block_ptr &
    (parse_tree, var_str ("HMX"), required=.false.)
if (.not. (associated (pn_block))) return
call set_data_item (pn_block, 1, var_str ("mu_h"), var_list)
call set_data_item (pn_block, 2, var_str ("tanb_h"), var_list)
end subroutine slha_handle_HMX

```

16.0.7 Parser

Read a SLHA file from stream, including preprocessing, and make up a parse tree.

(SLHA: procedures)+≡

```

subroutine slha_parse_stream (stream, parse_tree)
type(stream_t), intent(inout) :: stream
type(parse_tree_t), intent(out) :: parse_tree
type(ifile_t) :: ifile
type(lexer_t) :: lexer
type(stream_t) :: stream_tmp
call slha_preprocess (stream, ifile)
call stream_init (stream_tmp, ifile)
call lexer_init_slha (lexer)
call parse_tree_init (parse_tree, syntax_slha, lexer, stream_tmp)
call lexer_final (lexer)
call stream_final (stream_tmp)
call ifile_final (ifile)

```

```
end subroutine slha_parse_stream
```

Read a SLHA file chosen by name. Check first the current directory, then the directory where SUSY input files should be located.

<SLHA: procedures>+≡

```
subroutine slha_parse_file (file, os_data, parse_tree)
  type(string_t), intent(in) :: file
  type(os_data_t), intent(in) :: os_data
  type(parse_tree_t), intent(out) :: parse_tree
  logical :: exist
  integer :: unit
  type(string_t) :: filename
  type(stream_t) :: stream
  call msg_message ("Reading SLHA input file '" // char (file) // "'")
  filename = file
  inquire (file=char(filename), exist=exist)
  if (.not. exist) then
    filename = os_data%whizard_susypath // "/" // file
    inquire (file=char(filename), exist=exist)
    if (.not. exist) then
      call msg_fatal ("SLHA input file '" // char (file) // "' not found")
      return
    end if
  end if
  unit = free_unit ()
  open (unit=unit, file=char(filename), action="read", status="old")
  call stream_init (stream, unit)
  call slha_parse_stream (stream, parse_tree)
  call stream_final (stream)
  close (unit)
end subroutine slha_parse_file
```

16.0.8 API

Read the SLHA file, parse it, and interpret the parse tree. The model parameters retrieved from the file will be inserted into the appropriate model, which is loaded and modified in the background. The pointer to this model is returned as the last argument.

<SLHA: public>+≡

```
public :: slha_read_file
```

<SLHA: procedures>+≡

```
subroutine slha_read_file (file, os_data, model, input, spectrum, decays)
  type(string_t), intent(in) :: file
  type(os_data_t), intent(in) :: os_data
  ! type(model_t), pointer, intent(out) :: model
  type(model_t), pointer, intent(inout) :: model
  logical, intent(in) :: input, spectrum, decays
  type(parse_tree_t) :: parse_tree
  call slha_parse_file (file, os_data, parse_tree)
  if (associated (parse_tree_get_root_ptr (parse_tree))) then
    call slha_interpret_parse_tree &
```

```

        (parse_tree, os_data, model, input, spectrum, decays)
    call parse_tree_final (parse_tree)
    call model_parameters_update (model)
end if
end subroutine slha_read_file

```

Write the SLHA contents, as far as possible, to external file.

```

<SLHA: public>+=
    public :: slha_write_file

<SLHA: procedures>+=
    subroutine slha_write_file (file, model, input, spectrum, decays)
        type(string_t), intent(in) :: file
        type(model_t), target, intent(in) :: model
        logical, intent(in) :: input, spectrum, decays
        integer :: mssm_type
        integer :: u
        u = free_unit ()
        call msg_message ("Writing SLHA output file '" // char(file) // "'")
        open (unit=u, file=char(file), action="write", status="replace")
        write (u, "(A)")  "# SUSY Les Houches Accord"
        write (u, "(A)")  "# Output generated by " // trim(VERSION_STRING)
        call slha_write_MODSEL (u, model, mssm_type)
        if (input) then
            call slha_write_SMINPUTS (u, model)
            call slha_write_MINPAR (u, model, mssm_type)
        end if
        if (spectrum) then
            call msg_bug ("SLHA: spectrum output not supported yet")
        end if
        if (decays) then
            call msg_bug ("SLHA: decays output not supported yet")
        end if
        close (u)
    end subroutine slha_write_file

```

16.0.9 Test

```

<SLHA: public>+=
    public :: slha_test

<SLHA: procedures>+=
    subroutine slha_test ()
        type(os_data_t) :: os_data
        type(parse_tree_t) :: parse_tree
        integer :: unit
        character(*), parameter :: file_test = "slha_test.out"
        character(*), parameter :: file_slha = "slha_test.dat"
        type(model_t), pointer :: model
        call os_data_init (os_data)
        call slha_parse_file (var_str ("spslap_decays.slha"), os_data, parse_tree)
        call msg_message ("Writing parse tree to '" // file_test // "'")
        unit = free_unit ()
    end subroutine slha_test

```

```

open (unit=unit, file=file_test, action="write", status="replace")
call parse_tree_write (parse_tree, unit)
call slha_interpret_parse_tree (parse_tree, os_data, model, &
    input=.true., spectrum=.true., decays=.true.)
call parse_tree_final (parse_tree)
call var_list_write (model_get_var_list_ptr (model), only_type=V_REAL)
call msg_message ("Writing SLHA output to '" // file_slha // "'")
call slha_write_file (var_str (file_slha), model, input=.true., &
    spectrum=.false., decays=.false.)
end subroutine slha_test

```

Chapter 17

Top level API

17.1 Commands

This module defines the command language of the main input file.

`<commands.f90>`≡
<File header>

```
module commands

  <Use kinds>
    use kinds, only: double !NODEP!
  <Use strings>
    use limits, only: ITERATIONS_DEFAULT_LIST_SIZE !NODEP!
    use constants !NODEP!
  <Use file utils>
    use diagnostics !NODEP!
    use lorentz !NODEP!
    use tao_random_numbers !NODEP!
    use md5
    use os_interface
    use ifiles
    use lexers
    use syntax_rules
    use parser
    use analysis
    use pdg_arrays
    use variables
    use expressions
    use models
    use state_matrices
    use flavors
    use quantum_numbers
    use polarizations
    use les_houches_events
    use hepmc_interface
    use beams
    use sf_isr
    use sf_epa
```

```

use sf_ewa
use sf_lhapdf
use strfun
use mappings
use phs_forests
use cascades
use process_libraries
use processes
use decays
use events
use slha_interface

⟨Standard module head⟩

⟨Commands: public⟩

⟨Commands: parameters⟩

⟨Commands: types⟩

⟨Commands: variables⟩

contains

⟨Commands: procedures⟩

end module commands

```

17.1.1 Step lists for looping

An entry in the step list represents a triplet of initial value, final value, and step size. The latter could also be a factor, for multiplicative stepping. Alternatively, there may be only a single value, with no steps.

Each value is represented by an expression that can be evaluated.

```

⟨Commands: parameters⟩≡
integer, parameter :: ST_NONE = 0
integer, parameter :: ST_SINGLE = 1
integer, parameter :: ST_LINEAR = 2
integer, parameter :: ST_LOG = 3

⟨Commands: types⟩≡
type :: step_spec_t
private
integer :: type = ST_NONE
type(eval_tree_t) :: expr_beg
type(eval_tree_t) :: expr_end
type(eval_tree_t) :: expr_step
type(step_spec_t), pointer :: next => null ()
end type step_spec_t

⟨Commands: types⟩+≡
type :: step_list_t

```

```

private
type(step_spec_t), pointer :: first => null ()
type(step_spec_t), pointer :: last => null ()
end type step_list_t

```

If the type is SINGLE, there is one parse node. For LINEAR and LOG, there are three.

```

⟨Commands: procedures⟩≡
subroutine step_list_append_val (step_list, type, var_list, pn1, pn2, pn3)
type(step_list_t), intent(inout) :: step_list
integer, intent(in) :: type
type(var_list_t), intent(in), target :: var_list
type(parse_node_t), intent(in), target :: pn1
type(parse_node_t), intent(in), optional, target :: pn2, pn3
type(step_spec_t), pointer :: current
allocate (current)
current%type = type
call eval_tree_init_expr (current%expr_beg, pn1, var_list)
select case (type)
case (ST_LINEAR, ST_LOG)
call eval_tree_init_expr (current%expr_end, pn2, var_list)
call eval_tree_init_expr (current%expr_step, pn3, var_list)
end select
if (associated (step_list%last)) then
step_list%last%next => current
else
step_list%first => current
end if
step_list%last => current
end subroutine step_list_append_val

```

Finalize.

```

⟨Commands: procedures⟩+≡
subroutine step_list_final (step_list)
type(step_list_t), intent(inout) :: step_list
type(step_spec_t), pointer :: current
do while (associated (step_list%first))
current => step_list%first
step_list%first => current%next
call eval_tree_final (current%expr_beg)
call eval_tree_final (current%expr_end)
call eval_tree_final (current%expr_step)
deallocate (current)
end do
step_list%last => null ()
end subroutine step_list_final

```

17.1.2 Structure-function configuration

Mapping configuration

A mapping is defined for a particular set of x -parameters. It has a type and a set of real parameters whose meaning depends on the type.

```
<Commands: types>+≡
  type :: sf_mapping_t
  private
    integer, dimension(:), allocatable :: index
    integer :: type = SFM_NONE
    real(default), dimension(:), allocatable :: par
  end type sf_mapping_t
```

Output

```
<Commands: procedures>+≡
  subroutine sf_mapping_write (sf_mapping, unit)
    type(sf_mapping_t), intent(in) :: sf_mapping
    integer, intent(in), optional :: unit
    integer :: u
    u = output_unit (unit); if (u < 0) return
    write (u, "(1x,A,I0,I0(' , #',I0))") "Mapping for parameters #", &
      sf_mapping%index
    select case (sf_mapping%type)
    case (SFM_NONE); write (u, "(3x,A)") "[none]"
    case (SFM_PDFPAIR); write (u, "(3x,A)") "PDF pair mapping"
    case (SFM_ISRPAIR); write (u, "(3x,A)") "ISR pair mapping"
    case (SFM_EPAPAIR); write (u, "(3x,A)") "EPA pair mapping"
    end select
    if (allocated (sf_mapping%par)) then
      write (u, "(3x,A)", advance="no") "Parameters = "
      write (u, *) sf_mapping%par
    end if
  end subroutine sf_mapping_write
```

Single structure function

This type holds the configuration of a structure function or function pair.

```
<Commands: types>+≡
  type :: sf_data_t
  private
    integer :: type = STRF_NONE
    logical, dimension(2) :: affects_beam = .false.
    integer :: n_parameters = 0
    type(isr_data_t), dimension(2) :: isr
    type(epa_data_t), dimension(2) :: epa
    type(lhapdf_data_t), dimension(2) :: lhpdf
    logical :: has_mapping = .false.
    type(sf_mapping_t) :: mapping
    type(sf_data_t), pointer :: next => null ()
  end type sf_data_t
```

Output:

(Commands: procedures)+≡

```

subroutine sf_data_write (sf_data, unit)
  type(sf_data_t), intent(in) :: sf_data
  integer, intent(in), optional :: unit
  integer :: u, i
  u = output_unit (unit); if (u < 0) return
  write (u, "(A)") "Structure function"
  do i = 1, 2
    if (sf_data%affects_beam(i)) then
      select case (sf_data%type)
        case (STRF_NONE)
          write (u, "(1x,A)") "[none]"
        case (STRF_ISR)
          call isr_data_write (sf_data%isr(i), unit)
        case (STRF_EPA)
          call epa_data_write (sf_data%epa(i), unit)
        case (STRF_LHAPDF)
          call lhpdf_data_write (sf_data%lhpdf(i), unit)
      end select
    end if
  end do
  write (u, *) "affects beams = ", sf_data%affects_beam
  write (u, *) "n_parameters = ", sf_data%n_parameters
  if (sf_data%has_mapping) then
    call sf_mapping_write (sf_data%mapping, unit)
  end if
end subroutine sf_data_write

```

Initialize a dataset in the list with LHAPDF-specific options.

For the PDF pair case, we apply a mapping of the unit square which has a real-valued power as parameter. The default value is two.

(Commands: procedures)+≡

```

subroutine sf_data_init_lhpdf &
  (sf_data, lhpdf_status, model, flv, file, member, photon_scheme)
  type(sf_data_t), intent(inout) :: sf_data
  type(lhpdf_status_t), intent(inout) :: lhpdf_status
  type(model_t), intent(in), target :: model
  type(flavor_t), dimension(2), intent(in) :: flv
  type(string_t), intent(in), optional :: file
  integer, intent(in), optional :: member
  integer, intent(in), optional :: photon_scheme
  integer :: i
  do i = 1, 2
    if (sf_data%affects_beam(i)) then
      call lhpdf_data_init (sf_data%lhpdf(i), lhpdf_status, &
        model, flv(i), file, member, photon_scheme)
    end if
  end do
  if (all (sf_data%affects_beam)) then
    allocate (sf_data%mapping%index (2))
    sf_data%mapping%index = (/1, sf_data%n_parameters+1/)
    sf_data%mapping%type = SFM_PDFPAIR
  end if
end subroutine sf_data_init_lhpdf

```

```

        allocate (sf_data%mapping%par (1))
        sf_data%mapping%par = 2._default
        sf_data%has_mapping = .true.
    end if
end subroutine sf_data_init_lhapdf

```

(Commands: procedures)+≡

```

subroutine sf_data_init_isr &
    (sf_data, model, flv, alpha, q_max, mass, order)
type(sf_data_t), intent(inout) :: sf_data
type(model_t), intent(in), target :: model
type(flavor_t), dimension(2), intent(in) :: flv
real(default), intent(in) :: alpha, q_max
real(default), intent(in), optional :: mass
integer, intent(in), optional :: order
integer :: i
do i = 1, 2
    if (sf_data%affects_beam(i)) then
        call isr_data_init (sf_data%isr(i), &
            model, flv(i), alpha, q_max, mass)
        if (present (order)) &
            call isr_data_set_order (sf_data%isr(i), order)
        call isr_data_check (sf_data%isr(i))
    end if
end do
!   if (all (sf_data%affects_beam)) then
!       allocate (sf_data%mapping%index (2))
!       sf_data%mapping%index = (/1, sf_data%n_parameters+1/)
!       sf_data%mapping%type = SFM_ISRPAIR
!       allocate (sf_data%mapping%par (1))
!       sf_data%mapping%par = 2._default
!       sf_data%has_mapping = .true.
!   end if
end subroutine sf_data_init_isr

```

(Commands: procedures)+≡

```

subroutine sf_data_init_epa &
    (sf_data, model, flv, alpha, x_min, q_min, E_max, mass)
type(sf_data_t), intent(inout) :: sf_data
type(model_t), intent(in), target :: model
type(flavor_t), dimension(2), intent(in) :: flv
real(default), intent(in) :: alpha, x_min, q_min, E_max
real(default), intent(in), optional :: mass
integer :: i
do i = 1, 2
    if (sf_data%affects_beam(i)) then
        call epa_data_init (sf_data%epa(i), &
            model, flv(i), alpha, x_min, q_min, E_max, mass)
        call epa_data_check (sf_data%epa(i))
    end if
end do
if (all (sf_data%affects_beam)) then
    allocate (sf_data%mapping%index (2))

```

```

        sf_data%mapping%index = (/1, sf_data%n_parameters+1/)
        sf_data%mapping%type = SFM_EPAPAIR
        allocate (sf_data%mapping%par (1))
        sf_data%mapping%par = 1._default
        sf_data%has_mapping = .true.
    end if
end subroutine sf_data_init_epa

```

Structure function list

A list of structure functions and associated mappings.

(Commands: types)+≡

```

type :: sf_list_t
private
integer :: n_strfun = 0
integer :: n_mapping = 0
type(sf_data_t), pointer :: first => null ()
type(sf_data_t), pointer :: last => null ()
character(32) :: md5sum = ""
end type sf_list_t

```

Output

(Commands: procedures)+≡

```

subroutine sf_list_write (sf_list, unit)
type(sf_list_t), intent(in) :: sf_list
integer, intent(in), optional :: unit
integer :: u
type(sf_data_t), pointer :: current
u = output_unit (unit); if (u < 0) return
write (u, "(A)") "Structure function list"
if (associated (sf_list%first)) then
    current => sf_list%first
    do while (associated (current))
        call sf_data_write (current, unit)
        current => current%next
    end do
else
    write (u, "(1x,A)") "[empty]"
end if
end subroutine sf_list_write

```

Append a data set to the list. For EPA, several data sets may be used in parallel.

Allocate only one.

(Commands: procedures)+≡

```

subroutine sf_list_append (sf_list, type, affects_beam, n_parameters, current)
type(sf_list_t), intent(inout) :: sf_list
integer, intent(in) :: type
logical, dimension(2), intent(in) :: affects_beam
integer, intent(in) :: n_parameters
type(sf_data_t), pointer :: current
allocate (current)

```

```

current%type = type
current%affects_beam = affects_beam
current%n_parameters = n_parameters
if (associated (sf_list%last)) then
    sf_list%last%next => current
else
    sf_list%first => current
end if
sf_list%last => current
sf_list%n_strfun = sf_list%n_strfun + count (affects_beam)
end subroutine sf_list_append

```

Count mappings.

```

<Commands: procedures>+≡
subroutine sf_list_freeze (sf_list)
    type(sf_list_t), intent(inout) :: sf_list
    type(sf_data_t), pointer :: current
    sf_list%n_mapping = 0
    current => sf_list%first
    do while (associated (current))
        if (current%has_mapping) then
            sf_list%n_mapping = sf_list%n_mapping + 1
        end if
        current => current%next
    end do
end subroutine sf_list_freeze

```

Finalize.

```

<Commands: procedures>+≡
subroutine sf_list_final (sf_list)
    type(sf_list_t), intent(inout) :: sf_list
    type(sf_data_t), pointer :: current
    do while (associated (sf_list%first))
        current => sf_list%first
        sf_list%first => sf_list%first%next
        deallocate (current)
    end do
    sf_list%last => null ()
    sf_list%n_strfun = 0
end subroutine sf_list_final

```

Return number of structure functions.

```

<Commands: procedures>+≡
function sf_list_get_n_strfun (sf_list) result (n)
    integer :: n
    type(sf_list_t), intent(in) :: sf_list
    n = sf_list%n_strfun
end function sf_list_get_n_strfun

```

Return number of mappings.

```

<Commands: procedures>+≡
function sf_list_get_n_mapping (sf_list) result (n)

```

```

integer :: n
type(sf_list_t), intent(in) :: sf_list
n = sf_list%n_mapping
end function sf_list_get_n_mapping

```

Return the MD5 checksum.

```

<Commands: procedures>+≡
function sf_list_get_md5sum (sf_list) result (sf_md5sum)
character(32) :: sf_md5sum
type(sf_list_t), intent(in) :: sf_list
sf_md5sum = sf_list%md5sum
end function sf_list_get_md5sum

```

Compute the MD5 checksum.

```

<Commands: procedures>+≡
subroutine sf_list_compute_md5sum (sf_list)
type(sf_list_t), intent(inout) :: sf_list
integer :: unit
unit = free_unit ()
open (unit = unit, status = "scratch", action = "readwrite")
call sf_list_write (sf_list, unit)
rewind (unit)
sf_list%md5sum = md5sum (unit)
end subroutine sf_list_compute_md5sum

```

Transfer to the process object

Initialize actual structure functions, once the `sf_list` is complete. Beam initialization has to come before this.

```

<Commands: procedures>+≡
subroutine process_setup_strfun (process, sf_list)
type(process_t), intent(inout), target :: process
type(sf_list_t), intent(in) :: sf_list
type(sf_data_t), pointer :: current
integer :: i_sf, j, i_map, i_par
i_sf = 0
i_map = 0
i_par = 0
current => sf_list%first
do while (associated (current))
  if (current%has_mapping) then
    i_map = i_map + 1
    call process_set_strfun_mapping &
      (process, i_map, i_par + current%mapping%index, &
       current%mapping%type, current%mapping%par)
  end if
  do j = 1, 2
    if (current%affects_beam(j)) then
      i_sf = i_sf + 1
      select case (current%type)
      case (STRF_ISR)

```

```

        call process_set_strfun &
            (process, i_sf, j, current%isr(j), current%n_parameters)
    case (STRF_EPA)
        call process_set_strfun &
            (process, i_sf, j, current%epa(j), current%n_parameters)
    case (STRF_LHAPDF)
        call process_set_strfun &
            (process, i_sf, j, current%lhpdf(j), current%n_parameters)
    end select
    i_par = i_par + current%n_parameters
end if
end do
current => current%next
end do
end subroutine process_setup_strfun

```

17.1.3 Integration passes

Each integration pass has a number of iterations and a number of calls per iteration. The last pass produces the end result; the previous passes are used for adaptation.

TODO: Allow for more options.

```

<Commands: types>+≡
    type :: iterations_spec_t
    private
        integer :: n_it = 0
        integer :: n_calls = 0
    end type iterations_spec_t

```

We build up a list of iterations.

```

<Commands: types>+≡
    type :: iterations_list_t
    private
        integer :: n_pass = 0
        type(iterations_spec_t), dimension(:), allocatable :: pass
    end type iterations_list_t

```

```

<Commands: procedures>+≡
    subroutine iterations_list_init (it_list, n_it, n_calls)
        type(iterations_list_t), intent(inout) :: it_list
        integer, dimension(:), intent(in) :: n_it, n_calls
        it_list%n_pass = size (n_it)
        allocate (it_list%pass (it_list%n_pass))
        it_list%pass%n_it = n_it
        it_list%pass%n_calls = n_calls
    end subroutine iterations_list_init

```

```

<Commands: procedures>+≡
    subroutine iterations_list_clear (it_list)
        type(iterations_list_t), intent(inout) :: it_list
        it_list%n_pass = 0
    end subroutine iterations_list_clear

```

```

        deallocate (it_list%pass)
    end subroutine iterations_list_clear

```

Write the list of iterations as a message.

(Commands: procedures)+≡

```

subroutine iterations_list_write (it_list, unit)
    type(iterations_list_t), intent(in) :: it_list
    integer, intent(in), optional :: unit
    type(string_t) :: buffer
    character(30) :: ibuf
    integer :: i
    buffer = "iterations = "
    if (it_list%n_pass > 0) then
        do i = 1, it_list%n_pass
            if (i > 1) buffer = buffer // ", "
            write (ibuf, "(I0,':',IO)") &
                it_list%pass(i)%n_it, it_list%pass(i)%n_calls
            buffer = buffer // trim (ibuf)
        end do
    else
        buffer = buffer // "[undefined]"
    end if
    call msg_message (char (buffer), unit)
end subroutine iterations_list_write

```

Transform the iterations list into arrays that indicate pass index and number of calls for each iteration.

(Commands: procedures)+≡

```

function iterations_list_get_pass_array (it_list) result (pass)
    integer, dimension(:), allocatable :: pass
    type(iterations_list_t), intent(in) :: it_list
    integer :: it, i
    allocate (pass (sum (it_list%pass%n_it)))
    it = 0
    do i = 1, it_list%n_pass
        pass(it+1 : it+it_list%pass(i)%n_it) = i
        it = it + it_list%pass(i)%n_it
    end do
end function iterations_list_get_pass_array

function iterations_list_get_n_calls_array (it_list) result (n_calls)
    integer, dimension(:), allocatable :: n_calls
    type(iterations_list_t), intent(in) :: it_list
    integer :: it, i
    allocate (n_calls (sum (it_list%pass%n_it)))
    it = 0
    do i = 1, it_list%n_pass
        n_calls(it+1 : it+it_list%pass(i)%n_it) = it_list%pass(i)%n_calls
        it = it + it_list%pass(i)%n_it
    end do
end function iterations_list_get_n_calls_array

```

Allocate the default iterations lists and fill with some sensible values. This is implemented as a pointer since it is not intended to be modified by the user; the local RT dataset will thus contain another pointer to the same list, not a copy.

```

<Limits: public parameters>+=
    integer, parameter, public :: ITERATIONS_DEFAULT_LIST_SIZE = 7
<Commands: procedures>+=
    subroutine iterations_lists_init_default (it_list)
        type(iterations_list_t), dimension(:), pointer :: it_list
        allocate (it_list (ITERATIONS_DEFAULT_LIST_SIZE))
        call iterations_list_init (it_list(2), (/ 3, 3 /), (/ 1000, 10000 /))
        call iterations_list_init (it_list(3), (/ 5, 3 /), (/ 5000, 10000 /))
        call iterations_list_init (it_list(4), (/ 10, 5 /), (/ 10000, 20000 /))
        call iterations_list_init (it_list(5), (/ 10, 5 /), (/ 20000, 50000 /))
        call iterations_list_init (it_list(6), (/ 15, 5 /), (/ 50000, 100000 /))
        call iterations_list_init (it_list(7), (/ 20, 5 /), (/ 50000, 200000 /))
    end subroutine iterations_lists_init_default

```

17.1.4 File configuration

Files have a name and a format; we need lists of file specifications. Writing LHEF files, we need beam information and overall process data.

```

<Commands: parameters>+=
    integer, parameter :: FMT_NONE = 0
    integer, parameter :: FMT_DEFAULT = 1
    integer, parameter :: FMT_DEBUG = 2
    integer, parameter :: FMT_HEPMC = 10
    integer, parameter :: FMT_LHEF = 20
<Commands: types>+=
    type :: file_spec_t
        private
        type(string_t) :: name
        integer :: format = FMT_NONE
        type(hePMC_iostream_t), pointer :: iostream => null ()
        integer :: unit = 0
        type(flavor_t), dimension(:), allocatable :: beam_flv
        real(default), dimension(:), allocatable :: beam_energy
        integer :: n_processes = 0
        logical :: unweighted = .true.
        logical :: negative_weights = .false.
        type(file_spec_t), pointer :: next => null ()
    end type file_spec_t

```

File lists.

```

<Commands: types>+=
    type :: file_list_t
        private
        type(file_spec_t), pointer :: first => null ()
        type(file_spec_t), pointer :: last => null ()
    end type file_list_t

```

```

⟨Commands: procedures⟩+≡
subroutine file_list_append_file_spec &
    (file_list, name, format, beam_flg, beam_energy, &
     n_processes, unweighted, negative_weights)
type(file_list_t), intent(inout) :: file_list
type(string_t), intent(in) :: name
integer, intent(in) :: format
type(flavor_t), dimension(:), intent(in) :: beam_flg
real(default), dimension(:), intent(in) :: beam_energy
integer, intent(in) :: n_processes
logical, intent(in) :: unweighted, negative_weights
type(file_spec_t), pointer :: current
allocate (current)
current%name = name
current%format = format
allocate (current%beam_flg (size (beam_flg)))
current%beam_flg = beam_flg
allocate (current%beam_energy (size (beam_energy)))
current%beam_energy = beam_energy
current%n_processes = n_processes
current%unweighted = unweighted
current%negative_weights = negative_weights
if (associated (file_list%last)) then
    file_list%last%next => current
else
    file_list%first => current
end if
file_list%last => current
end subroutine file_list_append_file_spec

```

```

⟨Commands: procedures⟩+≡
subroutine file_list_final (file_list)
type(file_list_t), intent(inout) :: file_list
type(file_spec_t), pointer :: current
do while (associated (file_list%first))
    current => file_list%first
    file_list%first => current%next
    deallocate (current)
end do
file_list%last => null ()
end subroutine file_list_final

```

Open appropriate event files.

LHEF: Initialize run data with beam and simulation parameters. (TODO:
For each process, we should also provide cross section etc.)

```

⟨Commands: procedures⟩+≡
subroutine file_list_open (file_list)
type(file_list_t), intent(inout), target :: file_list
type(file_spec_t), pointer :: current
integer :: i
current => file_list%first
do while (associated (current))
    select case (current%format)

```

```

case (FMT_DEFAULT)
  call msg_message ("Writing events in human-readable format " &
    // "to file '" // char (current%name) // "'")
  current%unit = free_unit ()
  open (unit=current%unit, file=char(current%name), &
    action="write", status="replace")
case (FMT_DEBUG)
  call msg_message ("Writing events in verbose format to file '" &
    // char (current%name) // "'")
  current%unit = free_unit ()
  open (unit=current%unit, file=char(current%name), &
    action="write", status="replace")
case (FMT_HEPMC)
  call msg_message ("Writing events in HepMC format to file '" &
    // char (current%name) // "'")
  if (hepmc_is_available ()) then
    allocate (current%iostream)
    call hepmc_iostream_open_out (current%iostream, current%name)
  else
    call msg_error ("HepMC event writing is disabled " &
      // "because HepMC library is not linked.")
  end if
case (FMT_LHEF)
  call msg_message ("Writing events in LHEF format to file '" &
    // char (current%name) // "'")
  current%unit = free_unit ()
  open (unit=current%unit, file=char(current%name), &
    action="write", status="replace")
  call les_houches_events_write_header (current%unit)
  call heprup_init &
    (flavor_get_pdg (current%beam_flg), &
    current%beam_energy, &
    n_processes = current%n_processes, &
    unweighted = current%unweighted, &
    negative_weights = current%negative_weights)
  do i = 1, current%n_processes
    call heprup_set_process_parameters (i, i)
  end do
  call heprup_write_lhef (current%unit)
end select
current => current%next
end do
end subroutine file_list_open

```

Scan the file list and write the event in the selected formats.

(Commands: procedures)+≡

```

subroutine file_list_write_event (file_list, event, i_proc, i_evt)
  type(file_list_t), intent(in), target :: file_list
  type(event_t), intent(in), target :: event
  integer, intent(in), optional :: i_proc, i_evt
  type(file_spec_t), pointer :: current
  type(hepmc_event_t) :: hepmc_event
  current => file_list%first
  do while (associated (current))

```

```

select case (current%format)
case (FMT_DEFAULT)
  call event_write (event, current%unit, verbose=.false.)
case (FMT_DEBUG)
  call event_write (event, current%unit, verbose=.true.)
case (FMT_HEPMC)
  if (hepmc_is_available ()) then
    call hepmc_event_init (hepmc_event, i_proc, i_evt)
    call event_write_to_hepmc (event, hepmc_event)
    call hepmc_iostream_write_event (current%iostream, hepmc_event)
    call hepmc_event_final (hepmc_event)
  end if
case (FMT_LHEF)
  call event_write_to_hepeup (event)
  call hepeup_write_lhef (current%unit)
end select
current => current%next
end do
end subroutine file_list_write_event

```

Close streams.

```

<Commands: procedures>+≡
subroutine file_list_close (file_list)
  type(file_list_t), intent(inout), target :: file_list
  type(file_spec_t), pointer :: current
  current => file_list%first
  do while (associated (current))
    select case (current%format)
    case (FMT_HEPMC)
      if (hepmc_is_available ()) then
        call hepmc_iostream_close (current%iostream)
        deallocate (current%iostream)
      end if
    case default
      close (current%unit)
    end select
    current => current%next
  end do
end subroutine file_list_close

```

17.1.5 Runtime data

These data are used and modified during the command flow. A local copy of this can be used to temporarily override defaults. The data set is transparent/

```

<Commands: types>+≡
public :: rt_data_t

<Commands: types>+≡
type :: rt_data_t
  type(var_list_t) :: var_list
  type(iterations_list_t) :: it_list
  type(iterations_list_t), dimension(:), pointer :: it_list_default

```

```

type(os_data_t) :: os_data
type(process_library_t), pointer :: prc_lib => null ()
type(model_t), pointer :: model => null ()
type(beam_data_t) :: beam_data
type(lhapdf_status_t) :: lhpdf_status
integer :: n_processes = 0
logical :: unweighted = .true.
logical :: negative_weights = .false.
logical :: read_raw = .true.
logical :: write_raw = .true.
logical :: write_default = .false.
logical :: write_debug = .false.
logical :: write_lhef = .false.
logical :: write_hepmc = .false.
type(string_t) :: file_raw
type(string_t) :: file_default
type(string_t) :: file_debug
type(string_t) :: file_lhef
type(string_t) :: file_hepmc
type(sf_list_t), pointer :: sf_list => null ()
type(parse_node_t), pointer :: pn_cuts_lexpr => null ()
type(parse_node_t), pointer :: pn_weight_lexpr => null ()
type(parse_node_t), pointer :: pn_scale_lexpr => null ()
type(parse_node_t), pointer :: pn_analysis_lexpr => null ()
type(tao_random_state), pointer :: rng => null ()
integer :: seed
logical :: quit = .false.
integer :: quit_code = 0
end type rt_data_t

```

Initialize runtime data. This defines special variables such as `sqrts`, and should be done only for the instance that is actually global. Local copies will inherit the special variables.

<Commands: public>≡

```
public :: rt_data_global_init
```

<Commands: procedures>+≡

```

subroutine rt_data_global_init (global)
  type(rt_data_t), intent(out), target :: global
  logical, target, save :: known = .true.
  call os_data_init (global%os_data)
  allocate (global%rng)
  call system_clock (global%seed)
  call tao_random_create (global%rng, global%seed)
  call var_list_append_int_ptr &
    (global%var_list, var_str ("seed_value"), global%seed, known, &
     intrinsic=.true.)
  call var_list_append_real &
    (global%var_list, var_str ("sqrts"), 0._default, &
     intrinsic=.true.)
  call var_list_append_string &
    (global%var_list, var_str ("model_name"), &
     intrinsic=.true.)
  call var_list_append_string &

```

```

(global%var_list, var_str ("restrictions"), var_str (""), &
intrinsic=.true.)
call var_list_append_log &
(global%var_list, var_str ("slha_read_input"), .true., &
intrinsic=.true.)
call var_list_append_log &
(global%var_list, var_str ("slha_read_spectrum"), .true., &
intrinsic=.true.)
call var_list_append_log &
(global%var_list, var_str ("slha_read_decays"), .false., &
intrinsic=.true.)
call var_list_append_string &
(global%var_list, var_str ("library_name"), &
intrinsic=.true.)
call var_list_append_real &
(global%var_list, var_str ("cm_momentum"), 0._default, &
intrinsic=.true.)
call var_list_append_real &
(global%var_list, var_str ("cm_theta"), 0._default, &
intrinsic=.true.)
call var_list_append_real &
(global%var_list, var_str ("cm_phi"), 0._default, &
intrinsic=.true.)
call var_list_append_real &
(global%var_list, var_str ("luminosity"), 0._default, &
intrinsic=.true.)
call var_list_append_string &
(global%var_list, var_str ("lhpdf_file"), &
intrinsic=.true.)
call var_list_append_int &
(global%var_list, var_str ("lhpdf_member"), 0, &
intrinsic=.true.)
call var_list_append_int &
(global%var_list, var_str ("lhpdf_photon_scheme"), 0, &
intrinsic=.true.)
call var_list_append_real &
(global%var_list, var_str ("isr_alpha"), 0._default, &
intrinsic=.true.)
call var_list_append_real &
(global%var_list, var_str ("isr_q_max"), 0._default, &
intrinsic=.true.)
call var_list_append_real &
(global%var_list, var_str ("isr_mass"), 0._default, &
intrinsic=.true.)
call var_list_append_int &
(global%var_list, var_str ("isr_order"), 3, &
intrinsic=.true.)
call var_list_append_real &
(global%var_list, var_str ("epa_alpha"), 0._default, &
intrinsic=.true.)
call var_list_append_real &
(global%var_list, var_str ("epa_x_min"), 0._default, &
intrinsic=.true.)
call var_list_append_real &

```

```

(global%var_list, var_str ("epa_q_min"), 0._default, &
intrinsic=.true.)
call var_list_append_real &
(global%var_list, var_str ("epa_e_max"), 0._default, &
intrinsic=.true.)
call var_list_append_real &
(global%var_list, var_str ("epa_mass"), 0._default, &
intrinsic=.true.)
call var_list_append_log &
(global%var_list, var_str ("?alpha_s_is_fixed"), .true., &
intrinsic=.true.)
call var_list_append_log &
(global%var_list, var_str ("?alpha_s_from_lhapdf"), .false., &
intrinsic=.true.)
call var_list_append_int &
(global%var_list, var_str ("alpha_s_order"), 0, &
intrinsic=.true.)
call var_list_append_int &
(global%var_list, var_str ("alpha_s_nf"), 5, &
intrinsic=.true.)
call var_list_append_log &
(global%var_list, var_str ("?alpha_s_from_mz"), .true., &
intrinsic=.true.)
call var_list_append_real &
(global%var_list, var_str ("lambda_qcd"), 200.e-3_default, &
intrinsic=.true.)
call var_list_append_log &
(global%var_list, var_str ("?helicity_selection_active"), .true., &
intrinsic=.true.)
call var_list_append_real &
(global%var_list, var_str ("helicity_selection_threshold"), &
1E10_default, &
intrinsic=.true.)
call var_list_append_int &
(global%var_list, var_str ("helicity_selection_cutoff"), 100, &
intrinsic=.true.)
call var_list_append_int &
(global%var_list, var_str ("threshold_calls"), 0, &
intrinsic=.true.)
call var_list_append_int &
(global%var_list, var_str ("min_calls_per_channel"), 10, &
intrinsic=.true.)
call var_list_append_int &
(global%var_list, var_str ("min_calls_per_bin"), 10, &
intrinsic=.true.)
call var_list_append_int &
(global%var_list, var_str ("min_bins"), 3, &
intrinsic=.true.)
call var_list_append_int &
(global%var_list, var_str ("max_bins"), 20, &
intrinsic=.true.)
call var_list_append_log &
(global%var_list, var_str ("?stratified"), .true., &
intrinsic=.true.)

```

```

call var_list_append_real &
  (global%var_list, var_str ("channel_weights_power"), 0.25_default, &
   intrinsic=.true.)
call var_list_append_string &
  (global%var_list, var_str ("phs_file"), &
   intrinsic=.true.)
call var_list_append_log &
  (global%var_list, var_str ("?phs_only"), .false., &
   intrinsic=.true.)
call var_list_append_real &
  (global%var_list, var_str ("phs_threshold_s"), 50._default, &
   intrinsic=.true.)
call var_list_append_real &
  (global%var_list, var_str ("phs_threshold_t"), 100._default, &
   intrinsic=.true.)
call var_list_append_int &
  (global%var_list, var_str ("phs_off_shell"), 1, &
   intrinsic=.true.)
call var_list_append_int &
  (global%var_list, var_str ("phs_t_channel"), 2, &
   intrinsic=.true.)
call var_list_append_int &
  (global%var_list, var_str ("n_events"), 0, &
   intrinsic=.true.)
call var_list_append_string (global%var_list, &
  var_str ("label"), var_str (""), &
  intrinsic=.true.)
call var_list_append_string (global%var_list, &
  var_str ("physical_unit"), var_str (""), &
  intrinsic=.true.)
call var_list_append_string (global%var_list, &
  var_str ("title"), var_str (""), &
  intrinsic=.true.)
call var_list_append_string (global%var_list, &
  var_str ("description"), var_str (""), &
  intrinsic=.true.)
call var_list_append_string (global%var_list, &
  var_str ("xlabel"), var_str (""), &
  intrinsic=.true.)
call var_list_append_string (global%var_list, &
  var_str ("ylabel"), var_str (""), &
  intrinsic=.true.)
call var_list_append_real (global%var_list, &
  var_str ("tolerance"), 0._default, &
  intrinsic=.true.)
call rt_data_init_pointer_variables (global)
call iterations_lists_init_default (global%it_list_default)
global%file_raw = "whizard.evx"
global%file_default = "whizard.default"
global%file_debug = "whizard.debug"
global%file_lhef = "whizard.lhef"
global%file_hePMC = "whizard.hePMC"
end subroutine rt_data_global_init

```

This is done at compile time when a local copy of runtime data is needed: Link the variable list and initialize all derived parameters. This allows for synchronizing them with local variable changes without affecting global data.

Also re-initialize pointer variables, so they point to local copies of their targets.

```
(Commands: procedures)+≡
subroutine rt_data_local_init (local, global)
  type(rt_data_t), intent(inout), target :: local
  type(rt_data_t), intent(in), target :: global
  call var_list_link (local%var_list, global%var_list)
  if (associated (global%model)) then
    call var_list_init_copies (local%var_list, &
      model_get_var_list_ptr (global%model), &
      derived_only = .true.)
  end if
  call rt_data_init_pointer_variables (local)
end subroutine rt_data_local_init
```

These variables point to objects which get local copies:

```
(Commands: procedures)+≡
subroutine rt_data_init_pointer_variables (local)
  type(rt_data_t), intent(inout), target :: local
  logical, target, save :: known = .true.
  call var_list_append_string_ptr &
    (local%var_list, var_str ("f"), local%os_data%fc, known, &
    intrinsic=.true.)
  call var_list_append_string_ptr &
    (local%var_list, var_str ("fcl"), local%os_data%fcflags, known, &
    intrinsic=.true.)
  call var_list_append_log_ptr (local%var_list, &
    var_str ("?read_raw"), local%read_raw, known, intrinsic=.true.)
  call var_list_append_log_ptr (local%var_list, &
    var_str ("?write_raw"), local%write_raw, known, intrinsic=.true.)
  call var_list_append_string_ptr (local%var_list, &
    var_str ("file_raw"), local%file_raw, known, intrinsic=.true.)
  call var_list_append_log_ptr (local%var_list, &
    var_str ("?write_default"), local%write_default, known, &
    intrinsic=.true.)
  call var_list_append_string_ptr (local%var_list, &
    var_str ("file_default"), local%file_default, known, intrinsic=.true.)
  call var_list_append_log_ptr (local%var_list, &
    var_str ("?write_debug"), local%write_debug, known, intrinsic=.true.)
  call var_list_append_string_ptr (local%var_list, &
    var_str ("file_debug"), local%file_debug, known, intrinsic=.true.)
  call var_list_append_log_ptr (local%var_list, &
    var_str ("?write_lhef"), local%write_lhef, known, intrinsic=.true.)
  call var_list_append_string_ptr (local%var_list, &
    var_str ("file_lhef"), local%file_lhef, known, intrinsic=.true.)
  call var_list_append_log_ptr (local%var_list, &
    var_str ("?write_hepmc"), local%write_hepmc, known, intrinsic=.true.)
  call var_list_append_string_ptr (local%var_list, &
    var_str ("file_hepmc"), local%file_hepmc, known, intrinsic=.true.)
end subroutine rt_data_init_pointer_variables
```

This is done at execution time: Copy data, transfer pointers. `local` has intent(inout) because its local variable list has already been prepared by the previous routine.

(Commands: procedures)+≡

```
subroutine rt_data_link (local, global)
  type(rt_data_t), intent(inout), target :: local
  type(rt_data_t), intent(in), target :: global
  call var_list_link (local%var_list, global%var_list)
  if (associated (global%model)) then
    call var_list_synchronize (local%var_list, &
      model_get_var_list_ptr (global%model), reset_pointers = .true.)
  end if
  local%it_list = global%it_list
  local%it_list_default => global%it_list_default
  local%os_data = global%os_data
  local%prc_lib => global%prc_lib
  local%model => global%model
  local%beam_data = global%beam_data
  local%lhpdf_status = global%lhpdf_status
  local%sf_list => global%sf_list
  local%pn_cuts_lexpr => global%pn_cuts_lexpr
  local%pn_weight_lexpr => global%pn_weight_lexpr
  local%pn_scale_lexpr => global%pn_scale_lexpr
  local%pn_analysis_lexpr => global%pn_analysis_lexpr
  local%rng => global%rng
  local%file_raw = global%file_raw
  local%file_default = global%file_default
  local%file_debug = global%file_debug
  local%file_lhef = global%file_lhef
  local%file_hepmc = global%file_hepmc
  local%read_raw = global%read_raw
  local%write_raw = global%write_raw
  local%write_default = global%write_default
  local%write_debug = global%write_debug
  local%write_lhef = global%write_lhef
  local%write_hepmc = global%write_hepmc
end subroutine rt_data_link
```

Restore the previous state of data; in particular, the variable list. This applies only to model variables (which are copies); other variables are automatically restored when local variables are removed.

Some command (`read_slha`) reads in model variables as local entities. In this case, the original values of model variables should not be restored, but the global variable list should be synchronized. However, this matters only if the local model is identical to the global model; otherwise, restoring will apply to a different model.

(Commands: procedures)+≡

```
subroutine rt_data_restore (global, local, keep_model_vars)
  type(rt_data_t), intent(inout) :: global
  type(rt_data_t), intent(in) :: local
  logical, intent(in), optional :: keep_model_vars
```

```

logical :: same_model, restore
if (associated (global%model)) then
  same_model = &
    model_get_name (global%model) == model_get_name (local%model)
  if (present (keep_model_vars) .and. same_model) then
    restore = .not. keep_model_vars
  else
    if (.not. same_model) call msg_message ("Restoring model '" // &
      char (model_get_name (global%model)) // "'")
    restore = .true.
  end if
  if (restore) then
    call var_list_restore (global%var_list)
  else
    call var_list_synchronize &
      (global%var_list, model_get_var_list_ptr (global%model))
  end if
end if
end subroutine rt_data_restore

```

Finalizer for the variable list and the structure-function list. This is done only for the global RT dataset; local copies contain pointers to this and do not need a finalizer.

```

<Commands: public>+≡
  public :: rt_data_global_final

<Commands: procedures>+≡
  subroutine rt_data_global_final (global)
    type(rt_data_t), intent(inout) :: global
    call var_list_final (global%var_list)
    if (associated (global%sf_list)) then
      call sf_list_final (global%sf_list)
      deallocate (global%sf_list)
    end if
    deallocate (global%it_list_default)
  end subroutine rt_data_global_final

```

17.1.6 The command type

The command type is a generic type that holds any command, compiled for execution. It is part of a command list. These are the possibilities:

```

<Commands: parameters>+≡
  integer, parameter :: CMD_NONE = 0
  integer, parameter :: CMD_PROCESS = 1
  integer, parameter :: CMD_INTEGRATE = 2
  integer, parameter :: CMD_SIMULATE = 3

  integer, parameter :: CMD_COMPILE = 10
  integer, parameter :: CMD_LOAD = 11
  integer, parameter :: CMD_EXEC = 13

  integer, parameter :: CMD_BEAMS = 21

```

```

integer, parameter :: CMD_MODEL = 31
integer, parameter :: CMD_LIBRARY = 32
integer, parameter :: CMD_CUTS = 33
integer, parameter :: CMD_WEIGHT = 34
integer, parameter :: CMD_SCALE = 35

integer, parameter :: CMD_VAR = 41
integer, parameter :: CMD_SHOW = 45
integer, parameter :: CMD_EXPECT = 46
integer, parameter :: CMD_ECHO = 47

integer, parameter :: CMD_UNSTABLE = 51

integer, parameter :: CMD_SEED = 63
integer, parameter :: CMD_ITERATIONS = 64

integer, parameter :: CMD_ANALYSIS = 70
integer, parameter :: CMD_WRITE_ANALYSIS = 71
integer, parameter :: CMD_OBSERVABLE = 72
integer, parameter :: CMD_HISTOGRAM = 73
integer, parameter :: CMD_PLOT = 74
integer, parameter :: CMD_CLEAR = 75

integer, parameter :: CMD_INCLUDE = 91
integer, parameter :: CMD_SCAN = 92
integer, parameter :: CMD_IF = 93
integer, parameter :: CMD_QUIT = 99

integer, parameter :: CMD_SLHA = 101

```

$\langle \text{Commands: types} \rangle + \equiv$

```

type :: command_t
private
integer :: type = CMD_NONE
type(cmd_model_t), pointer :: model => null ()
type(cmd_library_t), pointer :: library => null ()
type(cmd_process_t), pointer :: process => null ()
type(cmd_compile_t), pointer :: compile => null ()
type(cmd_load_t), pointer :: load => null ()
type(cmd_exec_t), pointer :: exec => null ()
type(cmd_var_t), pointer :: var => null ()
type(cmd_slha_t), pointer :: slha => null ()
type(cmd_show_t), pointer :: show => null ()
type(cmd_expect_t), pointer :: expect => null ()
type(cmd_echo_t), pointer :: echo => null ()
type(cmd_beams_t), pointer :: beams => null ()
type(cmd_cuts_t), pointer :: cuts => null ()
type(cmd_weight_t), pointer :: weight => null ()
type(cmd_scale_t), pointer :: scale => null ()
type(cmd_seed_t), pointer :: seed => null ()
type(cmd_iterations_t), pointer :: iterations => null ()
type(cmd_integrate_t), pointer :: integrate => null ()
type(cmd_observable_t), pointer :: observable => null ()

```

```

type(cmd_histogram_t), pointer :: histogram => null ()
type(cmd_plot_t), pointer :: plot => null ()
type(cmd_clear_t), pointer :: clear => null ()
type(cmd_analysis_t), pointer :: analysis => null ()
type(cmd_unstable_t), pointer :: unstable => null ()
type(cmd_simulate_t), pointer :: simulate => null ()
type(cmd_write_analysis_t), pointer :: write_analysis => null ()
type(cmd_scan_t), pointer :: loop => null ()
type(cmd_if_t), pointer :: cond => null ()
type(cmd_include_t), pointer :: include => null ()
type(cmd_quit_t), pointer :: quit => null ()
type(command_t), pointer :: next => null ()
end type command_t

```

Finalizer: Delete the specific command entry.

(Commands: procedures)+≡

```

recursive subroutine command_final (command)
  type(command_t), intent(inout) :: command
  select case (command%type)
  case (CMD_NONE)
  case (CMD_MODEL)
    deallocate (command%model)
  case (CMD_LIBRARY)
    deallocate (command%library)
  case (CMD_PROCESS)
    call cmd_process_final (command%process)
    deallocate (command%process)
  case (CMD_COMPILE)
    call cmd_compile_final (command%compile)
    deallocate (command%compile)
  case (CMD_LOAD)
    call cmd_load_final (command%load)
    deallocate (command%load)
  case (CMD_EXEC)
    call cmd_exec_final (command%exec)
    deallocate (command%exec)
  case (CMD_VAR)
    call cmd_var_final (command%var)
    deallocate (command%var)
  case (CMD_SLHA)
    call cmd_slha_final (command%slha)
    deallocate (command%slha)
  case (CMD_SHOW)
    call cmd_show_final (command%show)
    deallocate (command%show)
  case (CMD_EXPECT)
    call cmd_expect_final (command%expect)
    deallocate (command%expect)
  case (CMD_ECHO)
    call cmd_echo_final (command%echo)
    deallocate (command%echo)
  case (CMD_BEAMS)
    call cmd_beams_final (command%beams)

```

```

        deallocate (command%beams)
case (CMD_CUTS)
    deallocate (command%cuts)
case (CMD_WEIGHT)
    deallocate (command%weight)
case (CMD_SCALE)
    deallocate (command%scale)
case (CMD_SEED)
    call cmd_seed_final (command%seed)
    deallocate (command%seed)
case (CMD_ITERATIONS)
    call cmd_iterations_final (command%iterations)
    deallocate (command%iterations)
case (CMD_INTEGRATE)
    call cmd_integrate_final (command%integrate)
    deallocate (command%integrate)
case (CMD_OBSERVABLE)
    call cmd_observable_final (command%observable)
    deallocate (command%observable)
case (CMD_HISTOGRAM)
    call cmd_histogram_final (command%histogram)
    deallocate (command%histogram)
case (CMD_PLOT)
    call cmd_plot_final (command%plot)
    deallocate (command%plot)
case (CMD_CLEAR)
    call cmd_clear_final (command%clear)
    deallocate (command%clear)
case (CMD_ANALYSIS)
    deallocate (command%analysis)
case (CMD_UNSTABLE)
    call cmd_unstable_final (command%unstable)
    deallocate (command%unstable)
case (CMD_SIMULATE)
    call cmd_simulate_final (command%simulate)
    deallocate (command%simulate)
case (CMD_WRITE_ANALYSIS)
    call cmd_write_analysis_final (command%write_analysis)
    deallocate (command%write_analysis)
case (CMD_SCAN)
    call cmd_scan_final (command%loop)
    deallocate (command%loop)
case (CMD_IF)
    call cmd_if_final (command%cond)
    deallocate (command%cond)
case (CMD_INCLUDE)
    call cmd_include_final (command%include)
    deallocate (command%include)
case (CMD_QUIT)
    call cmd_quit_final (command%quit)
    deallocate (command%quit)
end select
end subroutine command_final

```

Output.

(Commands: procedures)+≡

```
recursive subroutine command_write (command, unit, indent)
  type(command_t), intent(in) :: command
  integer, intent(in), optional :: unit, indent
  integer :: u
  u = output_unit (unit); if (u < 0) return
  select case (command%type)
  case (CMD_NONE)
    write (u, *) "[Empty command]"
  case (CMD_MODEL)
    call cmd_model_write (command%model, unit, indent)
  case (CMD_LIBRARY)
    call cmd_library_write (command%library, unit, indent)
  case (CMD_VAR)
    call cmd_var_write (command%var, unit, indent)
  case (CMD_SLHA)
    call cmd_slha_write (command%slha, unit, indent)
  case (CMD_PROCESS)
    call cmd_process_write (command%process, unit, indent)
  case (CMD_COMPILE)
    call cmd_compile_write (command%compile, unit, indent)
  case (CMD_EXEC)
    call cmd_exec_write (command%exec, unit, indent)
  case (CMD_BEAMS)
    call cmd_beams_write (command%beams, unit, indent)
  case (CMD_CUTS)
    call cmd_cuts_write (command%cuts, unit, indent)
  case (CMD_WEIGHT)
    call cmd_weight_write (command%weight, unit, indent)
  case (CMD_SCALE)
    call cmd_scale_write (command%scale, unit, indent)
  case (CMD_SEED)
    call cmd_seed_write (command%seed, unit, indent)
  case (CMD_ITERATIONS)
    call cmd_iterations_write (command%iterations, unit, indent)
  case (CMD_INTEGRATE)
    call cmd_integrate_write (command%integrate, unit, indent)
  case (CMD_OBSERVABLE)
    call cmd_observable_write (command%observable, unit, indent)
  case (CMD_HISTOGRAM)
    call cmd_histogram_write (command%histogram, unit, indent)
  case (CMD_PLOT)
    call cmd_plot_write (command%plot, unit, indent)
  case (CMD_ANALYSIS)
    call cmd_analysis_write (command%analysis, unit, indent)
  case (CMD_UNSTABLE)
    call cmd_unstable_write (command%unstable, unit, indent)
  case (CMD_SIMULATE)
    call cmd_simulate_write (command%simulate, unit, indent)
  case (CMD_SCAN)
    call cmd_scan_write (command%loop, unit, indent)
  case (CMD_IF)
    call cmd_if_write (command%cond, unit, indent)
```

```

case (CMD_INCLUDE)
  call cmd_include_write (command%include, unit, indent)
case (CMD_QUIT)
  call cmd_quit_write (command%quit, unit, indent)
end select
end subroutine command_write

```

Compile a command. This allocates the command pointer. Some need a variable list to link to as an extra argument. (The variable list is assigned by the model command.)

(Commands: procedures)+≡

```

recursive subroutine command_compile (command, pn, global)
  type(command_t), pointer :: command
  type(parse_node_t), intent(in), target :: pn
  type(rt_data_t), intent(inout), target :: global
  ! call parse_node_write (pn)
  allocate (command)
  select case (char (parse_node_get_rule_key (pn)))
  case ("cmd_model")
    command%type = CMD_MODEL
    call cmd_model_compile (command%model, pn, global)
  case ("cmd_library")
    command%type = CMD_LIBRARY
    call cmd_library_compile (command%library, pn)
  case ("cmd_process")
    command%type = CMD_PROCESS
    call cmd_process_compile (command%process, pn, global)
  case ("cmd_compile")
    command%type = CMD_COMPILE
    call cmd_compile_compile (command%compile, pn, global)
  case ("cmd_load")
    command%type = CMD_LOAD
    call cmd_load_compile (command%load, pn, global)
  case ("cmd_exec")
    command%type = CMD_EXEC
    call cmd_exec_compile (command%exec, pn, global)
  case ("cmd_num", "cmd_cmplx", "cmd_real", "cmd_int", &
        "cmd_log", "cmd_string", "cmd_alias")
    command%type = CMD_VAR
    call cmd_var_compile (command%var, pn, global)
  case ("cmd_slha")
    command%type = CMD_SLHA
    call cmd_slha_compile (command%slha, pn, global)
  case ("cmd_show")
    command%type = CMD_SHOW
    call cmd_show_compile (command%show, pn, global)
  case ("cmd_expect")
    command%type = CMD_EXPECT
    call cmd_expect_compile (command%expect, pn, global)
  case ("cmd_echo")
    command%type = CMD_ECHO
    call cmd_echo_compile (command%echo, pn, global)
  case ("cmd_beams")

```

```

        command%type = CMD_BEAMS
        call cmd_beams_compile (command%beams, pn, global)
case ("cmd_cuts")
        command%type = CMD_CUTS
        call cmd_cuts_compile (command%cuts, pn)
case ("cmd_weight")
        command%type = CMD_WEIGHT
        call cmd_weight_compile (command%weight, pn)
case ("cmd_scale")
        command%type = CMD_SCALE
        call cmd_scale_compile (command%scale, pn)
case ("cmd_seed")
        command%type = CMD_SEED
        call cmd_seed_compile (command%seed, pn, global)
case ("cmd_iterations")
        command%type = CMD_ITERATIONS
        call cmd_iterations_compile (command%iterations, pn, global)
case ("cmd_integrate")
        command%type = CMD_INTEGRATE
        call cmd_integrate_compile (command%integrate, pn, global)
case ("cmd_observable")
        command%type = CMD_OBSERVABLE
        call cmd_observable_compile (command%observable, pn, global)
case ("cmd_histogram")
        command%type = CMD_HISTOGRAM
        call cmd_histogram_compile (command%histogram, pn, global)
case ("cmd_plot")
        command%type = CMD_PLOT
        call cmd_plot_compile (command%plot, pn, global)
case ("cmd_clear")
        command%type = CMD_CLEAR
        call cmd_clear_compile (command%clear, pn, global)
case ("cmd_analysis")
        command%type = CMD_ANALYSIS
        call cmd_analysis_compile (command%analysis, pn)
case ("cmd_unstable")
        command%type = CMD_UNSTABLE
        call cmd_unstable_compile (command%unstable, pn, global)
case ("cmd_simulate")
        command%type = CMD_SIMULATE
        call cmd_simulate_compile (command%simulate, pn, global)
case ("cmd_write_analysis")
        command%type = CMD_WRITE_ANALYSIS
        call cmd_write_analysis_compile (command%write_analysis, pn, global)
case ("cmd_scan")
        command%type = CMD_SCAN
        call cmd_scan_compile (command%loop, pn, global)
case ("cmd_if")
        command%type = CMD_IF
        call cmd_if_compile (command%cond, pn, global)
case ("cmd_include")
        command%type = CMD_INCLUDE
        call cmd_include_compile (command%include, pn, global)
case ("cmd_quit")

```

```

        command%type = CMD_QUIT
        call cmd_quit_compile (command%quit, pn, global)
    case default
        print *, char (parse_node_get_rule_key (pn))
        call msg_bug ("Command not implemented")
    end select
    ! call command_write (command)
end subroutine command_compile

```

Execute a command. This will use and/or modify the runtime data set. If the quit flag is set, the caller should terminate command execution.

(Commands: procedures)+≡

```

recursive subroutine command_execute (command, global, print)
    type(command_t), intent(inout) :: command
    type(rt_data_t), intent(inout), target :: global
    logical, intent(in), optional :: print
    select case (command%type)
    case (CMD_MODEL)
        call cmd_model_execute (command%model, global)
    case (CMD_LIBRARY)
        call cmd_library_execute (command%library, global)
    case (CMD_PROCESS)
        call cmd_process_execute (command%process, global)
    case (CMD_COMPILE)
        call cmd_compile_execute (command%compile, global)
    case (CMD_LOAD)
        call cmd_load_execute (command%load, global)
    case (CMD_EXEC)
        call cmd_exec_execute (command%exec, global)
    case (CMD_VAR)
        call cmd_var_execute (command%var, global)
    case (CMD_SLHA)
        call cmd_slha_execute (command%slha, global)
    case (CMD_SHOW)
        call cmd_show_execute (command%show, global)
    case (CMD_EXPECT)
        call cmd_expect_execute (command%expect, global)
    case (CMD_ECHO)
        call cmd_echo_execute (command%echo, global)
    case (CMD_BEAMS)
        call cmd_beams_execute (command%beams, global)
    case (CMD_CUTS)
        call cmd_cuts_execute (command%cuts, global)
    case (CMD_WEIGHT)
        call cmd_weight_execute (command%weight, global)
    case (CMD_SCALE)
        call cmd_scale_execute (command%scale, global)
    case (CMD_SEED)
        call cmd_seed_execute (command%seed, global)
    case (CMD_ITERATIONS)
        call cmd_iterations_execute (command%iterations, global)
    case (CMD_INTEGRATE)
        call cmd_integrate_execute (command%integrate, global)
    end select
end subroutine command_execute

```

```

case (CMD_OBSERVABLE)
    call cmd_observable_execute (command%observable, global)
case (CMD_HISTOGRAM)
    call cmd_histogram_execute (command%histogram, global)
case (CMD_PLOT)
    call cmd_plot_execute (command%plot, global)
case (CMD_CLEAR)
    call cmd_clear_execute (command%clear, global)
case (CMD_ANALYSIS)
    call cmd_analysis_execute (command%analysis, global)
case (CMD_UNSTABLE)
    call cmd_unstable_execute (command%unstable, global)
case (CMD_SIMULATE)
    call cmd_simulate_execute (command%simulate, global)
case (CMD_WRITE_ANALYSIS)
    call cmd_write_analysis_execute (command%write_analysis, global)
case (CMD_SCAN)
    call cmd_scan_execute (command%loop, global)
case (CMD_IF)
    call cmd_if_execute (command%cond, global)
case (CMD_INCLUDE)
    call cmd_include_execute (command%include, global)
case (CMD_QUIT)
    call cmd_quit_execute (command%quit, global)
end select
if (present (print)) then
    if (print) call command_write (command)
end if
end subroutine command_execute

```

Auxiliary for output:

```

<Commands: procedures>+≡
subroutine write_indent (unit, indent)
    integer, intent(in) :: unit
    integer, intent(in), optional :: indent
    if (present (indent)) then
        write (unit, "(A)", advance="no") repeat (" ", indent)
    end if
end subroutine write_indent

```

17.1.7 Specific command types

Model configuration

The command declares a model, looks for the specified file and loads it.

```

<Commands: types>+≡
type :: cmd_model_t
    private
    type(string_t) :: name
end type cmd_model_t

```

Output

```
<Commands: procedures>+≡
subroutine cmd_model_write (model, unit, indent)
  type(cmd_model_t), intent(in) :: model
  integer, intent(in), optional :: unit, indent
  integer :: u
  u = output_unit (unit); if (u < 0) return
  call write_indent (u, indent)
  write (u, "(1x,A,1x,'"',A,'\"') "model =", char (model%name)
end subroutine cmd_model_write
```

Compile. Get the model name and read the model from file, so it is readily available when the command list is executed.

```
<Commands: procedures>+≡
subroutine cmd_model_compile (model, pn, global)
  type(cmd_model_t), pointer :: model
  type(parse_node_t), intent(in), target :: pn
  type(rt_data_t), intent(inout), target :: global
  type(parse_node_t), pointer :: pn_name
  type(model_t), pointer :: mdl
  type(string_t) :: filename
  pn_name => parse_node_get_sub_ptr (pn, 3)
  allocate (model)
  if (associated (pn_name)) then
    model%name = parse_node_get_string (pn_name)
    filename = model%name // ".mdl"
    mdl => null ()
    call model_list_read_model (model%name, filename, global%os_data, mdl)
    if (associated (mdl)) then
      call var_list_init_copies &
        (global%var_list, model_get_var_list_ptr (mdl))
    end if
  else
    model%name = ""
  end if
end subroutine cmd_model_compile
```

Execute: Insert a pointer into the global data record and reassign the variable list.

```
<Commands: procedures>+≡
subroutine cmd_model_execute (model, global)
  type(cmd_model_t), intent(in) :: model
  type(rt_data_t), intent(inout), target :: global
  type(model_t), pointer :: mdl
  type(var_list_t), pointer :: model_vars
  if (model_get_name (global%model) /= model%name) then
    if (model_list_model_exists (model%name)) then
      mdl => model_list_get_model_ptr (model%name)
      global%model => mdl
      call var_list_set_string (global%var_list, var_str ("$model_name"), &
        model%name, is_known=.true.)
      call msg_message ("Switching to model '" &
        // char (model_get_name (mdl)) &
```

```

        // ': reassigning model parameters")
        model_vars => model_get_var_list_ptr (mdl)
        call var_list_synchronize &
            (global%var_list, model_vars, reset_pointers = .true.)
    end if
else
    model_vars => model_get_var_list_ptr (global%model)
    call var_list_synchronize &
        (global%var_list, model_vars, reset_pointers = .false.)
    end if
end subroutine cmd_model_execute

```

Library configuration

We configure a process library that should hold the subsequently defined processes.

```

<Commands: types>+≡
    type :: cmd_library_t
    private
    type(string_t) :: name
end type cmd_library_t

```

Output.

```

<Commands: procedures>+≡
    subroutine cmd_library_write (library, unit, indent)
        type(cmd_library_t), intent(in) :: library
        integer, intent(in), optional :: unit, indent
        integer :: u
        u = output_unit (unit); if (u < 0) return
        call write_indent (u, indent)
        write (u, "(1x,A,1x,'"',A,'\"') "library =", char (library%name)
    end subroutine cmd_library_write

```

Compile. Get the library name.

```

<Commands: procedures>+≡
    subroutine cmd_library_compile (library, pn)
        type(cmd_library_t), pointer :: library
        type(parse_node_t), intent(in), target :: pn
        type(parse_node_t), pointer :: pn_name
        pn_name => parse_node_get_sub_ptr (pn, 3)
        allocate (library)
        library%name = parse_node_get_string (pn_name)
    end subroutine cmd_library_compile

```

Execute: Initialize a new library and append to the library store (if it does not yet exist). Try to load the library. Insert a pointer to the library into the global data record.

```

<Commands: procedures>+≡
    subroutine cmd_library_execute (library, global)
        type(cmd_library_t), intent(in) :: library

```

```

type(rt_data_t), intent(inout), target :: global
logical :: rebuild_library, recompile_library
call process_library_store_append &
    (library%name, global%os_data, global%prc_lib)
rebuild_library = var_list_get_lval (global%var_list, var_str ("?rebuild_library"))
recompile_library = var_list_get_lval (global%var_list, var_str ("?recompile_library"))
if (.not. (rebuild_library .or. recompile_library)) then
    call process_library_load (global%prc_lib, &
        global%os_data, var_list=global%var_list, ignore=.true.)
else
    call var_list_set_string (global%var_list, var_str ("$_library_name"), &
        process_library_get_name (global%prc_lib), is_known=.true.)
end if
end subroutine cmd_library_execute

```

Process configuration

We define a process-configuration command as a specific type. The incoming and outgoing particles are given evaluation-trees which we transform to PDG-code arrays. For transferring to O'MEGA, they are reconverted to strings.

(Commands: types)+≡

```

type :: cmd_process_t
private
type(string_t) :: id
integer :: n_in = 0
integer :: n_out = 0
type(eval_tree_t), dimension(:), allocatable :: pdg_in
type(eval_tree_t), dimension(:), allocatable :: pdg_out
type(string_t), dimension(:), allocatable :: prt_in
type(string_t), dimension(:), allocatable :: prt_out
type(command_list_t), pointer :: options => null ()
type(rt_data_t) :: local
end type cmd_process_t

```

Finalize. The enclosed eval trees have to be deleted.

(Commands: procedures)+≡

```

subroutine cmd_process_final (process)
type(cmd_process_t), intent(inout) :: process
integer :: i
if (allocated (process%pdg_in)) then
    do i = 1, size (process%pdg_in)
        call eval_tree_final (process%pdg_in(i))
    end do
end if
if (allocated (process%pdg_out)) then
    do i = 1, size (process%pdg_out)
        call eval_tree_final (process%pdg_out(i))
    end do
end if
if (associated (process%options)) then
    call command_list_final (process%options)
    deallocate (process%options)
end if

```

```

        end if
    end subroutine cmd_process_final

```

Output.

(Commands: procedures)+≡

```

subroutine cmd_process_write (process, unit, indent)
    type(cmd_process_t), intent(in) :: process
    integer, intent(in), optional :: unit, indent
    integer :: u, i
    u = output_unit (unit); if (u < 0) return
    call write_indent (u, indent)
    write (u, "(1x,A,1x,A,1x,A,1x)", advance="no") &
        "process", char (process%id), "="
    do i = 1, process%n_in
        if (i /= 1) write (u, "(',')", advance="no")
        write (u, "(1x,A)", advance="no") char (process%prt_in(i))
    end do
    write (u, "(1x,A,1x)", advance="no") "->"
    do i = 1, process%n_out
        if (i /= 1) write (u, "(',')", advance="no")
        write (u, "(1x,A)", advance="no") char (process%prt_out(i))
    end do
    if (associated (process%options)) then
        write (u, "(1x,'{'")
        call command_list_write (process%options, unit, indent)
        call write_indent (u, indent)
        write (u, "(1x,'}')"
    else
        write (u, *)
    end if
end subroutine cmd_process_write

```

Compile.

(Commands: procedures)+≡

```

subroutine cmd_process_compile (process, pn, global)
    type(cmd_process_t), pointer :: process
    type(parse_node_t), intent(in), target :: pn
    type(rt_data_t), intent(in), target :: global
    type(parse_node_t), pointer :: pn_id, pn_in, pn_out, pn_codes, pn_opt
    integer :: i
    pn_id => parse_node_get_sub_ptr (pn, 2)
    pn_in  => parse_node_get_next_ptr (pn_id, 2)
    pn_out => parse_node_get_next_ptr (pn_in, 2)
    pn_opt => parse_node_get_next_ptr (pn_out)
    allocate (process)
    call rt_data_local_init (process%local, global)
    if (associated (pn_opt)) then
        allocate (process%options)
        call command_list_compile (process%options, pn_opt, process%local)
    end if
    process%id = parse_node_get_string (pn_id)
    process%n_in  = parse_node_get_n_sub (pn_in)
    process%n_out = parse_node_get_n_sub (pn_out)

```

```

pn_codes => parse_node_get_sub_ptr (pn_in)
allocate (process%pdg_in (process%n_in), process%prt_in (process%n_in))
do i = 1, process%n_in
  call eval_tree_init_cexpr &
    (process%pdg_in(i), pn_codes, process%local%var_list)
  process%prt_in(i) = "?"
  pn_codes => parse_node_get_next_ptr (pn_codes)
end do
pn_codes => parse_node_get_sub_ptr (pn_out)
allocate (process%pdg_out (process%n_out), process%prt_out (process%n_out))
do i = 1, process%n_out
  call eval_tree_init_cexpr &
    (process%pdg_out(i), pn_codes, process%local%var_list)
  process%prt_out(i) = "?"
  pn_codes => parse_node_get_next_ptr (pn_codes)
end do
end subroutine cmd_process_compile

```

Command execution. Evaluate the particle lists, transform PDG codes into strings, and add the current process configuration to the process library. If anything goes wrong in the particle code interpretation, the particle names will contain question marks. In that case, the process is not recorded.

(*Commands: procedures*) +=

```

subroutine cmd_process_execute (process, global)
  type(cmd_process_t), intent(inout), target :: process
  type(rt_data_t), intent(inout), target :: global
  type(pdg_array_t) :: pdg_in, pdg_out
  integer :: i
  logical :: rebuild_library
  type(string_t) :: restrictions
  call rt_data_link (process%local, global)
  if (associated (process%options)) then
    call command_list_execute (process%options, process%local)
  end if
  if (process_library_is_static (global%prc_lib)) then
    call msg_error ("Process library '" &
      // char (process_library_get_name (global%prc_lib)) &
      // "' is static, no processes can be added")
    return
  end if
  do i = 1, size (process%pdg_in)
    call eval_tree_evaluate (process%pdg_in(i))
    pdg_in = eval_tree_get_pdg_array (process%pdg_in(i))
    process%prt_in(i) = make_flavor_string (pdg_in, process%local%model)
  end do
  do i = 1, size (process%pdg_out)
    call eval_tree_evaluate (process%pdg_out(i))
    pdg_out = eval_tree_get_pdg_array (process%pdg_out(i))
    process%prt_out(i) = make_flavor_string (pdg_out, process%local%model)
  end do
  restrictions = var_list_get_sval &
    (process%local%var_list, var_str ("restrictions"))
  if (all (scan (process%prt_in, "?") == 0) .and. &

```

```

        all (scan (process%prt_out, "?") == 0)) then
        rebuild_library = var_list_get_lval &
            (process%local%var_list, var_str ("?rebuild_library"))
        call process_library_append (global%prc_lib, &
            process%id, process%local%model, &
            process%prt_in, process%prt_out, global%var_list, &
            restrictions = restrictions, &
            rebuild_library = rebuild_library, message = .true.)
    else
        call msg_error ("Broken process declaration: skipped")
    end if
    call rt_data_restore (global, process%local)
end subroutine cmd_process_execute

```

This is a method of the eval tree, but cannot be coded inside the expressions module since it uses the model and flv types which are not available there.

(Commands: procedures)+≡

```

function make_flavor_string (aval, model) result (prt)
    type(string_t) :: prt
    type(pdg_array_t), intent(in) :: aval
    type(model_t), intent(in), target :: model
    integer, dimension(:), allocatable :: pdg
    type(flavor_t), dimension(:), allocatable :: flv
    integer :: i
    pdg = aval
    allocate (flv (size (pdg)))
    call flavor_init (flv, pdg, model)
    if (size (pdg) /= 0) then
        prt = flavor_get_name (flv(1))
        do i = 2, size (flv)
            prt = prt // ":" // flavor_get_name (flv(i))
        end do
    else
        prt = "?"
    end if
end function make_flavor_string

```

Process compilation

(Commands: types)+≡

```

type :: cmd_compile_t
    private
    type(string_t), dimension(:), allocatable :: libname
    logical :: make_executable = .false.
    type(string_t) :: exec_name
    type(command_list_t), pointer :: options => null ()
    type(rt_data_t) :: local
end type cmd_compile_t

```

Finalize. Only options.

(Commands: procedures)+≡

```

subroutine cmd_compile_final (compile)
  type(cmd_compile_t), intent(inout) :: compile
  if (associated (compile%options)) then
    call command_list_final (compile%options)
    deallocate (compile%options)
  end if
end subroutine cmd_compile_final

```

Output

<Commands: procedures>+≡

```

subroutine cmd_compile_write (compile, unit, indent)
  type(cmd_compile_t), intent(in) :: compile
  integer, intent(in), optional :: unit, indent
  integer :: u, i
  u = output_unit (unit); if (u < 0) return
  call write_indent (u, indent)
  write (u, "(1x,A)", advance="no") "compile "
  if (compile%make_executable) then
    write (u, "(A)", advance="no") "as " // char (compile%exec_name) // " "
  end if
  write (u, "(A)", advance="no") "("
  do i = 1, size (compile%libname)
    if (i /= 1) write (u, "(',',1x)", advance="no")
    write (u, "(A)", advance="no") ''' // char (compile%libname(i)) // '''
  end do
  write (u, "(A)", advance="no") ")"
  if (associated (compile%options)) then
    write (u, "(1x,'{'")
    call command_list_write (compile%options, unit, indent)
    call write_indent (u, indent)
    write (u, "(1x,'}')")
  end if
end subroutine cmd_compile_write

```

Compile the libraries specified in the argument. If the argument is empty, compile all libraries which can be found in the process store.

<Commands: procedures>+≡

```

subroutine cmd_compile_compile (compile, pn, global)
  type(cmd_compile_t), pointer :: compile
  type(parse_node_t), intent(in), target :: pn
  type(rt_data_t), intent(in), target :: global
  type(parse_node_t), pointer :: pn_cmd, pn_clause, pn_arg, pn_lib, pn_opt
  type(parse_node_t), pointer :: pn_exec_name_spec, pn_exec_name
  type(process_library_t), pointer :: prc_lib
  integer :: n_lib, i
  pn_cmd => parse_node_get_sub_ptr (pn)
  pn_clause => parse_node_get_sub_ptr (pn_cmd)
  pn_exec_name_spec => parse_node_get_sub_ptr (pn_clause, 2)
  if (associated (pn_exec_name_spec)) then
    pn_exec_name => parse_node_get_sub_ptr (pn_exec_name_spec, 2)
  else
    pn_exec_name => null ()
  end if
end if

```

```

pn_arg => parse_node_get_next_ptr (pn_clause)
pn_opt => parse_node_get_next_ptr (pn_cmd)
allocate (compile)
call rt_data_local_init (compile%local, global)
if (associated (pn_opt)) then
    allocate (compile%options)
    call command_list_compile (compile%options, pn_opt, compile%local)
end if
if (associated (pn_arg)) then
    n_lib = parse_node_get_n_sub (pn_arg)
else
    n_lib = 0
end if
if (n_lib > 0) then
    allocate (compile%libname (n_lib))
    pn_lib => parse_node_get_sub_ptr (pn_arg)
    do i = 1, n_lib
        compile%libname(i) = parse_node_get_string (pn_lib)
        pn_lib => parse_node_get_next_ptr (pn_lib)
    end do
else
    n_lib = 0
    prc_lib => process_library_store_get_first ()
    do while (associated (prc_lib))
        n_lib = n_lib + 1
        call process_library_advance (prc_lib)
    end do
    allocate (compile%libname (n_lib))
    i = 0
    prc_lib => process_library_store_get_first ()
    do while (associated (prc_lib))
        i = i + 1
        compile%libname(i) = process_library_get_name (prc_lib)
        call process_library_advance (prc_lib)
    end do
end if
if (associated (pn_exec_name)) then
    compile%make_executable = .true.
    compile%exec_name = parse_node_get_string (pn_exec_name)
end if
end subroutine cmd_compile_compile

```

Command execution. Generate code, write driver, compile and link. Do this for all libraries in the list which have a nonzero number of processes defined so far.

(Commands: procedures)+≡

```

subroutine cmd_compile_execute (compile, global)
    type(cmd_compile_t), intent(inout), target :: compile
    type(rt_data_t), intent(inout), target :: global
    type(string_t) :: objlist
    type(process_library_t), pointer :: prc_lib
    integer :: i
    logical :: recompile_library

```

```

call rt_data_link (compile%local, global)
if (associated (compile%options)) then
    call command_list_execute (compile%options, compile%local)
end if
do i = 1, size (compile%libname)
    prc_lib => process_library_store_get_ptr (compile%libname(i))
    if (process_library_get_n_processes (prc_lib) > 0) then
        call process_library_generate_code (prc_lib, compile%local%os_data)
        call process_library_write_driver (prc_lib)
        recompile_library = var_list_get_lval &
            (compile%local%var_list, var_str ("?recompile_library"))
        call process_library_compile &
            (prc_lib, compile%local%os_data, recompile_library, objlist)
        call process_library_link &
            (prc_lib, compile%local%os_data, objlist)
    end if
end do
if (compile%make_executable) then
    call write_library_manager (compile%libname)
    call compile_library_manager (compile%local%os_data)
    call link_executable &
        (compile%libname, compile%exec_name, compile%local%os_data)
else
    do i = 1, size (compile%libname)
        call process_library_load (prc_lib, compile%local%os_data, &
            var_list=compile%local%var_list)
    end do
end if
call rt_data_restore (global, compile%local)
end subroutine cmd_compile_execute

```

Load library

For the most part, this is analogous to the compile command.

```

<Commands: types>+≡
type :: cmd_load_t
private
type(string_t), dimension(:), allocatable :: libname
type(command_list_t), pointer :: options => null ()
type(rt_data_t) :: local
end type cmd_load_t

```

Finalize. Only options.

```

<Commands: procedures>+≡
subroutine cmd_load_final (load)
type(cmd_load_t), intent(inout) :: load
if (associated (load%options)) then
    call command_list_final (load%options)
    deallocate (load%options)
end if
end subroutine cmd_load_final

```

Output.

(Commands: procedures)+≡

```
subroutine cmd_load_write (load, unit, indent)
  type(cmd_load_t), intent(in) :: load
  integer, intent(in), optional :: unit, indent
  integer :: u, i
  u = output_unit (unit); if (u < 0) return
  call write_indent (u, indent)
  write (u, "(1x,A)", advance="no") "load ("
  do i = 1, size (load%libname)
    if (i /= 1) write (u, "(',',1x)", advance="no")
    write (u, "(A)", advance="no") ''' // char (load%libname(i)) // '''
  end do
  write (u, "(A)", advance="no") ")"
end subroutine cmd_load_write
```

Compile the load command.

(Commands: procedures)+≡

```
subroutine cmd_load_compile (load, pn, global)
  type(cmd_load_t), pointer :: load
  type(parse_node_t), intent(in), target :: pn
  type(rt_data_t), intent(in), target :: global
  type(parse_node_t), pointer :: pn_arg, pn_lib, pn_opt
  type(process_library_t), pointer :: prc_lib
  integer :: n_lib, i
  pn_arg => parse_node_get_sub_ptr (pn, 2)
  allocate (load)
  if (associated (pn_arg)) then
    select case (char (parse_node_get_rule_key (pn_arg)))
    case ("load_arg")
      n_lib = parse_node_get_n_sub (pn_arg)
      pn_opt => parse_node_get_next_ptr (pn_arg)
    case default
      n_lib = 0
      pn_opt => pn_arg
    end select
  else
    n_lib = 0
    pn_opt => null ()
  end if
  call rt_data_local_init (load%local, global)
  if (associated (pn_opt)) then
    allocate (load%options)
    call command_list_compile (load%options, pn_opt, load%local)
  end if
  if (n_lib > 0) then
    allocate (load%libname (n_lib))
    pn_lib => parse_node_get_sub_ptr (pn_arg)
    do i = 1, n_lib
      load%libname(i) = parse_node_get_string (pn_lib)
      pn_lib => parse_node_get_next_ptr (pn_lib)
    end do
  else

```

```

n_lib = 0
prc_lib => process_library_store_get_first ()
do while (associated (prc_lib))
  n_lib = n_lib + 1
  call process_library_advance (prc_lib)
end do
allocate (load%libname (n_lib))
i = 0
prc_lib => process_library_store_get_first ()
do while (associated (prc_lib))
  i = i + 1
  load%libname(i) = process_library_get_name (prc_lib)
  call process_library_advance (prc_lib)
end do
end if
end subroutine cmd_load_compile

```

Execute: Load the specified shared libraries. Insert a pointer to the last library in the list into the global record.

```

<Commands: procedures>+≡
subroutine cmd_load_execute (load, global)
  type(cmd_load_t), intent(inout) :: load
  type(rt_data_t), intent(inout), target :: global
  type(process_library_t), pointer :: prc_lib
  integer :: i
  call rt_data_link (load%local, global)
  if (associated (load%options)) then
    call command_list_execute (load%options, load%local)
  end if
  do i = 1, size (load%libname)
    call process_library_store_append &
      (load%libname(i), load%local%os_data, prc_lib)
    call process_library_load &
      (prc_lib, load%local%os_data, var_list=load%local%var_list)
  end do
  global%prc_lib => prc_lib
  call rt_data_restore (global, load%local)
end subroutine cmd_load_execute

```

Execute a shell command

The argument is a string expression.

```

<Commands: types>+≡
type :: cmd_exec_t
  private
  type(eval_tree_t) :: command
end type cmd_exec_t

```

Delete the eval tree.

```

<Commands: procedures>+≡
subroutine cmd_exec_final (exec)

```

```

    type(cmd_exec_t), intent(inout) :: exec
    call eval_tree_final (exec%command)
end subroutine cmd_exec_final

```

Output.

```

<Commands: procedures>+≡
subroutine cmd_exec_write (exec, unit, indent)
    type(cmd_exec_t), intent(in) :: exec
    integer, intent(in), optional :: unit, indent
    integer :: u
    u = output_unit (unit); if (u < 0) return
    call write_indent (u, indent)
    write (u, "(1x,A)", advance="no") "exec ("
    call eval_tree_write (exec%command, unit)
    write (u, "(A)" )"
end subroutine cmd_exec_write

```

Compile the exec command.

```

<Commands: procedures>+≡
subroutine cmd_exec_compile (exec, pn, global)
    type(cmd_exec_t), pointer :: exec
    type(parse_node_t), intent(in), target :: pn
    type(rt_data_t), intent(in), target :: global
    type(parse_node_t), pointer :: pn_arg, pn_command
    pn_arg => parse_node_get_sub_ptr (pn, 2)
    pn_command => parse_node_get_sub_ptr (pn_arg)
    allocate (exec)
    call eval_tree_init_sexpr (exec%command, pn_command, global%var_list)
end subroutine cmd_exec_compile

```

Execute the specified shell command.

```

<Commands: procedures>+≡
subroutine cmd_exec_execute (exec, global)
    type(cmd_exec_t), intent(inout) :: exec
    type(rt_data_t), intent(in) :: global
    type(string_t) :: command
    integer :: status
    call eval_tree_evaluate (exec%command)
    if (eval_tree_result_is_known (exec%command)) then
        command = eval_tree_get_string (exec%command)
        if (command /= "") then
            call os_system_call (command, status, verbose=.true.)
            if (status /= 0) then
                write (msg_buffer, "(A,I0)") "Return code = ", status
                call msg_message ()
                call msg_error ("System command returned with nonzero status code")
            end if
        end if
    end if
end subroutine cmd_exec_execute

```

Variable declaration

A variable can have various types. Hold the definition as an eval tree.

```
(Commands: types)+≡
  type :: cmd_var_t
  private
  type(string_t) :: name
  integer :: type = V_NONE
  type(eval_tree_t) :: value
  logical, pointer :: is_known => null ()
  logical, pointer :: lval => null ()
  integer, pointer :: ival => null ()
  real(default), pointer :: rval => null ()
  complex(default), pointer :: cval => null ()
  type(string_t), pointer :: sval => null ()
  type(pdg_array_t), pointer :: aval => null ()
  logical :: is_copy = .false.
end type cmd_var_t
```

Delete the eval tree.

```
(Commands: procedures)+≡
  subroutine cmd_var_final (var)
    type(cmd_var_t), intent(inout) :: var
    call eval_tree_final (var%value)
  end subroutine cmd_var_final
```

Output

```
(Commands: procedures)+≡
  subroutine cmd_var_write (var, unit, indent)
    type(cmd_var_t), intent(in) :: var
    integer, intent(in), optional :: unit, indent
    integer :: u
    u = output_unit (unit); if (u < 0) return
    call write_indent (u, indent)
    write (u, "(1x,A)", advance="no") char (var%name)
    write (u, "(1x, A)") "="
    call eval_tree_write (var%value, unit)
  end subroutine cmd_var_write
```

Compile. Append the variable to the local list, compile the definition and assign the value (if constant) or a pointer (if variable) to the newly created variable.

```
(Commands: procedures)+≡
  subroutine cmd_var_compile (var, pn, global)
    type(cmd_var_t), pointer :: var
    type(parse_node_t), intent(in), target :: pn
    type(rt_data_t), intent(inout), target :: global
    type(parse_node_t), pointer :: pn_prefix, pn_name, pn_expr
    character :: prefix
    type(string_t) :: name
    type(var_entry_t), pointer :: var_entry
    integer :: u
    u = logfile_unit ()
```

```

pn_prefix => parse_node_get_sub_ptr (pn)
allocate (var)
select case (char (parse_node_get_rule_key (pn_prefix)))
case ("int"); var%type = V_INT
    pn_name => parse_node_get_next_ptr (pn_prefix)
case ("real"); var%type = V_REAL
    pn_name => parse_node_get_next_ptr (pn_prefix)
case ("cmplx"); var%type = V_CMPLX
    pn_name => parse_node_get_next_ptr (pn_prefix)
case ("?"); var%type = V_LOG; prefix = "?"
    pn_name => parse_node_get_next_ptr (pn_prefix)
case ("$"); var%type = V_STR; prefix = "$"
    pn_name => parse_node_get_next_ptr (pn_prefix)
case ("alias"); var%type = V_PDG
    pn_name => parse_node_get_next_ptr (pn_prefix)
case ("var_name")
    pn_name => pn_prefix
case default
    call parse_node_mismatch ("int|real|cmplx|?|$|alias|var_name", pn)
end select ! second $ sign here for fooling Emacs noweb mode
if (.not. associated (pn_name)) then ! handle masked syntax error
    var%type = V_NONE; return
end if
name = parse_node_get_string (pn_name)
select case (var%type)
case (V_LOG, V_STR)
    var%name = prefix // name
case default
    var%name = name
end select
if (string_is_observable_id (name)) then
    call msg_error ("Variable name '" // char (name) &
        // "' is reserved for an observable")
    var%type = V_NONE; return
end if
select case (var%type)
case (V_NONE)
    var_entry => var_list_get_var_ptr &
        (global%var_list, var%name, follow_link=.false.)
case default
    var_entry => var_list_get_var_ptr &
        (global%var_list, var%name, var%type, follow_link=.false.)
end select
if (associated (var_entry)) then
    if (var_entry_is_locked (var_entry)) then
        call msg_error ("Variable '" // char (var%name) &
            // "' is not user-definable")
        var%type = V_NONE
        return
    else if (var%type == V_NONE) then
        var%type = var_entry_get_type (var_entry)
        select case (var%type)
        case (V_CMPLX, V_REAL, V_INT)
        case default

```

```

        call msg_error ("Variable '" // char (var%name) &
            // "' has non-numeric type")
        var%type = V_NONE
        return
    end select
else if (var%type /= var_entry_get_type (var_entry)) then
    call var_list_write_var (global%var_list, var%name)
    call var_list_write_var (global%var_list, var%name, unit=u)
    flush (u)
    call msg_error ("Variable '" // char (var%name) &
        // "' has different type")
    var%type = V_NONE
    return
end if
var%is_copy = var_entry_is_copy (var_entry)
else
    select case (var%type)
    case (V_NONE)
        var_entry => var_list_get_var_ptr &
            (global%var_list, var%name, follow_link=.true.)
    case default
        var_entry => var_list_get_var_ptr &
            (global%var_list, var%name, var%type, follow_link=.true.)
    end select
    if (associated (var_entry)) then
        if (var_entry_is_copy (var_entry)) then
            var%is_copy = .true.
            call var_list_init_copy (global%var_list, var_entry)
        else if (var%type == V_NONE) then
            var%type = var_entry_get_type (var_entry)
            select case (var%type)
            case (V_CMPLX, V_REAL, V_INT)
            case default
                call msg_error ("Variable '" // char (var%name) &
                    // "' has non-numeric type")
                var%type = V_NONE
                return
            end select
        end if
    else if (var%type == V_NONE) then
        var%type = V_REAL
    end if
    if (.not. var%is_copy) then
        select case (var%type)
        case (V_LOG)
            call var_list_append_log (global%var_list, var%name)
        case (V_INT)
            call var_list_append_int (global%var_list, var%name)
        case (V_REAL)
            call var_list_append_real (global%var_list, var%name)
        case (V_CMPLX)
            call var_list_append_cmplx (global%var_list, var%name)
        case (V_PDG)
            call var_list_append_pdg_array (global%var_list, var%name)

```

```

        case (V_STR)
            call var_list_append_string (global%var_list, var%name)
        end select
!       call msg_message ("Defined user variable '" &
!       // char (var%name) // "'.")
    end if
end if
pn_expr => parse_node_get_next_ptr (pn_name, 2)
if (associated (pn_expr)) then
    select case (var%type)
    case (V_LOG)
        call eval_tree_init_lexpr (var%value, pn_expr, global%var_list)
        var%lval => eval_tree_get_log_ptr (var%value)
    case (V_INT)
        call eval_tree_init_expr (var%value, pn_expr, global%var_list)
        call eval_tree_convert_result (var%value, var%type)
        var%ival => eval_tree_get_int_ptr (var%value)
    case (V_REAL)
        call eval_tree_init_expr (var%value, pn_expr, global%var_list)
        call eval_tree_convert_result (var%value, var%type)
        var%rval => eval_tree_get_real_ptr (var%value)
    case (V_CMPLX)
        call eval_tree_init_expr (var%value, pn_expr, global%var_list)
        call eval_tree_convert_result (var%value, var%type)
        var%cval => eval_tree_get_cmplx_ptr (var%value)
    case (V_PDG)
        call eval_tree_init_cexpr (var%value, pn_expr, global%var_list)
        var%aval => eval_tree_get_pdg_array_ptr (var%value)
    case (V_STR)
        call eval_tree_init_sexpr (var%value, pn_expr, global%var_list)
        var%sval => eval_tree_get_string_ptr (var%value)
    end select
    var%is_known => eval_tree_result_is_known_ptr (var%value)
else
    var%type = V_NONE
end if
end subroutine cmd_var_compile

```

Execute. Evaluate the definition and assign the variable value. If the variable is a copy, the original is a model variable. The original is set automatically, and an update of the dependent parameters is in order.

```

<Commands: procedures>+≡
subroutine cmd_var_execute (var, global)
    type(cmd_var_t), intent(inout), target :: var
    type(rt_data_t), intent(inout), target :: global
    type(string_t) :: model_name
    type(var_list_t), pointer :: model_vars
    type(var_entry_t) :: model_var
    call eval_tree_evaluate (var%value)
    if (associated (global%model)) then
        model_name = model_get_name (global%model)
        model_vars => model_get_var_list_ptr (global%model)
        if (var%is_copy) then

```

```

        call var_list_set_original_pointer (global%var_list, var%name, &
            model_vars)
    end if
    select case (var%type)
    case (V_LOG)
        call var_list_set_log (global%var_list, var%name, &
            var%lval, var%is_known, verbose=.true., model_name=model_name)
    case (V_INT)
        call var_list_set_int (global%var_list, var%name, &
            var%ival, var%is_known, verbose=.true., model_name=model_name)
    case (V_REAL)
        call var_list_set_real (global%var_list, var%name, &
            var%rval, var%is_known, verbose=.true., model_name=model_name)
    case (V_CMPLX)
        call var_list_set_cmplx (global%var_list, var%name, &
            var%cval, var%is_known, verbose=.true., model_name=model_name)
    case (V_PDG)
        call var_list_set_pdg_array (global%var_list, var%name, &
            var%aval, var%is_known, verbose=.true., model_name=model_name)
    case (V_STR)
        call var_list_set_string (global%var_list, var%name, &
            var%sval, var%is_known, verbose=.true., model_name=model_name)
    end select
    if (var%is_copy) then
        call model_parameters_update (global%model)
        call var_list_synchronize (global%var_list, model_vars)
    end if
else
    select case (var%type)
    case (V_LOG)
        call var_list_set_log (global%var_list, var%name, &
            var%lval, var%is_known, verbose=.true.)
    case (V_INT)
        call var_list_set_int (global%var_list, var%name, &
            var%ival, var%is_known, verbose=.true.)
    case (V_REAL)
        call var_list_set_real (global%var_list, var%name, &
            var%rval, var%is_known, verbose=.true.)
    case (V_CMPLX)
        call var_list_set_cmplx (global%var_list, var%name, &
            var%cval, var%is_known, verbose=.true.)
    case (V_PDG)
        call var_list_set_pdg_array (global%var_list, var%name, &
            var%aval, var%is_known, verbose=.true.)
    case (V_STR)
        call var_list_set_string (global%var_list, var%name, &
            var%sval, var%is_known, verbose=.true.)
    end select
end if
end subroutine cmd_var_execute

```

SLHA

Read a SLHA (SUSY Les Houches Accord) file to fill the appropriate model parameters. We do not access the current variable record, but directly work on the appropriate SUSY model, which is loaded if necessary.

We may be in read or write mode. In the latter case, we may write just input parameters, or the complete spectrum, or the spectrum with all decays.

```
(Commands: types)+≡
  type :: cmd_slha_t
  private
  type(string_t) :: file
  logical :: write = .false.
  type(command_list_t), pointer :: options => null ()
  type(rt_data_t) :: local
end type cmd_slha_t
```

Finalizer.

```
(Commands: procedures)+≡
  subroutine cmd_slha_final (slha)
    type(cmd_slha_t), intent(inout) :: slha
    if (associated (slha%options)) then
      call command_list_final (slha%options)
      deallocate (slha%options)
    end if
  end subroutine cmd_slha_final
```

Output

```
(Commands: procedures)+≡
  subroutine cmd_slha_write (slha, unit, indent)
    type(cmd_slha_t), intent(in) :: slha
    integer, intent(in), optional :: unit, indent
    integer :: u
    u = output_unit (unit); if (u < 0) return
    call write_indent (u, indent)
    if (slha%write) then
      write (u, "(A)", advance="no") "write_"
    else
      write (u, "(A)", advance="no") "read_"
    end if
    write (u, "(A)", advance="no") "slha"
    write (u, "(1x,A)") "(" // char (slha%file) // ")"
    if (associated (slha%options)) then
      write (u, "(1x,'{')")
      call command_list_write (slha%options, unit, indent)
      call write_indent (u, indent)
      write (u, "(1x,'}')")
    end if
  end subroutine cmd_slha_write
```

Compile. Read the filename and store it.

```
(Commands: procedures)+≡
  subroutine cmd_slha_compile (slha, pn, global)
```

```

type(cmd_slha_t), pointer :: slha
type(parse_node_t), intent(in), target :: pn
type(rt_data_t), intent(in), target :: global
type(parse_node_t), pointer :: pn_key, pn_arg, pn_file
type(parse_node_t), pointer :: pn_opt
pn_key => parse_node_get_sub_ptr (pn)
pn_arg => parse_node_get_next_ptr (pn_key)
pn_file => parse_node_get_sub_ptr (pn_arg)
pn_opt => parse_node_get_next_ptr (pn_arg)
allocate (slha)
call rt_data_local_init (slha%local, global)
if (associated (pn_opt)) then
  allocate (slha%options)
  call command_list_compile (slha%options, pn_opt, slha%local)
end if
select case (char (parse_node_get_key (pn_key)))
case ("read_slha")
  slha%write = .false.
case ("write_slha")
  slha%write = .true.
case default
  call parse_node_mismatch ("read_slha|write_slha", pn)
end select
slha%file = parse_node_get_string (pn_file)
end subroutine cmd_slha_compile

```

Execute. Read or write the specified SLHA file.

(Commands: procedures)+≡

```

subroutine cmd_slha_execute (slha, global)
  type(cmd_slha_t), intent(inout), target :: slha
  type(rt_data_t), intent(inout), target :: global
  type(model_t), pointer :: mdl
  logical :: input, spectrum, decays
  call rt_data_link (slha%local, global)
  if (associated (slha%options)) then
    call command_list_execute (slha%options, slha%local)
  end if
  if (slha%write) then
    input = .true.
    spectrum = .false.
    decays = .false.
    call slha_write_file &
      (slha%file, slha%local%model, &
       input = input, spectrum = spectrum, decays = decays)
  else
    input = var_list_get_lval (slha%local%var_list, &
      var_str ("?slha_read_input"))
    spectrum = var_list_get_lval (slha%local%var_list, &
      var_str ("?slha_read_spectrum"))
    decays = var_list_get_lval (slha%local%var_list, &
      var_str ("?slha_read_decays"))
    call slha_read_file &
      (slha%file, slha%local%os_data, slha%local%model, &
       input = input, spectrum = spectrum, decays = decays)
  end if
end subroutine cmd_slha_execute

```

```

end if
call rt_data_restore (global, slha%local, keep_model_vars = .true.)
end subroutine cmd_slha_execute

```

Show values of variables

(Commands: types)+≡

```

type :: cmd_show_t
private
type(string_t), dimension(:), allocatable :: name
type(eval_tree_t), dimension(:), allocatable :: expr
type(var_entry_t), dimension(:), allocatable :: value
end type cmd_show_t

```

Finalize.

(Commands: procedures)+≡

```

subroutine cmd_show_final (show)
type(cmd_show_t), intent(inout) :: show
integer :: i
if (allocated (show%expr)) then
do i = 1, size (show%expr)
call eval_tree_final (show%expr(i))
end do
end if
if (allocated (show%value)) then
do i = 1, size (show%value)
call var_entry_final (show%value(i))
end do
end if
end subroutine cmd_show_final

```

Compile. Allocate an array which is filled with the names of the variables to show.

(Commands: procedures)+≡

```

subroutine cmd_show_compile (show, pn, global)
type(cmd_show_t), pointer :: show
type(parse_node_t), intent(in), target :: pn
type(rt_data_t), intent(in), target :: global
type(parse_node_t), pointer :: pn_arg, pn_var, pn_prefix, pn_name
type(string_t) :: key
integer :: i, n_args
pn_arg => parse_node_get_sub_ptr (pn, 2)
allocate (show)
if (associated (pn_arg)) then
n_args = parse_node_get_n_sub (pn_arg)
allocate (show%name (n_args), show%expr (n_args), show%value (n_args))
pn_var => parse_node_get_sub_ptr (pn_arg)
i = 0
do while (associated (pn_var))
i = i + 1
select case (char (parse_node_get_rule_key (pn_var)))

```

```

case ("model", "beams", "results", "unstable", &
     "real", "int", "intrinsic", &
     "cuts", "weight", "scale", "analysis", &
     "expect")
    show%name(i) = parse_node_get_key (pn_var)
case ("library_spec")
    pn_prefix => parse_node_get_sub_ptr (pn_var)
    pn_name => parse_node_get_next_ptr (pn_prefix)
    key = parse_node_get_key (pn_prefix)
    if (associated (pn_name)) then
        show%name(i) = "L " // parse_node_get_string (pn_name)
    else
        show%name(i) = key
    end if
case ("result_var")
    pn_prefix => parse_node_get_sub_ptr (pn_var)
    pn_name => parse_node_get_next_ptr (pn_prefix)
    if (associated (pn_name)) then
        show%name(i) = parse_node_get_key (pn_prefix) &
            // "(" // parse_node_get_string (pn_name) // ")"
    else
        show%name(i) = parse_node_get_key (pn_prefix)
    end if
case ("log_var", "alias_var", "string_var")
    pn_prefix => parse_node_get_sub_ptr (pn_var)
    pn_name => parse_node_get_next_ptr (pn_prefix)
    key = parse_node_get_key (pn_prefix)
    if (associated (pn_name)) then
        select case (char (parse_node_get_rule_key (pn_name)))
        case ("variable")
            select case (char (key))
            case ("?", "$") ! $ sign
                show%name(i) = key // parse_node_get_string (pn_name)
            case ("alias")
                show%name(i) = "A " // parse_node_get_string (pn_name)
            case ("library")
                show%name(i) = "L " // parse_node_get_string (pn_name)
            end select
        case ("lexpr")
            show%name(i) = "<expr>"
            call eval_tree_init_lexpr &
                (show%expr(i), pn_name, global%var_list)
            call var_entry_init_log_ptr (show%value(i), &
                var_str ("logical value"), &
                eval_tree_get_log_ptr (show%expr(i)), &
                eval_tree_result_is_known_ptr (show%expr(i)))
        case ("cexpr")
            show%name(i) = "<expr>"
            call eval_tree_init_cexpr &
                (show%expr(i), pn_name, global%var_list)
            call var_entry_init_pdg_array_ptr (show%value(i), &
                var_str ("PDG-array value"), &
                eval_tree_get_pdg_array_ptr (show%expr(i)), &
                eval_tree_result_is_known_ptr (show%expr(i)))

```

```

case ("sexpr")
  show%name(i) = "<expr>"
  call eval_tree_init_sexpr &
    (show%expr(i), pn_name, global%var_list)
  call var_entry_init_string_ptr (show%value(i), &
    var_str ("string value"), &
    eval_tree_get_string_ptr (show%expr(i)), &
    eval_tree_result_is_known_ptr (show%expr(i)))
case default
  call parse_node_mismatch &
    ("variable|expr|lexpr|cexpr|sexpr", pn_name)
end select
else
  show%name(i) = key
end if
case ("num_var")
  pn_name => parse_node_get_sub_ptr (pn_var)
  if (associated (pn_name)) then
    select case (char (parse_node_get_rule_key (pn_name)))
    case ("variable")
      show%name(i) = parse_node_get_string (pn_name)
    case ("expr")
      show%name(i) = "<expr>"
      call eval_tree_init_expr &
        (show%expr(i), pn_name, global%var_list)
      select case (eval_tree_get_result_type (show%expr(i)))
      case (V_INT)
        call var_entry_init_int_ptr (show%value(i), &
          var_str ("integer value"), &
          eval_tree_get_int_ptr (show%expr(i)), &
          eval_tree_result_is_known_ptr (show%expr(i)))
      case (V_REAL)
        call var_entry_init_real_ptr (show%value(i), &
          var_str ("real value"), &
          eval_tree_get_real_ptr (show%expr(i)), &
          eval_tree_result_is_known_ptr (show%expr(i)))
      case (V_CMPLX)
        call var_entry_init_cmplx_ptr (show%value(i), &
          var_str ("complex value"), &
          eval_tree_get_cmplx_ptr (show%expr(i)), &
          eval_tree_result_is_known_ptr (show%expr(i)))
      end select
    case default
      call parse_node_mismatch &
        ("variable|expr", pn_name)
    end select
  else
    show%name(i) = key
  end if
case default
  pn_prefix => null ()
  pn_name => parse_node_get_sub_ptr (pn_var)
  if (associated (pn_name)) then
    show%name(i) = parse_node_get_string (pn_name)
  end if
end if

```

```

        else
            show%name(i) = ""
        end if
    end select
    pn_var => parse_node_get_next_ptr (pn_var)
end do
else
    allocate (show%name (0))
end if
end subroutine cmd_show_compile

```

Execute. Scan the list of variables to show. Special cases of an empty list (show all) and keywords `int`, `real`, `alias` have to be handled as well.

(Commands: procedures)+≡

```

subroutine cmd_show_execute (show, global)
    type(cmd_show_t), intent(inout) :: show
    type(rt_data_t), intent(in), target :: global
    type(string_t) :: name
    type(process_library_t), pointer :: prc_lib
    integer :: i, u
    u = logfile_unit ()
    if (size (show%name) == 0) then
        call var_list_write (global%var_list)
    else
        if (associated (global%model)) then
            name = model_get_name (global%model)
        else
            name = "[undefined]"
        end if
        do i = 1, size (show%name)
            select case (char (show%name(i)))
            case ("model")
                print *, "model* = ", char (name)
                write (u, *) "model* = ", char (name)
            case ("library")
                if (associated (global%prc_lib)) then
                    call process_library_write (global%prc_lib)
                    call process_library_write (global%prc_lib, unit=u)
                else
                    call msg_message ("Show library: no library is loaded")
                end if
            case ("beams")
                call beam_data_write (global%beam_data)
                call beam_data_write (global%beam_data, unit=u)
            case ("results")
                call process_store_write_results ()
                call process_store_write_results (unit=u)
            case ("unstable")
                call decay_store_write ()
                call decay_store_write (unit=u)
            case ("cuts")
                if (associated (global%pn_cuts_lexpr)) then
                    call parse_node_write_rec (global%pn_cuts_lexpr)
                end if
            end select
        end do
    end if
end subroutine cmd_show_execute

```

```

        if (u >= 0) call parse_node_write_rec (global%pn_cuts_lexpr)
    else
        call msg_message ("No cut expression defined")
    end if
case ("weight")
    if (associated (global%pn_weight_expr)) then
        call parse_node_write_rec (global%pn_weight_expr)
        if (u >= 0) call parse_node_write_rec (global%pn_weight_expr)
    else
        call msg_message ("No weight expression defined")
    end if
case ("scale")
    if (associated (global%pn_scale_expr)) then
        call parse_node_write_rec (global%pn_scale_expr)
        if (u >= 0) call parse_node_write_rec (global%pn_scale_expr)
    else
        call msg_message ("No scale expression defined")
    end if
case ("analysis")
    if (associated (global%pn_analysis_lexpr)) then
        call parse_node_write_rec (global%pn_analysis_lexpr)
        if (u >= 0) call parse_node_write_rec (global%pn_analysis_lexpr)
    else
        call msg_message ("No cut expression defined")
    end if
case ("expect")
    call expect_summary ()
case ("?")
    if (associated (global%model)) then
        call var_list_write (global%var_list, only_type=V_LOG, &
            model_name = name)
        call var_list_write (global%var_list, only_type=V_LOG, &
            model_name = name, unit=u)
    else
        call var_list_write (global%var_list, only_type=V_LOG)
        call var_list_write (global%var_list, only_type=V_LOG, unit=u)
    end if
case ("intrinsic")
    if (associated (global%model)) then
        call var_list_write (global%var_list, intrinsic=.true., &
            model_name = name)
        call var_list_write (global%var_list, intrinsic=.true., &
            model_name = name, unit=u)
    else
        call var_list_write (global%var_list, intrinsic=.true.)
        call var_list_write (global%var_list, intrinsic=.true., unit=u)
    end if
case ("int")
    if (associated (global%model)) then
        call var_list_write (global%var_list, only_type=V_INT, &
            model_name = name)
        call var_list_write (global%var_list, only_type=V_INT, &
            model_name = name, unit=u)
    else

```

```

        call var_list_write (global%var_list, only_type=V_INT)
        call var_list_write (global%var_list, only_type=V_INT, unit=u)
    end if
case ("real")
    if (associated (global%model)) then
        call var_list_write (global%var_list, only_type=V_REAL, &
            model_name = name)
        call var_list_write (global%var_list, only_type=V_REAL, &
            model_name = name, unit=u)
    else
        call var_list_write (global%var_list, only_type=V_REAL)
        call var_list_write (global%var_list, only_type=V_REAL, unit=u)
    end if
case ("cmplx")
    if (associated (global%model)) then
        call var_list_write (global%var_list, only_type=V_CMPLX, &
            model_name = name)
        call var_list_write (global%var_list, only_type=V_CMPLX, &
            model_name = name, unit=u)
    else
        call var_list_write (global%var_list, only_type=V_CMPLX)
        call var_list_write (global%var_list, only_type=V_CMPLX, unit=u)
    end if
case ("alias")
    if (associated (global%model)) then
        call var_list_write (global%var_list, only_type=V_PDG, &
            model_name = name)
        call var_list_write (global%var_list, only_type=V_PDG, &
            model_name = name, unit=u)
    else
        call var_list_write (global%var_list, only_type=V_PDG)
        call var_list_write (global%var_list, only_type=V_PDG, unit=u)
    end if
case ("$$") !$ sign
    if (associated (global%model)) then
        call var_list_write (global%var_list, only_type=V_STR, &
            model_name = name)
        call var_list_write (global%var_list, only_type=V_STR, &
            model_name = name, unit=u)
    else
        call var_list_write (global%var_list, only_type=V_STR)
        call var_list_write (global%var_list, only_type=V_STR, unit=u)
    end if
case ("n_calls", &
    "integral", "error", "accuracy", "chi2", "efficiency")
    call var_list_write (global%var_list, prefix=char(show%name(i)))
    call var_list_write (global%var_list, prefix=char(show%name(i)), &
        unit=u)
case ("<expr>")
    call eval_tree_evaluate (show%expr(i))
    call var_entry_write (show%value(i))
    call var_entry_write (show%value(i), unit=u)
case default
    select case (char (extract (show%name(i), 1, 2)))

```

```

case ("L ")
  name = extract (show%name(i), 3)
  prc_lib => process_library_store_get_ptr (name)
  if (associated (prc_lib)) then
    call process_library_write (prc_lib)
    call process_library_write (prc_lib, unit=u)
  else
    call msg_message ("Library '" // char (name) &
      // "' not loaded")
  end if
case ("A ")
  name = extract (show%name(i), 3)
  call var_list_write_var (global%var_list, name, &
    model_name = name, type = V_PDG)
  call var_list_write_var (global%var_list, name, &
    model_name = name, type = V_PDG, unit=u)
case default
  if (associated (global%model)) then
    call var_list_write_var (global%var_list, show%name(i), &
      model_name = name)
    call var_list_write_var (global%var_list, show%name(i), &
      model_name = name, unit=u)
  else
    call var_list_write_var (global%var_list, show%name(i))
    call var_list_write_var (global%var_list, show%name(i), &
      unit=u)
  end if
end select
end select
end do
end if
flush (u)
end subroutine cmd_show_execute

```

Compare values of variables to expectation

The implementation is similar to the `show` command. There are just two arguments: two values that should be compared. For providing local values for the numerical tolerance, the command has a local argument list.

If the expectation fails, an error condition is recorded.

```

⟨Commands: types⟩+≡
  type :: cmd_expect_t
  private
  type(eval_tree_t) :: lexpr
  type(command_list_t), pointer :: options => null ()
  type(rt_data_t) :: local
end type cmd_expect_t

```

Finalize.

```

⟨Commands: procedures⟩+≡
  subroutine cmd_expect_final (expect)
    type(cmd_expect_t), intent(inout) :: expect
  end subroutine

```

```

call eval_tree_final (expect%lexpr)
if (associated (expect%options)) then
  call command_list_final (expect%options)
  deallocate (expect%options)
end if
end subroutine cmd_expect_final

```

Compile. Allocate an array which is filled with the names of the variables to expect.

```

⟨Commands: procedures⟩+≡
subroutine cmd_expect_compile (expect, pn, global)
  type(cmd_expect_t), pointer :: expect
  type(parse_node_t), intent(in), target :: pn
  type(rt_data_t), intent(in), target :: global
  type(parse_node_t), pointer :: pn_arg, pn_expr, pn_opt
  pn_arg => parse_node_get_sub_ptr (pn, 2)
  pn_opt => parse_node_get_next_ptr (pn_arg)
  allocate (expect)
  call rt_data_local_init (expect%local, global)
  if (associated (pn_opt)) then
    allocate (expect%options)
    call command_list_compile (expect%options, pn_opt, expect%local)
  end if
  pn_expr => parse_node_get_sub_ptr (pn_arg)
  call eval_tree_init_lexpr (expect%lexpr, pn_expr, expect%local%var_list)
end subroutine cmd_expect_compile

```

Execute. Evaluate both arguments, print them and their difference (if numerical), and whether they agree. Record the result.

```

⟨Commands: procedures⟩+≡
subroutine cmd_expect_execute (expect, global)
  type(cmd_expect_t), intent(inout) :: expect
  type(rt_data_t), intent(inout), target :: global
  logical :: success
  integer :: u
  u = logfile_unit ()
  call rt_data_link (expect%local, global)
  if (associated (expect%options)) then
    call command_list_execute (expect%options, expect%local)
  end if
  call eval_tree_evaluate (expect%lexpr)
  if (eval_tree_result_is_known (expect%lexpr)) then
    success = eval_tree_get_log (expect%lexpr)
    if (success) then
      call msg_message ("expect: success")
    else
      if (u >= 0) then
        call eval_tree_write (expect%lexpr, unit=u)
        flush (u)
      end if
      call msg_error ("expect: failure")
    end if
  else

```

```

        call msg_error ("expect: undefined result")
        success = .false.
    end if
    call expect_record (success)
    call rt_data_restore (global, expect%local)
end subroutine cmd_expect_execute

```

Echo strings

```

⟨Commands: types⟩+≡
    type :: cmd_echo_t
    private
    type(eval_tree_t), dimension(:), allocatable :: expr
end type cmd_echo_t

```

Finalize.

```

⟨Commands: procedures⟩+≡
    subroutine cmd_echo_final (echo)
        type(cmd_echo_t), intent(inout) :: echo
        integer :: i
        if (allocated (echo%expr)) then
            do i = 1, size (echo%expr)
                call eval_tree_final (echo%expr(i))
            end do
        end if
    end subroutine cmd_echo_final

```

Compile. Allocate an array which is filled with the names of the variables to echo.

```

⟨Commands: procedures⟩+≡
    subroutine cmd_echo_compile (echo, pn, global)
        type(cmd_echo_t), pointer :: echo
        type(parse_node_t), intent(in), target :: pn
        type(rt_data_t), intent(in), target :: global
        type(parse_node_t), pointer :: pn_arg, pn_sexpr
        integer :: i, n_args
        pn_arg => parse_node_get_sub_ptr (pn, 2)
        allocate (echo)
        if (associated (pn_arg)) then
            n_args = parse_node_get_n_sub (pn_arg)
            allocate (echo%expr (n_args))
            pn_sexpr => parse_node_get_sub_ptr (pn_arg)
            i = 0
            do while (associated (pn_sexpr))
                i = i + 1
                call eval_tree_init_sexpr &
                    (echo%expr(i), pn_sexpr, global%var_list)
                pn_sexpr => parse_node_get_next_ptr (pn_sexpr)
            end do
        else
            allocate (echo%expr (0))
        end if
    end subroutine cmd_echo_compile

```

```

end if
end subroutine cmd_echo_compile

```

Execute. Scan the list of expressions, evaluate them and print the result.

(Commands: procedures)+≡

```

subroutine cmd_echo_execute (echo, global)
  type(cmd_echo_t), intent(inout) :: echo
  type(rt_data_t), intent(in), target :: global
  type(string_t) :: string
  integer :: i, u_out, u_log
  u_out = output_unit ()
  u_log = logfile_unit (u_out)
  do i = 1, size (echo%expr)
    call eval_tree_evaluate (echo%expr(i))
    if (eval_tree_result_is_known (echo%expr(i))) then
      string = eval_tree_get_string (echo%expr(i))
      write (u_out, "(A)") char (string)
      if (u_log >= 0) write (u_log, "(A)") char (string)
    end if
  end do
  flush (u_log)
end subroutine cmd_echo_execute

```

Beams

The beam command includes both beam and structure-function definition. To hold the structure functions, we define two special container types.

(Commands: types)+≡

```

type :: strfun_def_t
  private
  integer :: type = STRF_NONE
  integer :: n_parameters = 1
  type(command_list_t), pointer :: options => null ()
  type(rt_data_t) :: local
end type strfun_def_t

type :: strfun_pair_t
  private
  integer :: n
  type(strfun_def_t), dimension(2) :: def
end type strfun_pair_t

type :: cmd_beams_t
  private
  integer :: n_in = 0
  type(eval_tree_t), dimension(:), allocatable :: pdg
  type(string_t), dimension(:), allocatable :: prt
  type(command_list_t), pointer :: options => null ()
  type(rt_data_t) :: local
  logical :: use_sqrts = .true.
  integer :: n_strfun = 0
  type(strfun_pair_t), dimension(:), allocatable :: strfun_pair

```

```
end type cmd_beams_t
```

Delete the eval trees.

(Commands: procedures)+≡

```
subroutine cmd_beams_final (beams)
  type(cmd_beams_t), intent(inout) :: beams
  integer :: i
  do i = 1, beams%n_in
    call eval_tree_final (beams%pdg(i))
  end do
  if (associated (beams%options)) then
    call command_list_final (beams%options)
    deallocate (beams%options)
  end if
end subroutine cmd_beams_final
```

Output

(Commands: procedures)+≡

```
subroutine cmd_beams_write (beams, unit, indent)
  type(cmd_beams_t), intent(in) :: beams
  integer, intent(in), optional :: unit, indent
  integer :: u, i, ind
  u = output_unit (unit); if (u < 0) return
  call write_indent (u, indent)
  write (u, "(1x,A)", advance="no") "beams ("
  do i = 1, beams%n_in
    if (i /= 1) write (u, "(", advance="no")
    write (u, "(A)", advance="no") char (beams%prt(i))
  end do
  write (u, "(A)", advance="no") ")"
  if (associated (beams%options)) then
    write (u, "(1x,'{'")
    call command_list_write (beams%options, unit, indent)
    call write_indent (u, indent)
    write (u, "(1x,'}')")
  end if
  do i = 1, beams%n_strfun
    ind = 0; if (present (indent)) ind = indent
    call strfun_pair_write (beams%strfun_pair(i), unit, indent=ind+3)
  end do
end subroutine cmd_beams_write

subroutine strfun_pair_write (strfun_pair, unit, indent)
  type(strfun_pair_t), intent(in) :: strfun_pair
  integer, intent(in), optional :: unit, indent
  integer :: u
  u = output_unit (unit); if (u < 0) return
  call write_indent (u, indent)
  write (u, "(1x,A)", advance="no") "->"
  call strfun_def_write (strfun_pair%def(1), unit, indent)
  if (strfun_pair%n == 2) then
    write (u, "(1x,A)", advance="no") ","
    call strfun_def_write (strfun_pair%def(2), unit, indent)
  end if
end subroutine strfun_pair_write
```

```

        end if
        write (u, *)
    end subroutine strfun_pair_write

    subroutine strfun_def_write (strfun_def, unit, indent)
        type(strfun_def_t), intent(in) :: strfun_def
        integer, intent(in), optional :: unit, indent
        integer :: u
        u = output_unit (unit); if (u < 0) return
        select case (strfun_def%type)
        case (STRF_NONE);    write (u, "(1x,A)") "none"
        case (STRF_LHAPDF);  write (u, "(1x,A)") "lhpdf"
        case (STRF_ISR);     write (u, "(1x,A)") "isr"
        case (STRF_EPA);     write (u, "(1x,A)") "epa"
        end select
        if (associated (strfun_def%options)) then
            write (u, "(1x,'{'")
            call command_list_write (strfun_def%options, unit, indent)
            call write_indent (u, indent)
            write (u, "(1x,'}')" )
        end if
    end subroutine strfun_def_write

```

Compile.

(Commands: procedures)+≡

```

    subroutine cmd_beams_compile (beams, pn, global)
        type(cmd_beams_t), pointer :: beams
        type(parse_node_t), intent(in), target :: pn
        type(rt_data_t), intent(in), target :: global
        type(parse_node_t), pointer :: pn_beam_def, pn_beam_spec
        type(parse_node_t), pointer :: pn_beam_list, pn_opt
        type(parse_node_t), pointer :: pn_codes
        type(parse_node_t), pointer :: pn_strfun_seq, pn_strfun_pair
        integer :: i
        pn_beam_def => parse_node_get_sub_ptr (pn, 3)
        pn_beam_spec => parse_node_get_sub_ptr (pn_beam_def)
        pn_strfun_seq => parse_node_get_next_ptr (pn_beam_spec)
        pn_beam_list => parse_node_get_sub_ptr (pn_beam_spec)
        pn_opt => parse_node_get_next_ptr (pn_beam_list)
        allocate (beams)
        call rt_data_local_init (beams%local, global)
        if (associated (pn_opt)) then
            allocate (beams%options)
            call command_list_compile (beams%options, pn_opt, beams%local)
        end if
        beams%n_in = parse_node_get_n_sub (pn_beam_list)
        select case (beams%n_in)
        case (1)
            if (associated (pn_strfun_seq)) then
                call parse_node_write (pn_beam_def)
                call msg_error ("Structure functions can't be defined " &
                    // "for decay processes")
                pn_strfun_seq => null ()
            end if
        end case
    end subroutine cmd_beams_compile

```

```

end select
allocate (beams%pdg (beams%n_in))
allocate (beams%prt (beams%n_in))
pn_codes => parse_node_get_sub_ptr (pn_beam_list)
do i = 1, beams%n_in
    call eval_tree_init_cexpr (beams%pdg(i), pn_codes, global%var_list)
    beams%prt(i) = "?"
    pn_codes => parse_node_get_next_ptr (pn_codes)
end do
if (associated (pn_strfun_seq)) then
    beams%n_strfun = parse_node_get_n_sub (pn_beam_def) - 1
    allocate (beams%strfun_pair (beams%n_strfun))
    do i = 1, beams%n_strfun
        pn_strfun_pair => parse_node_get_sub_ptr (pn_strfun_seq, 2)
        call strfun_pair_compile &
            (beams%strfun_pair(i), pn_strfun_pair, beams%local)
        pn_strfun_seq => parse_node_get_next_ptr (pn_strfun_seq)
    end do
end if
end subroutine cmd_beams_compile

subroutine strfun_pair_compile (strfun_pair, pn_strfun_pair, global)
    type(strfun_pair_t), intent(out) :: strfun_pair
    type(parse_node_t), intent(in), target :: pn_strfun_pair
    type(rt_data_t), intent(in), target :: global
    type(parse_node_t), pointer :: pn_strfun_def
    integer :: i
    strfun_pair%n = parse_node_get_n_sub (pn_strfun_pair)
    pn_strfun_def => parse_node_get_sub_ptr (pn_strfun_pair)
    do i = 1, strfun_pair%n
        call strfun_def_compile (strfun_pair%def(i), pn_strfun_def, global)
        pn_strfun_def => parse_node_get_next_ptr (pn_strfun_def)
    end do
end subroutine strfun_pair_compile

subroutine strfun_def_compile (strfun_def, pn_strfun_def, global)
    type(strfun_def_t), intent(out) :: strfun_def
    type(parse_node_t), intent(in), target :: pn_strfun_def
    type(rt_data_t), intent(in), target :: global
    type(parse_node_t), pointer :: pn_key, pn_opt
    pn_key => parse_node_get_sub_ptr (pn_strfun_def)
    pn_opt => parse_node_get_next_ptr (pn_key)
    select case (char (parse_node_get_key (pn_key)))
    case ("none")
        strfun_def%type = STRF_NONE
    case ("lhpdf")
        strfun_def%type = STRF_LHAPDF
    case ("isr")
        strfun_def%type = STRF_ISR
    case ("epa")
        strfun_def%type = STRF_EPA
    end select
    call rt_data_local_init (strfun_def%local, global)
    if (associated (pn_opt)) then

```

```

        allocate (strfun_def%options)
        call command_list_compile &
            (strfun_def%options, pn_opt, strfun_def%local)
    end if
end subroutine strfun_def_compile

```

Command execution: Beam initialization. The output is a beam-data object, which is copied to the global data block.

Structure functions are configured in the option section. They are linked to the global data block, where they can be found by the integration command.

(*Commands: procedures*) +=

```

subroutine cmd_beams_execute (beams, global)
    type(cmd_beams_t), intent(inout), target :: beams
    type(rt_data_t), intent(inout), target :: global
    real(default) :: sqrts, p_cm, p_cm_theta, p_cm_phi
    type(pdg_array_t), dimension(2) :: aval
    type(flavor_t), dimension(:), allocatable :: flv_tmp
    type(flavor_t), dimension(2) :: flv
    type(polarization_t), dimension(2) :: pol
    integer :: i, u
    u = logfile_unit ()
    call lhpdf_status_reset (global%lhpdf_status)
    call rt_data_link (beams%local, global)
    if (associated (beams%options)) then
        call command_list_execute (beams%options, beams%local)
    end if
    do i = 1, beams%n_in
        call eval_tree_evaluate (beams%pdg(i))
        aval(i) = eval_tree_get_pdg_array (beams%pdg(i))
        call flavor_init (flv_tmp, aval(i), beams%local%model)
        select case (size (flv_tmp))
            case (1); flv(i) = flv_tmp(1)
            case default
                call pdg_array_write (aval(i))
                call msg_fatal &
                    ("Beam expression does not evaluate to a unique particle")
                return
        end select
        beams%prt(i) = flavor_get_name (flv(i))
        select case (beams%n_in)
            case (1)
                call polarization_init_trivial (pol(i), flv(i))
            case (2)
                call polarization_init_unpolarized (pol(i), flv(i))
        end select
    end do
    p_cm = var_list_get_rval (beams%local%var_list, var_str ("cm_momentum"))
    p_cm_theta = &
        var_list_get_rval (beams%local%var_list, var_str ("cm_theta"))
    p_cm_phi = &
        var_list_get_rval (beams%local%var_list, var_str ("cm_phi"))
    select case (beams%n_in)
        case (1)

```

```

    if (p_cm == 0 .and. p_cm_theta == 0) then
        call beam_data_init_decay (global%beam_data, flv, pol)
    else
        call beam_data_init_decay &
            (global%beam_data, flv, pol, p_cm, p_cm_theta, p_cm_phi)
    end if
case (2)
    if (beams%use_sqrts) then
        sqrts = var_list_get_rval (beams%local%var_list, var_str ("sqrts"))
        if (sqrts > 0) then
            if (p_cm == 0 .and. p_cm_theta == 0) then
                call beam_data_init_sqrts (global%beam_data, sqrts, flv, pol)
            else
                call beam_data_init_sqrts (global%beam_data, &
                    sqrts, flv, pol, p_cm, p_cm_theta, p_cm_phi)
            end if
        else
            call msg_fatal ("Beam setup: value of sqrts " &
                // "must be set and positive")
        end if
    else
        call msg_bug ("Beam setup: individual beam setup not supported yet")
    end if
    if (associated (global%sf_list)) then
        call sf_list_final (global%sf_list)
        deallocate (global%sf_list)
    end if
    allocate (global%sf_list)
    do i = 1, beams%n_strfun
        call strfun_pair_register (beams%strfun_pair(i), global)
    end do
    call sf_list_freeze (global%sf_list)
    call sf_list_compute_md5sum (global%sf_list)
end select
call beam_data_write (global%beam_data, verbose=.false.)
call beam_data_write (global%beam_data, verbose=.false., unit=u)
flush (u)
call rt_data_restore (global, beams%local)
end subroutine cmd_beams_execute

subroutine strfun_pair_register (strfun_pair, global)
    type(strfun_pair_t), intent(inout) :: strfun_pair
    type(rt_data_t), intent(inout), target :: global
    logical, dimension(2) :: affects_beam
    integer :: i
    select case (strfun_pair%n)
    case (1)
        affects_beam = .true.
        call strfun_def_register (strfun_pair%def(1), affects_beam, global)
    case (2)
        affects_beam = (/ .true., .false. /)
        call strfun_def_register (strfun_pair%def(1), affects_beam, global)
        affects_beam = (/ .false., .true. /)
        call strfun_def_register (strfun_pair%def(2), affects_beam, global)
    end select
end subroutine

```

```

end select
end subroutine strfun_pair_register

subroutine strfun_def_register (strfun_def, affects_beam, global)
  type(strfun_def_t), intent(inout) :: strfun_def
  logical, dimension(2), intent(in) :: affects_beam
  type(rt_data_t), intent(inout), target :: global
  type(string_t) :: lhpdf_file
  type(sf_data_t), pointer :: sf_data
  integer :: lhpdf_member, lhpdf_photon_scheme
  real(default) :: isr_alpha, isr_q_max, isr_mass
  integer :: isr_order
  real(default) :: epa_alpha, epa_x_min, epa_q_min, epa_e_max, epa_mass
  call rt_data_link (strfun_def%local, global)
  if (associated (strfun_def%options)) then
    call command_list_execute (strfun_def%options, strfun_def%local)
  end if
  if (strfun_def%type /= STRF_NONE) then
    call sf_list_append (global%sf_list, &
      strfun_def%type, affects_beam, strfun_def%n_parameters, sf_data)
    select case (strfun_def%type)
    case (STRF_LHAPDF)
      lhpdf_file = var_list_get_sval (strfun_def%local%var_list, &
        var_str ("lhpdf_file")) ! $
      lhpdf_member = var_list_get_ival (strfun_def%local%var_list, &
        var_str ("lhpdf_member"))
      lhpdf_photon_scheme = var_list_get_ival (strfun_def%local%var_list, &
        var_str ("lhpdf_photon_scheme"))
      call sf_data_init_lhpdf (sf_data, global%lhpdf_status, &
        global%model, global%beam_data%flv, &
        lhpdf_file, lhpdf_member, lhpdf_photon_scheme)
    case (STRF_ISR)
      isr_alpha = var_list_get_rval (strfun_def%local%var_list, &
        var_str ("isr_alpha"))
      if (isr_alpha == 0) then
        isr_alpha = (var_list_get_rval (strfun_def%local%var_list, &
          var_str ("ee"))) ** 2 / (4 * pi)
      end if
      isr_q_max = var_list_get_rval (strfun_def%local%var_list, &
        var_str ("isr_q_max"))
      if (isr_q_max == 0) then
        isr_q_max = var_list_get_rval (strfun_def%local%var_list, &
          var_str ("sqrts"))
      end if
      isr_mass = var_list_get_rval (strfun_def%local%var_list, &
        var_str ("isr_mass"))
      isr_order = var_list_get_ival (strfun_def%local%var_list, &
        var_str ("isr_order"))
      if (isr_mass /= 0) then
        call sf_data_init_isr (sf_data, &
          global%model, global%beam_data%flv, &
          isr_alpha, isr_q_max, isr_mass, isr_order)
      else
        call sf_data_init_isr (sf_data, &

```

```

        global%model, global%beam_data%flv, &
        isr_alpha, isr_q_max, order = isr_order)
    end if
case (STRF_EPA)
    epa_alpha = var_list_get_rval (strfun_def%local%var_list, &
        var_str ("epa_alpha"))
    if (epa_alpha == 0) then
        epa_alpha = (var_list_get_rval (strfun_def%local%var_list, &
            var_str ("ee"))) ** 2 / (4 * pi)
    end if
    epa_x_min = var_list_get_rval (strfun_def%local%var_list, &
        var_str ("epa_x_min"))
    epa_q_min = var_list_get_rval (strfun_def%local%var_list, &
        var_str ("epa_q_min"))
    epa_e_max = var_list_get_rval (strfun_def%local%var_list, &
        var_str ("epa_e_max"))
    if (epa_e_max == 0) then
        epa_e_max = var_list_get_rval (strfun_def%local%var_list, &
            var_str ("sqrts"))
    end if
    epa_mass = var_list_get_rval (strfun_def%local%var_list, &
        var_str ("epa_mass"))
    if (epa_mass /= 0) then
        call sf_data_init_epa (sf_data, &
            global%model, global%beam_data%flv, &
            epa_alpha, epa_x_min, epa_q_min, epa_e_max, epa_mass)
    else
        call sf_data_init_epa (sf_data, &
            global%model, global%beam_data%flv, &
            epa_alpha, epa_x_min, epa_q_min, epa_e_max)
    end if
end select
end if
call rt_data_restore (global, strfun_def%local)
end subroutine strfun_def_register

```

Cuts

Define a cut expression. We store the parse tree for the right-hand side instead of compiling it. Compilation is deferred to the process environment where the cut expression is used.

```

<Commands: types>+≡
    type :: cmd_cuts_t
    private
        type(parse_node_t), pointer :: pn_lexpr => null ()
    end type cmd_cuts_t

```

Output. Print the right-hand side as a parse tree.

```

<Commands: procedures>+≡
    subroutine cmd_cuts_write (cuts, unit, indent)
        type(cmd_cuts_t), intent(in) :: cuts
        integer, intent(in), optional :: unit, indent
    end subroutine cmd_cuts_write

```

```

integer :: u
u = output_unit (unit); if (u < 0) return
call write_indent (u, indent)
write (u, "(1x,A)") "cuts ="
call parse_node_write_rec (cuts%pn_lexpr, unit)
end subroutine cmd_cuts_write

```

Compile. Simply store the parse (sub)tree.

```

⟨Commands: procedures⟩+≡
subroutine cmd_cuts_compile (cuts, pn)
  type(cmd_cuts_t), pointer :: cuts
  type(parse_node_t), intent(in), target :: pn
  allocate (cuts)
  cuts%pn_lexpr => parse_node_get_sub_ptr (pn, 3)
end subroutine cmd_cuts_compile

```

Instead of evaluating the cut expression, link the parse tree to the global data set, such that it is compiled and executed in the appropriate process context.

```

⟨Commands: procedures⟩+≡
subroutine cmd_cuts_execute (cuts, global)
  type(cmd_cuts_t), intent(inout), target :: cuts
  type(rt_data_t), intent(inout), target :: global
  global%pn_cuts_lexpr => cuts%pn_lexpr
end subroutine cmd_cuts_execute

```

Weight

Define a weight expression. We store the parse tree for the right-hand side instead of compiling it. Compilation is deferred to the process environment where the expression is used.

```

⟨Commands: types⟩+≡
type :: cmd_weight_t
  private
  type(parse_node_t), pointer :: pn_expr => null ()
end type cmd_weight_t

```

Output. Print the right-hand side as a parse tree.

```

⟨Commands: procedures⟩+≡
subroutine cmd_weight_write (weight, unit, indent)
  type(cmd_weight_t), intent(in) :: weight
  integer, intent(in), optional :: unit, indent
  integer :: u
  u = output_unit (unit); if (u < 0) return
  call write_indent (u, indent)
  write (u, "(1x,A)") "weight ="
  call parse_node_write_rec (weight%pn_expr, unit)
end subroutine cmd_weight_write

```

Compile. Simply store the parse (sub)tree.

```

(Commands: procedures) +=
  subroutine cmd_weight_compile (weight, pn)
    type(cmd_weight_t), pointer :: weight
    type(parse_node_t), intent(in), target :: pn
    allocate (weight)
    weight%pn_expr => parse_node_get_sub_ptr (pn, 3)
  end subroutine cmd_weight_compile

```

Instead of evaluating the expression, link the parse tree to the global data set, such that it is compiled and executed in the appropriate process context.

```

(Commands: procedures) +=
  subroutine cmd_weight_execute (weight, global)
    type(cmd_weight_t), intent(inout), target :: weight
    type(rt_data_t), intent(inout), target :: global
    global%pn_weight_expr => weight%pn_expr
  end subroutine cmd_weight_execute

```

Scale

Define a scale expression. We store the parse tree for the right-hand side instead of compiling it. Compilation is deferred to the process environment where the expression is used.

```

(Commands: types) +=
  type :: cmd_scale_t
  private
    type(parse_node_t), pointer :: pn_expr => null ()
  end type cmd_scale_t

```

Output. Print the right-hand side as a parse tree.

```

(Commands: procedures) +=
  subroutine cmd_scale_write (scale, unit, indent)
    type(cmd_scale_t), intent(in) :: scale
    integer, intent(in), optional :: unit, indent
    integer :: u
    u = output_unit (unit); if (u < 0) return
    call write_indent (u, indent)
    write (u, "(1x,A)") "scale ="
    call parse_node_write_rec (scale%pn_expr, unit)
  end subroutine cmd_scale_write

```

Compile. Simply store the parse (sub)tree.

```

(Commands: procedures) +=
  subroutine cmd_scale_compile (scale, pn)
    type(cmd_scale_t), pointer :: scale
    type(parse_node_t), intent(in), target :: pn
    allocate (scale)
    scale%pn_expr => parse_node_get_sub_ptr (pn, 3)
  end subroutine cmd_scale_compile

```

Instead of evaluating the scale expression, link the parse tree to the global data set, such that it is compiled and executed in the appropriate process context.

```

<Commands: procedures>+≡
  subroutine cmd_scale_execute (scale, global)
    type(cmd_scale_t), intent(inout), target :: scale
    type(rt_data_t), intent(inout), target :: global
    global%pn_scale_expr => scale%pn_expr
  end subroutine cmd_scale_execute

```

Integration

Integrate several processes, consecutively with identical parameters.

```

<Commands: types>+≡
  type :: cmd_integrate_t
  private
  integer :: n_proc = 0
  type(string_t), dimension(:), allocatable :: process_id
  type(grid_parameters_t) :: grid_parameters
  type(phs_parameters_t) :: phs_par
  type(mapping_defaults_t) :: mapping_defaults
  type(command_list_t), pointer :: options => null ()
  type(rt_data_t) :: local
end type cmd_integrate_t

```

Finalizer.

```

<Commands: procedures>+≡
  subroutine cmd_integrate_final (integrate)
    type(cmd_integrate_t), intent(inout) :: integrate
    if (associated (integrate%options)) then
      call command_list_final (integrate%options)
      deallocate (integrate%options)
    end if
  end subroutine cmd_integrate_final

```

Output.

```

<Commands: procedures>+≡
  subroutine cmd_integrate_write (integrate, unit, indent)
    type(cmd_integrate_t), intent(in) :: integrate
    integer, intent(in), optional :: unit, indent
    integer :: u, i
    u = output_unit (unit); if (u < 0) return
    call write_indent (u, indent)
    write (u, "(1x,A)", advance="no") "integrate ("
    do i = 1, integrate%n_proc
      if (i /= 1) write (u, "(", advance="no")
      write (u, "(A)", advance="no") char (integrate%process_id(i))
    end do
    write (u, "(A)") ")"
    if (associated (integrate%options)) then
      write (u, "(1x,'{'")
      call command_list_write (integrate%options, unit, indent)
    end if
  end subroutine cmd_integrate_write

```

```

        call write_indent (u, indent)
        write (u, "(1x,')')")
    end if
end subroutine cmd_integrate_write

```

Compile.

```

<Commands: procedures>+≡
subroutine cmd_integrate_compile (integrate, pn, global)
    type(cmd_integrate_t), pointer :: integrate
    type(parse_node_t), intent(in), target :: pn
    type(rt_data_t), intent(in), target :: global
    type(parse_node_t), pointer :: pn_proclist, pn_proc, pn_opt
    integer :: i
    pn_proclist => parse_node_get_sub_ptr (pn, 2)
    pn_opt => parse_node_get_next_ptr (pn_proclist)
    allocate (integrate)
    call rt_data_local_init (integrate%local, global)
    if (associated (pn_opt)) then
        allocate (integrate%options)
        call command_list_compile (integrate%options, pn_opt, integrate%local)
    end if
    integrate%n_proc = parse_node_get_n_sub (pn_proclist)
    allocate (integrate%process_id (integrate%n_proc))
    pn_proc => parse_node_get_sub_ptr (pn_proclist)
    do i = 1, integrate%n_proc
        integrate%process_id(i) = parse_node_get_string (pn_proc)
        pn_proc => parse_node_get_next_ptr (pn_proc)
    end do
    ! API for setting grid_parameters etc. missing
end subroutine cmd_integrate_compile

```

Command execution. Integrate the process with the predefined number of passes, iterations and calls. For structure functions, cuts, weight and scale, use local definitions if present; by default, the local definitions are initialized with the global ones.

NOTE: The process must be linked to the global variable list; the local list is deleted when the `cmd_integrate` object is deleted, but the process object exists independent of this. (This matters in interactive mode only.) We should look for a robust implementation of local variables that avoids this problem.

```

<Commands: procedures>+≡
subroutine cmd_integrate_execute (integrate, global)
    type(cmd_integrate_t), intent(inout), target :: integrate
    type(rt_data_t), intent(inout), target :: global
    logical :: use_beams
    type(process_t), pointer :: process
    integer :: proc, n_out, pass, i, n_calls
    type(iterations_spec_t) :: it_spec
    logical :: ok, use_default_iterations, rebuild_phs, phs_only, rebuild_grids
    type(string_t) :: phs_filename, grids_filename
    logical :: hs_active
    real(default) :: hs_threshold
    integer :: hs_cutoff

```

```

real(default) :: alpha_s, sqrts
character(32) :: md5sum_beams, md5sum_sf_list
character(32) :: md5sum_cuts, md5sum_weight, md5sum_scale
integer :: current_pass, current_it, it
integer :: u
u = logfile_unit ()
call rt_data_link (integrate%local, global)
if (associated (integrate%options)) then
    call command_list_execute (integrate%options, integrate%local)
end if
integrate%grid_parameters%threshold_calls = &
    var_list_get_ival (integrate%local%var_list, &
        var_str ("threshold_calls"))
integrate%grid_parameters%min_calls_per_channel = &
    var_list_get_ival (integrate%local%var_list, &
        var_str ("min_calls_per_channel"))
integrate%grid_parameters%min_calls_per_bin = &
    var_list_get_ival (integrate%local%var_list, &
        var_str ("min_calls_per_bin"))
integrate%grid_parameters%min_bins = &
    var_list_get_ival (integrate%local%var_list, &
        var_str ("min_bins"))
integrate%grid_parameters%max_bins = &
    var_list_get_ival (integrate%local%var_list, &
        var_str ("max_bins"))
integrate%grid_parameters%stratified = &
    var_list_get_lval (integrate%local%var_list, &
        var_str ("?stratified"))
integrate%grid_parameters%channel_weights_power = &
    var_list_get_rval (integrate%local%var_list, &
        var_str ("channel_weights_power"))
integrate%phs_par%m_threshold_s = &
    var_list_get_rval (integrate%local%var_list, &
        var_str ("phs_threshold_s"))
integrate%phs_par%m_threshold_t = &
    var_list_get_rval (integrate%local%var_list, &
        var_str ("phs_threshold_t"))
integrate%phs_par%off_shell = &
    var_list_get_ival (integrate%local%var_list, &
        var_str ("phs_off_shell"))
integrate%phs_par%t_channel = &
    var_list_get_ival (integrate%local%var_list, &
        var_str ("phs_t_channel"))
use_beams = beam_data_are_valid (integrate%local%beam_data)
if (use_beams) then
    if (.not. beam_data_masses_are_consistent &
        (integrate%local%beam_data)) then
        call msg_warning &
            ("Masses of beam particle(s) differ from beam masses")
    end if
end if
use_default_iterations = integrate%local%it_list%n_pass == 0
LOOP_PROC: do proc = 1, integrate%n_proc
    call msg_message ("Integrating process '" // &

```

```

        char (integrate%process_id(proc)) // "'")
call process_store_init_process (process, &
    integrate%local%prc_lib, &
    integrate%process_id(proc), integrate%local%model, &
    global%lhpdf_status, &
    integrate%local%var_list, use_beams=use_beams)
if (.not. process_is_valid (process)) then
    call msg_fatal ("Integrating process '" &
        // char (integrate%process_id(proc)) // "': initialization " &
        // "failed, skipping")
    cycle LOOP_PROC
end if
sqrts = var_list_get_rval (integrate%local%var_list, var_str ("sqrts"))
md5sum_beams = beam_data_get_md5sum (integrate%local%beam_data, sqrts)
md5sum_sf_list = ""
if (use_beams) then
    if (beam_data_get_n_in (integrate%local%beam_data) &
        /= process_get_n_in (process)) then
        call msg_fatal ("Process '" // char (integrate%process_id(proc)) &
            // "': beam/process mismatch (collision/decay)")
        return
    end if
    if (associated (integrate%local%sf_list)) then
        md5sum_sf_list = sf_list_get_md5sum (integrate%local%sf_list)
        call process_setup_beams (process, integrate%local%beam_data, &
            sf_list_get_n_strfun (integrate%local%sf_list), &
            sf_list_get_n_mapping (integrate%local%sf_list))
        call process_setup_strfun (process, integrate%local%sf_list)
    else
        call process_setup_beams (process, integrate%local%beam_data, 0, 0)
    end if
else
    call process_setup_beams (process, integrate%local%beam_data, 0, 0, &
        sqrts = sqrts)
end if
call process_connect_strfun (process, ok)
if (.not. ok) then
    call msg_error ("Process '" // char (integrate%process_id(proc)) &
        // "': beam/structure function setup failed, skipped")
    cycle LOOP_PROC
end if
rebuild_phs = var_list_get_lval (integrate%local%var_list, &
    var_str ("?rebuild_phase_space"))
phs_filename = var_list_get_sval (integrate%local%var_list, &
    var_str ("$phs_file"))
phs_only = var_list_get_lval (integrate%local%var_list, &
    var_str ("?phs_only"))
if (phs_filename == "") then
    call process_setup_phase_space (process, rebuild_phs, &
        integrate%phs_par, integrate%mapping_defaults, &
        filename_out = integrate%process_id(proc) // ".phs", &
        ok = ok)
else
    call process_setup_phase_space (process, rebuild_phs, &

```

```

        integrate%phs_par, integrate%mapping_defaults, &
        filename_in = phs_filename, &
        filename_out = integrate%process_id(proc) // ".phs", &
        ok = ok)
    end if
    if (.not. ok) then
        call msg_error ("Process '" // char (integrate%process_id(proc)) &
            // "': phase space setup failed, skipped")
        cycle LOOP_PROC
    end if
    if (phs_only) then
        call msg_message ("Process '" // char (integrate%process_id(proc)) &
            // "': phase space setup complete.")
        cycle LOOP_PROC
    end if
    if (associated (integrate%local%pn_cuts_lexpr)) then
        call process_setup_cuts (process, integrate%local%pn_cuts_lexpr)
        md5sum_cuts = parse_node_get_md5sum (integrate%local%pn_cuts_lexpr)
        call msg_message ("Applying user-defined cuts.")
    else
        md5sum_cuts = ""
        call msg_warning ("No cuts have been defined.")
    end if
    if (associated (integrate%local%pn_weight_expr)) then
        call process_setup_weight (process, integrate%local%pn_weight_expr)
        md5sum_weight = parse_node_get_md5sum (integrate%local%pn_weight_expr)
        call msg_message ("Using user-defined integration weight.")
    else
        md5sum_weight = ""
    end if
    if (associated (integrate%local%pn_scale_expr)) then
        call process_setup_scale (process, integrate%local%pn_scale_expr)
        md5sum_scale = parse_node_get_md5sum (integrate%local%pn_scale_expr)
        call msg_message ("Using user-defined event scale setup.")
    else
        md5sum_scale = ""
        call msg_message ("Using partonic energy as event scale.")
    end if
    if (var_list_is_known (integrate%local%var_list, &
        var_str ("alphas"))) then
        alpha_s = var_list_get_rval (integrate%local%var_list, &
            var_str ("alphas"))
        call process_set_alpha_s (process, alpha_s)
    end if

    n_out = process_get_n_out (process)
    if (use_default_iterations) then
        select case (n_out)
        case (:1)
            call msg_error ("Integrate: number of outgoing particles " &
                // "must be at least 2")
            cycle LOOP_PROC
        case (2:ITERATIONS_DEFAULT_LIST_SIZE)
            integrate%local%it_list = integrate%local%it_list_default(n_out)

```

```

        case default
            integrate%local%it_list = &
                integrate%local%it_list_default(ITERATIONS_DEFAULT_LIST_SIZE)
        end select
    end if
    call iterations_list_write (integrate%local%it_list)

    if (integrate%local%it_list%n_pass > 0) then
        it_spec = integrate%local%it_list%pass(1)
        n_calls = max (it_spec%n_calls, &
            process_get_n_channels (process) &
            * integrate%grid_parameters%min_calls_per_channel)
        if (n_calls /= it_spec%n_calls) then
            write (msg_buffer, "(A,I0)") "Resetting n_calls to ", n_calls
            call msg_warning ()
        end if
        grids_filename = process_get_id (process) // ".vg"
        rebuild_grids = var_list_get_lval (integrate%local%var_list, &
            var_str ("?rebuild_grids"))
        if (.not. rebuild_grids) then
            call process_read_grid_file (process, &
                grids_filename, &
                md5sum_beams, md5sum_sf_list, &
                md5sum_cuts, md5sum_weight, md5sum_scale, &
                integrate%grid_parameters, &
                iterations_list_get_pass_array (integrate%local%it_list), &
                iterations_list_get_n_calls_array (integrate%local%it_list), &
                ok)
            rebuild_grids = .not. ok
        end if
        if (rebuild_grids) then
            call process_setup_grids &
                (process, integrate%grid_parameters, calls=n_calls)
            write (msg_buffer, "(4(I0,A),A,L1)") &
                n_calls, " calls, ", &
                process_get_n_channels (process), " channels, ", &
                process_get_n_parameters (process), " dimensions, ", &
                process_get_n_bins (process), " bins, ", &
                "stratified = ", integrate%grid_parameters%stratified
            call msg_message ()
        else
            write (msg_buffer, "(3(I0,A),A,L1)") &
                n_calls, " calls, ", &
                process_get_n_channels (process), " channels, ", &
                process_get_n_parameters (process), " dimensions, ", &
                "stratified = ", integrate%grid_parameters%stratified
            call msg_message ()
        end if
        current_pass = process_get_current_pass (process)
        current_it = process_get_current_it (process)
    end if

    hs_active = var_list_get_lval (integrate%local%var_list, &
        var_str ("?helicity_selection_active"))

```

```

if (hs_active) then
  hs_threshold = var_list_get_rval (integrate%local%var_list, &
    var_str ("helicity_selection_threshold"))
  hs_cutoff = var_list_get_ival (integrate%local%var_list, &
    var_str ("helicity_selection_cutoff"))
else
  hs_threshold = -1
  hs_cutoff = 1000
end if
call process_reset_helicity_selection &
  (process, hs_threshold, hs_cutoff)

call process_results_write_header (process, logfile=.false.)
call process_results_write_header (process, unit=u)
flush (u)
it = 0
LOOP_PASS: do pass = 1, integrate%local%it_list%n_pass - 1
  it_spec = integrate%local%it_list%pass(pass)
  n_calls = max (it_spec%n_calls, &
    process_get_n_channels (process) &
    * integrate%grid_parameters%min_calls_per_channel)
  LOOP_IT: do i = 1, it_spec%n_it
    it = it + 1
    if (pass < current_pass &
      .or. pass == current_pass .and. i <= current_it) then
      call process_results_write_entry (process, it)
      call process_results_write_entry (process, it, unit=u)
      flush (u)
    else
      call process_integrate (process, &
        integrate%local%rng, integrate%grid_parameters, &
        pass, 1, 1, n_calls, &
        i==1, .true., i>2, .true., &
        grids_filename, &
        md5sum_beams, md5sum_sf_list, &
        md5sum_cuts, md5sum_weight, md5sum_scale)
    end if
  end do LOOP_IT
  call process_results_write_average (process, pass)
  call process_results_write_average (process, pass, unit=u)
  flush (u)
  call process_record_integral (process)
end do LOOP_PASS

pass = integrate%local%it_list%n_pass
if (pass > current_pass) current_it = 0
if (pass > 0 .and. pass >= current_pass) then
  it_spec = integrate%local%it_list%pass(pass)
  do i = 1, current_it
    it = it + 1
    call process_results_write_entry (process, it)
    call process_results_write_entry (process, it, unit=u)
    flush (u)
  end do

```

```

        n_calls = max (it_spec%n_calls, &
            process_get_n_channels (process) &
            * integrate%grid_parameters%min_calls_per_channel)
    call process_integrate (process, &
        integrate%local%rng, integrate%grid_parameters, &
        pass, current_it+1, it_spec%n_it, n_calls, &
        .true., .false., .true., .true., &
        grids_filename, &
        md5sum_beams, md5sum_sf_list, &
        md5sum_cuts, md5sum_weight, md5sum_scale)
    call process_record_integral (process)
end if
call process_results_write_footer (process)
call process_results_write_footer (process, unit=u)
flush (u)
end do LOOP_PROC

    call rt_data_restore (global, integrate%local)
end subroutine cmd_integrate_execute

```

Observables

Declare an observable. After the declaration, it can be used to record data, and at the end one can retrieve average and error.

(Commands: types)+≡

```

    type :: cmd_observable_t
    private
    logical :: use_id_expr = .false.
    type(string_t) :: id
    type(eval_tree_t) :: expr_id
end type cmd_observable_t

```

Finalizer for the ID string expression

(Commands: procedures)+≡

```

    subroutine cmd_observable_final (observable)
    type(cmd_observable_t), intent(inout) :: observable
    call eval_tree_final (observable%expr_id)
end subroutine cmd_observable_final

```

Output.

(Commands: procedures)+≡

```

    subroutine cmd_observable_write (observable, unit, indent)
    type(cmd_observable_t), intent(in) :: observable
    integer, intent(in), optional :: unit, indent
    integer :: u
    u = output_unit (unit); if (u < 0) return
    call write_indent (u, indent)
    write (u, "(1x,A)", advance="no") "observable"
    if (observable%use_id_expr) then
        call eval_tree_write (observable%expr_id, unit)
    else

```

```

        write (u, "(1x,A)", advance="no") char (observable%id)
    end if
    write (u, *)
end subroutine cmd_observable_write

```

Compile. Just record the observable ID.

```

<Commands: procedures>+≡
subroutine cmd_observable_compile (observable, pn, global)
    type(cmd_observable_t), pointer :: observable
    type(parse_node_t), intent(in), target :: pn
    type(rt_data_t), intent(in), target :: global
    type(parse_node_t), pointer :: pn_tag
    pn_tag => parse_node_get_sub_ptr (pn, 2)
    allocate (observable)
    select case (char (parse_node_get_rule_key (pn_tag)))
    case ("analysis_id")
        observable%id = parse_node_get_string (pn_tag)
    case default
        observable%use_id_expr = .true.
        call eval_tree_init_sexpr (observable%expr_id, pn_tag, global%var_list)
    end select
end subroutine cmd_observable_compile

```

Command execution. This declares the observable and allocates it in the analysis store.

```

<Commands: procedures>+≡
subroutine cmd_observable_execute (observable, global)
    type(cmd_observable_t), intent(inout), target :: observable
    type(rt_data_t), intent(inout), target :: global
    type(string_t) :: label, physical_unit, title
    type(plot_labels_t) :: plot_labels
    if (observable%use_id_expr) then
        call eval_tree_evaluate (observable%expr_id)
        observable%id = eval_tree_get_string (observable%expr_id)
    end if
    label = var_list_get_sval (global%var_list, var_str ("$label"))
    physical_unit = &
        var_list_get_sval (global%var_list, var_str ("$physical_unit"))
    title = var_list_get_sval (global%var_list, var_str ("$title"))
    call plot_labels_init (plot_labels, title)
    call analysis_init_observable &
        (observable%id, label, physical_unit, plot_labels)
end subroutine cmd_observable_execute

```

Histograms

Declare a histogram. At minimum, we have to set lower and upper bound and bin width.

```

<Commands: types>+≡
type :: cmd_histogram_t
    private

```

```

type(string_t) :: id
logical :: use_id_expr = .false.
type(eval_tree_t) :: expr_id
type(eval_tree_t) :: expr_lower_bound
type(eval_tree_t) :: expr_upper_bound
type(eval_tree_t) :: expr_bin_width
end type cmd_histogram_t

```

Finalizer for the eval trees.

```

<Commands: procedures>+≡
subroutine cmd_histogram_final (histogram)
  type(cmd_histogram_t), intent(inout) :: histogram
  call eval_tree_final (histogram%expr_id)
  call eval_tree_final (histogram%expr_lower_bound)
  call eval_tree_final (histogram%expr_upper_bound)
  call eval_tree_final (histogram%expr_bin_width)
end subroutine cmd_histogram_final

```

Output.

```

<Commands: procedures>+≡
subroutine cmd_histogram_write (histogram, unit, indent)
  type(cmd_histogram_t), intent(in) :: histogram
  integer, intent(in), optional :: unit, indent
  integer :: u
  u = output_unit (unit); if (u < 0) return
  call write_indent (u, indent)
  write (u, "(1x,A)", advance="no") "histogram"
  if (histogram%use_id_expr) then
    call eval_tree_write (histogram%expr_id, unit)
  else
    write (u, "(1x,A)", advance="no") char (histogram%id)
  end if
  write (u, "(1x,A)") "("
  call eval_tree_write (histogram%expr_lower_bound, unit)
  call write_indent (u, indent)
  write (u, "(1x,A)") ","
  call eval_tree_write (histogram%expr_upper_bound, unit)
  call write_indent (u, indent)
  write (u, "(1x,A)") ","
  call eval_tree_write (histogram%expr_bin_width, unit)
  call write_indent (u, indent)
  write (u, "(1x,A)") ")"
end subroutine cmd_histogram_write

```

Compile. Record the histogram ID and initialize lower, upper bound and bin width.

```

<Commands: procedures>+≡
subroutine cmd_histogram_compile (histogram, pn, global)
  type(cmd_histogram_t), pointer :: histogram
  type(parse_node_t), intent(in), target :: pn
  type(rt_data_t), intent(in), target :: global
  type(parse_node_t), pointer :: pn_tag, pn_args, pn_arg1, pn_arg2, pn_arg3

```

```

pn_tag => parse_node_get_sub_ptr (pn, 2)
allocate (histogram)
select case (char (parse_node_get_rule_key (pn_tag)))
case ("analysis_id")
    histogram%id = parse_node_get_string (pn_tag)
case default
    histogram%use_id_expr = .true.
    call eval_tree_init_sexpr (histogram%expr_id, pn_tag, global%var_list)
end select
pn_args => parse_node_get_next_ptr (pn_tag)
pn_arg1 => parse_node_get_sub_ptr (pn_args)
pn_arg2 => parse_node_get_next_ptr (pn_arg1)
pn_arg3 => parse_node_get_next_ptr (pn_arg2)
call eval_tree_init_expr &
    (histogram%expr_lower_bound, pn_arg1, global%var_list)
call eval_tree_init_expr &
    (histogram%expr_upper_bound, pn_arg2, global%var_list)
call eval_tree_init_expr &
    (histogram%expr_bin_width, pn_arg3, global%var_list)
end subroutine cmd_histogram_compile

```

Command execution. This declares the histogram and allocates it in the analysis store.

(Commands: procedures)+≡

```

subroutine cmd_histogram_execute (histogram, global)
    type(cmd_histogram_t), intent(inout), target :: histogram
    type(rt_data_t), intent(inout), target :: global
    real(default) :: lower_bound, upper_bound, bin_width
    logical :: bounds_are_known
    type(string_t) :: label, physical_unit
    type(string_t) :: title, description, xlabel, ylabel
    type(plot_labels_t) :: plot_labels
    if (histogram%use_id_expr) then
        call eval_tree_evaluate (histogram%expr_id)
        histogram%id = eval_tree_get_string (histogram%expr_id)
    end if
    bounds_are_known = .true.
    call eval_tree_evaluate (histogram%expr_lower_bound)
    call eval_tree_evaluate (histogram%expr_upper_bound)
    call eval_tree_evaluate (histogram%expr_bin_width)
    if (eval_tree_result_is_known (histogram%expr_lower_bound)) then
        lower_bound = eval_tree_get_real (histogram%expr_lower_bound)
    else
        call msg_error ("Histogram '" &
            // char (histogram%id) // "' : lower bound is undefined")
        bounds_are_known = .false.
    end if
    if (eval_tree_result_is_known (histogram%expr_upper_bound)) then
        upper_bound = eval_tree_get_real (histogram%expr_upper_bound)
    else
        call msg_error ("Histogram '" &
            // char (histogram%id) // "' : upper bound is undefined")
        bounds_are_known = .false.
    end if

```

```

end if
if (eval_tree_result_is_known (histogram%expr_bin_width)) then
  bin_width = eval_tree_get_real (histogram%expr_bin_width)
else
  call msg_error ("Histogram '" &
    // char (histogram%id) // "' : bin width is undefined")
  bounds_are_known = .false.
end if
label = var_list_get_sval (global%var_list, var_str ("label"))
physical_unit = &
  var_list_get_sval (global%var_list, var_str ("physical_unit"))
title = var_list_get_sval (global%var_list, var_str ("title"))
description = &
  var_list_get_sval (global%var_list, var_str ("description"))
xlabel = var_list_get_sval (global%var_list, var_str ("xlabel"))
ylabel = var_list_get_sval (global%var_list, var_str ("ylabel"))
call plot_labels_init (plot_labels, title, &
  description, xlabel, ylabel)
if (bounds_are_known) then
  call analysis_init_histogram &
    (histogram%id, lower_bound, upper_bound, bin_width, &
    label, physical_unit, plot_labels)
else
  call msg_error ("Histogram '" &
    // char (histogram%id) // "' : invalid declaration, skipping")
end if
end subroutine cmd_histogram_execute

```

Plots

Declare a plot. At minimum, we have to set lower and upper bound and bin width.

```

⟨Commands: types⟩+≡
  type :: cmd_plot_t
  private
  type(string_t) :: id
  logical :: use_id_expr = .false.
  type(eval_tree_t) :: expr_id
  type(eval_tree_t) :: expr_lower_bound
  type(eval_tree_t) :: expr_upper_bound
end type cmd_plot_t

```

Finalizer for the eval trees.

```

⟨Commands: procedures⟩+≡
  subroutine cmd_plot_final (plot)
    type(cmd_plot_t), intent(inout) :: plot
    call eval_tree_final (plot%expr_id)
    call eval_tree_final (plot%expr_lower_bound)
    call eval_tree_final (plot%expr_upper_bound)
  end subroutine cmd_plot_final

```

Output.

```

<Commands: procedures>+≡
subroutine cmd_plot_write (plot, unit, indent)
  type(cmd_plot_t), intent(in) :: plot
  integer, intent(in), optional :: unit, indent
  integer :: u
  u = output_unit (unit); if (u < 0) return
  call write_indent (u, indent)
  write (u, "(1x,A)", advance="no") "plot"
  if (plot%use_id_expr) then
    call eval_tree_write (plot%expr_id, unit)
  else
    write (u, "(1x,A)", advance="no") char (plot%id)
  end if
  write (u, "(1x,A)") "("
  call eval_tree_write (plot%expr_lower_bound, unit)
  call write_indent (u, indent)
  write (u, "(1x,A)") ","
  call eval_tree_write (plot%expr_upper_bound, unit)
  call write_indent (u, indent)
  write (u, "(1x,A)") ")"
end subroutine cmd_plot_write

```

Compile. Record the plot ID and initialize lower, upper bound and bin width.

```

<Commands: procedures>+≡
subroutine cmd_plot_compile (plot, pn, global)
  type(cmd_plot_t), pointer :: plot
  type(parse_node_t), intent(in), target :: pn
  type(rt_data_t), intent(in), target :: global
  type(parse_node_t), pointer :: pn_tag, pn_args, pn_arg1, pn_arg2
  pn_tag => parse_node_get_sub_ptr (pn, 2)
  allocate (plot)
  select case (char (parse_node_get_rule_key (pn_tag)))
  case ("analysis_id")
    plot%id = parse_node_get_string (pn_tag)
  case default
    plot%use_id_expr = .true.
    call eval_tree_init_sexpr (plot%expr_id, pn_tag, global%var_list)
  end select
  pn_args => parse_node_get_next_ptr (pn_tag)
  pn_arg1 => parse_node_get_sub_ptr (pn_args)
  pn_arg2 => parse_node_get_next_ptr (pn_arg1)
  call eval_tree_init_expr (plot%expr_lower_bound, pn_arg1, global%var_list)
  call eval_tree_init_expr (plot%expr_upper_bound, pn_arg2, global%var_list)
end subroutine cmd_plot_compile

```

Command execution. This declares the plot and allocates it in the analysis store.

```

<Commands: procedures>+≡
subroutine cmd_plot_execute (plot, global)
  type(cmd_plot_t), intent(inout), target :: plot
  type(rt_data_t), intent(inout), target :: global
  real(default) :: lower_bound, upper_bound

```

```

logical :: bounds_are_known
type(string_t) :: title, description, xlabel, ylabel
type(plot_labels_t) :: plot_labels
if (plot%use_id_expr) then
    call eval_tree_evaluate (plot%expr_id)
    plot%id = eval_tree_get_string (plot%expr_id)
end if
bounds_are_known = .true.
call eval_tree_evaluate (plot%expr_lower_bound)
call eval_tree_evaluate (plot%expr_upper_bound)
if (eval_tree_result_is_known (plot%expr_lower_bound)) then
    lower_bound = eval_tree_get_real (plot%expr_lower_bound)
else
    call msg_error ("Plot '" &
        // char (plot%id) // "': lower bound is undefined")
    bounds_are_known = .false.
end if
if (eval_tree_result_is_known (plot%expr_upper_bound)) then
    upper_bound = eval_tree_get_real (plot%expr_upper_bound)
else
    call msg_error ("Plot '" &
        // char (plot%id) // "': upper bound is undefined")
    bounds_are_known = .false.
end if
title = var_list_get_sval (global%var_list, var_str ("title"))
description = &
    var_list_get_sval (global%var_list, var_str ("description"))
xlabel = var_list_get_sval (global%var_list, var_str ("xlabel"))
ylabel = var_list_get_sval (global%var_list, var_str ("ylabel"))
call plot_labels_init (plot_labels, title, &
    description, xlabel, ylabel)
if (bounds_are_known) then
    call analysis_init_plot &
        (plot%id, lower_bound, upper_bound, plot_labels)
else
    call msg_error ("Plot '" &
        // char (plot%id) // "': invalid declaration, skipping")
end if
end subroutine cmd_plot_execute

```

Analysis

Define the analysis expression. We store the parse tree for the right-hand side instead of compiling it. Compilation is deferred to the process environment where the analysis expression is used.

```

(Commands: types)+≡
    type :: cmd_analysis_t
    private
    type(parse_node_t), pointer :: pn_lexpr => null ()
end type cmd_analysis_t

```

Output. Print the right-hand side as a parse tree.

```

⟨Commands: procedures⟩+≡
  subroutine cmd_analysis_write (analysis, unit, indent)
    type(cmd_analysis_t), intent(in) :: analysis
    integer, intent(in), optional :: unit, indent
    integer :: u
    u = output_unit (unit); if (u < 0) return
    call write_indent (u, indent)
    write (u, "(1x,A)") "analysis ="
    call parse_node_write_rec (analysis%pn_lexpr, unit)
  end subroutine cmd_analysis_write

```

Compile. Simply store the parse (sub)tree.

```

⟨Commands: procedures⟩+≡
  subroutine cmd_analysis_compile (analysis, pn)
    type(cmd_analysis_t), pointer :: analysis
    type(parse_node_t), intent(in), target :: pn
    allocate (analysis)
    analysis%pn_lexpr => parse_node_get_sub_ptr (pn, 3)
  end subroutine cmd_analysis_compile

```

Instead of evaluating the cut expression, link the parse tree to the global data set, such that it is compiled and executed in the appropriate process context.

```

⟨Commands: procedures⟩+≡
  subroutine cmd_analysis_execute (analysis, global)
    type(cmd_analysis_t), intent(inout), target :: analysis
    type(rt_data_t), intent(inout), target :: global
    global%pn_analysis_lexpr => analysis%pn_lexpr
  end subroutine cmd_analysis_execute

```

Write analysis results

Depending on the argument, write one, several, or all analysis objects to a file. Write a L^AT_EX driver file as well.

```

⟨Commands: types⟩+≡
  type :: cmd_write_analysis_t
  private
  integer :: n_args = 0
  type(string_t), dimension(:), allocatable :: id
  logical, dimension(:), allocatable :: use_id_expr
  type(eval_tree_t), dimension(:), allocatable :: expr_id
  end type cmd_write_analysis_t

```

Finalizer for the eval trees.

```

⟨Commands: procedures⟩+≡
  subroutine cmd_write_analysis_final (write)
    type(cmd_write_analysis_t), intent(inout) :: write
    integer :: i
    do i = 1, write%n_args
      call eval_tree_final (write%expr_id(i))
    end do
  end subroutine cmd_write_analysis_final

```

```

end do
end subroutine cmd_write_analysis_final

```

Compile. Record the write ID and initialize lower, upper bound and bin width.

(Commands: procedures)+≡

```

subroutine cmd_write_analysis_compile (write, pn, global)
  type(cmd_write_analysis_t), pointer :: write
  type(parse_node_t), intent(in), target :: pn
  type(rt_data_t), intent(in), target :: global
  type(parse_node_t), pointer :: pn_args, pn_tag
  integer :: i
  pn_args => parse_node_get_sub_ptr (pn, 2)
  allocate (write)
  if (associated (pn_args)) then
    write%n_args = parse_node_get_n_sub (pn_args)
    allocate (write%id (write%n_args), write%use_id_expr (write%n_args))
    write%use_id_expr = .false.
    allocate (write%expr_id (write%n_args))
    pn_tag => parse_node_get_sub_ptr (pn_args)
    i = 1
    do while (associated (pn_tag))
      select case (char (parse_node_get_rule_key (pn_tag)))
        case ("analysis_id")
          write%id(i) = parse_node_get_string (pn_tag)
        case default
          write%use_id_expr(i) = .true.
          call eval_tree_init_sexpr &
            (write%expr_id(i), pn_tag, global%var_list)
      end select
      i = i + 1
      pn_tag => parse_node_get_next_ptr (pn_tag)
    end do
  end if
end subroutine cmd_write_analysis_compile

```

Command execution.

(Commands: procedures)+≡

```

subroutine cmd_write_analysis_execute (write, global)
  type(cmd_write_analysis_t), intent(inout), target :: write
  type(rt_data_t), intent(inout), target :: global
  type(string_t) :: filename, data_file, driver_file
  integer :: i, u_data, u_driver, u_log
  logical :: has_gmlcode
  u_log = logfile_unit ()
  if (var_list_is_known (global%var_list, &
    var_str ("analysis_filename"))) then
    filename = var_list_get_sval (global%var_list, &
      var_str ("analysis_filename"))
    data_file = filename // ".dat"
    driver_file = filename // ".tex"
    call msg_message ("Writing analysis results to '" &
      // char (data_file) // "'")
    u_data = free_unit ()

```

```

        open (unit=u_data, file=char(data_file), &
              action="write", status="replace")
        call msg_message ("Writing analysis results display to '" &
                          // char (driver_file) // "'")
        u_driver = free_unit ()
        open (unit=u_driver, file=char(driver_file), &
              action="write", status="replace")
    else
        u_data = -1
        u_driver = -1
    end if
    if (write%n_args == 0) then
        if (u_data >= 0) then
            call analysis_write (unit=u_data)
        else
            call analysis_write ()
            call analysis_write (unit=u_log)
            flush (u_log)
        end if
        if (u_driver >= 0) then
            call analysis_write_driver (data_file, unit=u_driver)
        end if
    else
        do i = 1, write%n_args
            if (write%use_id_expr(i)) then
                call eval_tree_evaluate (write%expr_id(i))
                write%id(i) = eval_tree_get_string (write%expr_id(i))
            end if
            if (u_data >= 0) then
                call analysis_write (write%id(i), unit=u_data)
            else
                call analysis_write (write%id(i))
                call analysis_write (write%id(i), unit=u_log)
                flush (u_log)
            end if
            if (u_driver >= 0) then
                call analysis_write_driver (data_file, write%id, unit=u_driver)
            end if
        end do
    end if
    if (u_data >= 0) close (u_data)
    if (u_driver >= 0) then
        close (u_driver)
        if (write%n_args == 0) then
            has_gmlcode = analysis_has_plots ()
        else
            has_gmlcode = analysis_has_plots (write%id)
        end if
        call msg_message ("Compiling analysis results display in '" &
                          // char (driver_file) // "'")
        call analysis_compile_tex (filename, has_gmlcode, global%os_data)
    end if
end subroutine cmd_write_analysis_execute

```

Clear analysis objects

The syntax is analogous to `write_analysis`. Each argument clears a particular analysis object. No argument clears the whole analysis store. The objects are cleared, but not deleted.

(Commands: types)+≡

```
type :: cmd_clear_t
  private
  integer :: n_args = 0
  type(string_t), dimension(:), allocatable :: id
  logical, dimension(:), allocatable :: use_id_expr
  type(eval_tree_t), dimension(:), allocatable :: expr_id
end type cmd_clear_t
```

Finalizer for the eval trees.

(Commands: procedures)+≡

```
subroutine cmd_clear_final (clear)
  type(cmd_clear_t), intent(inout) :: clear
  integer :: i
  do i = 1, clear%n_args
    call eval_tree_final (clear%expr_id(i))
  end do
end subroutine cmd_clear_final
```

Compile. Record the clear ID and initialize lower, upper bound and bin width.

(Commands: procedures)+≡

```
subroutine cmd_clear_compile (clear, pn, global)
  type(cmd_clear_t), pointer :: clear
  type(parse_node_t), intent(in), target :: pn
  type(rt_data_t), intent(in), target :: global
  type(parse_node_t), pointer :: pn_args, pn_tag
  type(string_t) :: key
  integer :: i
  pn_args => parse_node_get_sub_ptr (pn, 2)
  allocate (clear)
  if (associated (pn_args)) then
    clear%n_args = parse_node_get_n_sub (pn_args)
    allocate (clear%id (clear%n_args), clear%use_id_expr (clear%n_args))
    clear%use_id_expr = .false.
    allocate (clear%expr_id (clear%n_args))
    pn_tag => parse_node_get_sub_ptr (pn_args)
    i = 1
    do while (associated (pn_tag))
      key = parse_node_get_rule_key (pn_tag)
      select case (char (key))
        case ("iterations", "cuts", "weight", "scale", "analysis", "expect")
          clear%id(i) = key
        case ("analysis_id")
          clear%id(i) = parse_node_get_string (pn_tag)
        case default
          clear%use_id_expr(i) = .true.
          call eval_tree_init_sexpr &
            (clear%expr_id(i), pn_tag, global%var_list)
      end select
      pn_tag => parse_node_get_sub_ptr (pn_tag)
    end do
  end if
end subroutine cmd_clear_compile
```

```

        end select
        i = i + 1
        pn_tag => parse_node_get_next_ptr (pn_tag)
    end do
end if
end subroutine cmd_clear_compile

```

Command execution.

(Commands: procedures)+≡

```

subroutine cmd_clear_execute (clear, global)
    type(cmd_clear_t), intent(inout), target :: clear
    type(rt_data_t), intent(inout), target :: global
    integer :: i
    if (clear%n_args == 0) then
        call analysis_clear ()
        call msg_message ("Cleared all analysis objects")
    else
        do i = 1, clear%n_args
            select case (char (clear%id(i)))
            case ("iterations")
                call iterations_list_clear (global%it_list)
                call msg_message ("Cleared iteration list setup")
            case ("cuts")
                global%pn_cuts_lexpr => null ()
                call msg_message ("Cleared cut setup")
            case ("weight")
                global%pn_weight_expr => null ()
                call msg_message ("Cleared integration weight setup")
            case ("scale")
                global%pn_scale_expr => null ()
                call msg_message ("Cleared event scale setup")
            case ("analysis")
                global%pn_analysis_lexpr => null ()
                call msg_message ("Cleared analysis setup")
            case ("expect")
                call expect_clear ()
                call msg_message ("Cleared counters of value checks")
            case default
                if (clear%use_id_expr(i)) then
                    call eval_tree_evaluate (clear%expr_id(i))
                    clear%id(i) = eval_tree_get_string (clear%expr_id(i))
                end if
                call analysis_clear (clear%id(i))
                call msg_message ("Cleared analysis object '" &
                    // char (clear%id(i)) // "'")
            end select
        end do
    end if
end subroutine cmd_clear_execute

```

Unstable particles

Mark a particle as unstable. For each unstable particle, we store a number of decay channels and compute their respective BRs.

(Commands: types)+≡

```
type :: cmd_unstable_t
private
type(eval_tree_t) :: pdg
type(string_t) :: prt
type(flavor_t) :: flv
integer :: n_proc = 0
type(string_t), dimension(:), allocatable :: process_id
real(default), dimension(:), allocatable :: br
end type cmd_unstable_t
```

Delete the eval tree.

(Commands: procedures)+≡

```
subroutine cmd_unstable_final (unstable)
type(cmd_unstable_t), intent(inout) :: unstable
call eval_tree_final (unstable%pdg)
end subroutine cmd_unstable_final
```

Output.

(Commands: procedures)+≡

```
subroutine cmd_unstable_write (unstable, unit, indent)
type(cmd_unstable_t), intent(in) :: unstable
integer, intent(in), optional :: unit, indent
integer :: u, i
u = output_unit (unit); if (u < 0) return
call write_indent (u, indent)
write (u, "(1x,A)", advance="no") "unstable"
write (u, "(1x,A)", advance="no") char (unstable%prt)
write (u, "(1x,A)", advance="no") "("
do i = 1, unstable%n_proc
if (i /= 1) write (u, "(", advance="no")
write (u, "(A)", advance="no") char (unstable%process_id(i))
end do
write (u, "(A)") ")"
end subroutine cmd_unstable_write
```

Compile. Initiate an eval tree for the decaying particle and determine the decay channel process IDs.

(Commands: procedures)+≡

```
subroutine cmd_unstable_compile (unstable, pn, global)
type(cmd_unstable_t), pointer :: unstable
type(parse_node_t), intent(in), target :: pn
type(rt_data_t), intent(in), target :: global
type(parse_node_t), pointer :: pn_prt, pn_arg, pn_proc
integer :: i
pn_prt => parse_node_get_sub_ptr (pn, 2)
pn_arg => parse_node_get_next_ptr (pn_prt)
allocate (unstable)
```

```

call eval_tree_init_cexpr (unstable%pdg, pn_prt, global%var_list)
unstable%prt = "?"
unstable%n_proc = parse_node_get_n_sub (pn_arg)
allocate (unstable%process_id (unstable%n_proc))
allocate (unstable%br (unstable%n_proc))
pn_proc => parse_node_get_sub_ptr (pn_arg)
do i = 1, unstable%n_proc
    unstable%process_id(i) = parse_node_get_string (pn_proc)
    pn_proc => parse_node_get_next_ptr (pn_proc)
end do
end subroutine cmd_unstable_compile

```

Command execution. Evaluate the decaying particle and compute the BRs for the decays, using previous integration runs. For each decay channel, initialize event generation.

(*Commands: procedures*) \equiv

```

subroutine cmd_unstable_execute (unstable, global)
    type(cmd_unstable_t), intent(inout), target :: unstable
    type(rt_data_t), intent(inout), target :: global
    type(pdg_array_t) :: aval
    type(flavor_t), dimension(:), allocatable :: flv_tmp
    type(flavor_t) :: flv
    real(default), dimension(:), allocatable :: integral
    real(default) :: integral_sum
    type(process_t), pointer :: process
    integer :: proc
    type(particle_data_t), pointer :: prt_data
    type(decay_configuration_t), pointer :: decay_conf
    call eval_tree_evaluate (unstable%pdg)
    aval = eval_tree_get_pdg_array (unstable%pdg)
    call flavor_init (flv_tmp, aval, global%model)
    select case (size (flv_tmp))
    case (1); flv = flv_tmp(1)
    case default
        call pdg_array_write (aval)
        call msg_fatal ("Unstable particle expression " &
            // "does not evaluate to a unique particle")
        return
    end select
    unstable%prt = flavor_get_name (flv)
    allocate (integral (unstable%n_proc))
    LOOP_PROC: do proc = 1, unstable%n_proc
        process => process_store_get_process_ptr (unstable%process_id(proc))
        if (associated (process)) then
            integral(proc) = process_get_integral (process)
            call process_setup_event_generation (process, qn_mask_in = &
                new_quantum_numbers_mask (.false., .false., .false.))
        else
            call msg_error ("Decay channel process '" // &
                char (unstable%process_id(proc)) // "' is undefined")
            integral(proc) = 0
        end if
    end do LOOP_PROC

```

```

prt_data => model_get_particle_ptr (global%model, flavor_get_pdg (flv))
if (associated (prt_data)) then
    call particle_data_set (prt_data, is_stable=.false.)
else
    call msg_fatal ("Particle '" // char (unstable%prt) &
        // "' is not contained in model '" &
        // char (model_get_name (global%model)) // "'")
end if
integral_sum = sum (integral)
if (integral_sum /= 0) then
    unstable%br = integral / integral_sum
else
    call msg_fatal ("Unstable particle: Computed total width vanishes")
    unstable%br = 0
end if
call decay_store_append_decay &
    (flv, integral_sum, unstable%n_proc, decay_conf)
ASSIGN_DECAYS: do proc = 1, unstable%n_proc
    process => process_store_get_process_ptr (unstable%process_id(proc))
    if (associated (process)) then
        call decay_configuration_set_channel &
            (decay_conf, proc, process, unstable%br(proc))
    end if
end do ASSIGN_DECAYS
call decay_configuration_write (decay_conf)
end subroutine cmd_unstable_execute

```

Simulation

```

<Commands: types>+≡
type :: cmd_simulate_t
    private
    integer :: n_evt = 0
    integer :: n_proc = 0
    type(string_t), dimension(:), allocatable :: process_id
    type(command_list_t), pointer :: options => null ()
    type(rt_data_t) :: local
end type cmd_simulate_t

```

Finalizer.

```

<Commands: procedures>+≡
subroutine cmd_simulate_final (simulate)
    type(cmd_simulate_t), intent(inout) :: simulate
    if (associated (simulate%options)) then
        call command_list_final (simulate%options)
        deallocate (simulate%options)
    end if
end subroutine cmd_simulate_final

```

Output.

```

<Commands: procedures>+≡
subroutine cmd_simulate_write (simulate, unit, indent)

```

```

type(cmd_simulate_t), intent(in) :: simulate
integer, intent(in), optional :: unit, indent
integer :: u, i
u = output_unit (unit); if (u < 0) return
call write_indent (u, indent)
write (u, "(1x,A)", advance="no") "simulate ("
do i = 1, simulate%n_proc
  if (i /= 1) write (u, "(", advance="no")
  write (u, "A)", advance="no") char (simulate%process_id(i))
end do
write (u, "(A)") ")"
if (associated (simulate%options)) then
  write (u, "(1x,'{'}")
  call command_list_write (simulate%options, unit, indent)
  call write_indent (u, indent)
  write (u, "(1x,'}')")
end if
end subroutine cmd_simulate_write

```

Compile.

(Commands: procedures)+≡

```

subroutine cmd_simulate_compile (simulate, pn, global)
  type(cmd_simulate_t), pointer :: simulate
  type(parse_node_t), intent(in), target :: pn
  type(rt_data_t), intent(in), target :: global
  type(parse_node_t), pointer :: pn_proclist, pn_proc, pn_opt
  integer :: i
  pn_proclist => parse_node_get_sub_ptr (pn, 2)
  pn_opt => parse_node_get_next_ptr (pn_proclist)
  allocate (simulate)
  call rt_data_local_init (simulate%local, global)
  if (associated (pn_opt)) then
    allocate (simulate%options)
    call command_list_compile (simulate%options, pn_opt, simulate%local)
  end if
  simulate%n_proc = parse_node_get_n_sub (pn_proclist)
  allocate (simulate%process_id (simulate%n_proc))
  pn_proc => parse_node_get_sub_ptr (pn_proclist)
  do i = 1, simulate%n_proc
    simulate%process_id(i) = parse_node_get_string (pn_proc)
    pn_proc => parse_node_get_next_ptr (pn_proc)
  end do
end subroutine cmd_simulate_compile

```

Execute command: Simulate events.

TODO: support weighted events and negative weights.

(Commands: procedures)+≡

```

subroutine cmd_simulate_execute (simulate, global)
  type(cmd_simulate_t), intent(inout), target :: simulate
  type(rt_data_t), intent(inout), target :: global
  type(file_list_t) :: file_list
  type :: process_p
  type(process_t), pointer :: ptr

```

```

end type process_p
type(process_p), dimension(:), allocatable :: prc_array
real(default), dimension(:), allocatable :: integral
real(default) :: integral_sum, integral_cmp
real(default) :: luminosity
type(string_t) :: file_raw
type(decay_tree_t), dimension(:), allocatable, target :: decay_tree
type(event_t), target :: event
integer :: n_events, i_evt
integer :: proc
type(process_t), pointer :: process
integer :: n_in
type(flavor_t), dimension(:), allocatable :: beam_flv
real(default), dimension(:), allocatable :: beam_energy
real(double) :: x
character(32), dimension(:), allocatable :: md5sum_process
character(32), dimension(:), allocatable :: md5sum_parameters
character(32), dimension(:), allocatable :: md5sum_results
logical :: read_raw, write_raw, exist, ok
integer :: i, u_raw, iostat
character(30) :: n_events_string
call rt_data_link (simulate%local, global)
simulate%local%n_processes = simulate%n_proc
simulate%local%unweighted = .true.
simulate%local%negative_weights = .false.
if (associated (simulate%options)) then
    call command_list_execute (simulate%options, simulate%local)
end if
do proc = 1, simulate%n_proc
    process => process_store_get_process_ptr (simulate%process_id(proc))
    if (.not. associated (process)) then
        call msg_fatal ("Process '" // char (simulate%process_id(proc)) &
            // "' must be integrated before simulation.")
        call rt_data_restore (global, simulate%local)
        return
    end if
    select case (proc)
    case (1)
        n_in = process_get_n_in (process)
        allocate (beam_flv (n_in), beam_energy (n_in))
        beam_flv = process_get_beam_flv (process)
        beam_energy = process_get_beam_energy (process)
    case default
        if (process_get_n_in (process) /= n_in) then
            call msg_fatal ("Simulation: " &
                // "Mixture of scattering and decays")
            call rt_data_restore (global, simulate%local)
            return
        else if (any (process_get_beam_flv (process) /= beam_flv)) then
            call msg_fatal ("Simulation: " &
                // "Mismatch in beam particles")
            call rt_data_restore (global, simulate%local)
            return
        else if (any (process_get_beam_energy (process) /= beam_energy)) then

```

```

        call msg_fatal ("Simulation: " &
            // "Mismatch in beam energies")
        call rt_data_restore (global, simulate%local)
        return
    end if
end select
end do
if (simulate%local%write_default) &
    call file_list_append_file_spec (file_list, &
        simulate%local%file_default, FMT_DEFAULT, &
        beam_flv, beam_energy, simulate%n_proc, &
        simulate%local%unweighted, simulate%local%negative_weights)
if (simulate%local%write_debug) &
    call file_list_append_file_spec (file_list, &
        simulate%local%file_debug, FMT_DEBUG, &
        beam_flv, beam_energy, simulate%n_proc, &
        simulate%local%unweighted, simulate%local%negative_weights)
if (simulate%local%write_hePMC) &
    call file_list_append_file_spec (file_list, &
        simulate%local%file_hePMC, FMT_HEPMC, &
        beam_flv, beam_energy, simulate%n_proc, &
        simulate%local%unweighted, simulate%local%negative_weights)
if (simulate%local%write_lhef) &
    call file_list_append_file_spec (file_list, &
        simulate%local%file_lhef, FMT_LHEF, &
        beam_flv, beam_energy, simulate%n_proc, &
        simulate%local%unweighted, simulate%local%negative_weights)
allocate (prc_array (simulate%n_proc), integral (simulate%n_proc))
allocate (decay_tree (simulate%n_proc))
allocate (md5sum_process (simulate%n_proc))
allocate (md5sum_parameters (simulate%n_proc))
allocate (md5sum_results (simulate%n_proc))
do proc = 1, simulate%n_proc
    process => process_store_get_process_ptr (simulate%process_id(proc))
    if (associated (simulate%local%pn_analysis_lexpr)) then
        call process_setup_analysis &
            (process, simulate%local%pn_analysis_lexpr)
        call msg_message ("Using user-defined analysis setup.")
    else
        call msg_message ("No analysis setup has been provided.")
    end if
    call process_setup_event_generation (process)
    call decay_tree_init (decay_tree(proc), process)
    prc_array(proc)%ptr => process
    integral(proc) = process_get_integral (process)
    md5sum_process(proc) = process_get_md5sum (process)
    md5sum_parameters(proc) = process_get_md5sum_parameters (process)
    md5sum_results(proc) = process_get_md5sum_results (process)
end do
integral_sum = sum (integral)
if (integral_sum <= 0) then
    call msg_error ("Event generation: " &
        // "sum of process integrals must be positive; skipping")
    return
end if

```

```

end if
luminosity = var_list_get_rval &
    (simulate%local%var_list, var_str ("luminosity"))
n_events = var_list_get_ival &
    (simulate%local%var_list, var_str ("n_events"))
simulate%n_evt = choose_n_evt (luminosity, n_events, integral_sum)

call file_list_open (file_list)

read_raw = simulate%local%read_raw
write_raw = simulate%local%write_raw
file_raw = simulate%local%file_raw
if (read_raw) then
    inquire (file = char (file_raw), exist = exist)
    if (exist) then
        call msg_message ("Reading events from file '" &
            // char (file_raw) // "' ...")
        u_raw = free_unit ()
        open (file = char (file_raw), unit = u_raw, form = "unformatted", &
            action = "read", status = "old")
        call raw_event_file_read_header (u_raw, &
            md5sum_process, md5sum_parameters, md5sum_results, &
            ok, iostat)
        if (iostat /= 0) then
            call msg_error ("Event file '" &
                // char (file_raw) // "' is corrupt, discarding.")
            close (u_raw)
            read_raw = .false.
        else if (.not. ok) then
            close (u_raw)
            read_raw = .false.
        end if
    else
        read_raw = .false.
    end if
end if
i_evt = 0
if (read_raw) then
    READ_EVENTS: do while (i_evt < simulate%n_evt)
        call event_read_raw (event, u_raw, iostat=iostat)
        if (iostat /= 0) exit READ_EVENTS
        i_evt = i_evt + 1
        call event_do_analysis (event)
        call file_list_write_event (file_list, event, proc, i_evt)
        call event_final (event)
    end do READ_EVENTS
    write (msg_buffer, "(A,1x,I0,1x,A)" "..." i_evt, "events read.")
    call msg_message ()
end if

if (simulate%n_evt > i_evt) then
    write (n_events_string, "(I0)") simulate%n_evt - i_evt
    call msg_message ("Generating " // trim (n_events_string) &
        // " events ...")

```

```

else
    write_raw = .false.
end if
if (write_raw) then
    call msg_message ("Writing events in internal format to file '" &
        // char (file_raw) // "'")
    if (read_raw) then
        close (u_raw)
        open (file = char (file_raw), unit = u_raw, form = "unformatted", &
            action = "write", status = "old", position = "append")
    else
        u_raw = free_unit ()
        open (file = char (file_raw), unit = u_raw, form = "unformatted", &
            action = "write", status = "replace")
        call raw_event_file_write_header (u_raw, &
            md5sum_process, md5sum_parameters, md5sum_results)
    end if
else if (read_raw) then
    close (u_raw)
end if
do i = i_evt + 1, simulate%n_evt
    call tao_random_number (simulate%local%rng, x)
    integral_cmp = 0
    do proc = 1, simulate%n_proc
        integral_cmp = integral_cmp + integral(proc)
        if (integral_cmp > x * integral_sum) exit
    end do
    if (proc > simulate%n_proc) proc = simulate%n_proc
    process => prc_array(proc)%ptr
    call event_init (event, process)
    call event_generate_unweighted &
        (event, decay_tree(proc), simulate%local%rng, &
            FM_IGNORE_HELICITY, &
            keep_correlations=.false., &
            keep_virtual=.true.)
    call file_list_write_event (file_list, event, proc, i)
    if (write_raw) call event_write_raw (event, u_raw)
    call event_final (event)
end do

if (write_raw) close (u_raw)
call file_list_close (file_list)
do proc = 1, simulate%n_proc
    call decay_tree_final (decay_tree(proc))
end do
if (simulate%n_evt > i_evt) call msg_message ("... done")
call rt_data_restore (global, simulate%local)
end subroutine cmd_simulate_execute

```

Choose the number of events to generate from either the luminosity or the specified `n_events`, whatever is larger.

(Commands: procedures)+≡

```
function choose_n_evt (luminosity, n_evt_in, integral) result (n_evt)
```

```

integer :: n_evt
real(default), intent(in) :: luminosity
integer, intent(in) :: n_evt_in
real(default), intent(in) :: integral
n_evt = max (nint (luminosity * integral), n_evt_in)
end function choose_n_evt

```

Parameters: random-number generator seed

Specify a new random-number generator seed and set it.

(Commands: types)+≡

```

type :: cmd_seed_t
private
type(eval_tree_t) :: expr
end type cmd_seed_t

```

Finalizer.

(Commands: procedures)+≡

```

subroutine cmd_seed_final (seed)
type(cmd_seed_t), intent(inout) :: seed
call eval_tree_final (seed%expr)
end subroutine cmd_seed_final

```

Output.

(Commands: procedures)+≡

```

subroutine cmd_seed_write (seed, unit, indent)
type(cmd_seed_t), intent(in) :: seed
integer, intent(in), optional :: unit, indent
integer :: u
u = output_unit (unit); if (u < 0) return
call write_indent (u, indent)
write (u, "(1x,A)") "seed ="
call eval_tree_write (seed%expr, unit)
end subroutine cmd_seed_write

```

Compile. Initialize evaluation trees.

(Commands: procedures)+≡

```

subroutine cmd_seed_compile (seed, pn, global)
type(cmd_seed_t), pointer :: seed
type(parse_node_t), intent(in), target :: pn
type(rt_data_t), intent(in), target :: global
type(parse_node_t), pointer :: pn_expr
allocate (seed)
pn_expr => parse_node_get_sub_ptr (pn, 3)
call eval_tree_init_expr (seed%expr, pn_expr, global%var_list)
end subroutine cmd_seed_compile

```

Execute. Evaluate the trees and add the result to the iteration list in the runtime data set.

(Commands: procedures)+≡

```

subroutine cmd_seed_execute (seed, global)
  type(cmd_seed_t), intent(inout) :: seed
  type(rt_data_t), intent(inout) :: global
  integer :: seed_val
  call eval_tree_evaluate (seed%expr)
  if (eval_tree_result_is_known (seed%expr)) then
    seed_val = eval_tree_get_int (seed%expr)
    call set_rng_seed (global%rng, global%var_list, seed_val, verbose=.true.)
  else
    call msg_error ("Setting seed value: " &
      // "undefined result of integer expression evaluation")
  end if
end subroutine cmd_seed_execute

```

<Commands: procedures>+≡

```

subroutine set_rng_seed (rng, var_list, seed_val, verbose)
  type(tao_random_state), intent(inout) :: rng
  type(var_list_t), intent(inout), target :: var_list
  integer, intent(in) :: seed_val
  logical, intent(in) :: verbose
  character(30) :: buffer
  if (verbose) then
    write (buffer, "(I0)") seed_val
    call msg_message ("Setting seed for random-number generator to " &
      // trim (buffer))
  end if
  call tao_random_seed (rng, seed_val)
  call var_list_set_int (var_list, var_str ("seed_value"), &
    seed_val, is_known=.true.)
end subroutine set_rng_seed

```

Parameters: number of iterations

Specify number of iterations and number of calls for one integration pass.

<Commands: types>+≡

```

type :: cmd_iterations_t
  private
  integer :: n_pass = 0
  type(eval_tree_t), dimension(:), allocatable :: expr_n_it
  type(eval_tree_t), dimension(:), allocatable :: expr_n_calls
end type cmd_iterations_t

```

Finalizer.

<Commands: procedures>+≡

```

subroutine cmd_iterations_final (iterations)
  type(cmd_iterations_t), intent(inout) :: iterations
  integer :: i
  if (allocated (iterations%expr_n_it)) then
    do i = 1, size (iterations%expr_n_it)
      call eval_tree_final (iterations%expr_n_it(i))
    end do
  end if
end subroutine cmd_iterations_final

```

```

end if
if (allocated (iterations%expr_n_calls)) then
  do i = 1, size (iterations%expr_n_calls)
    call eval_tree_final (iterations%expr_n_calls(i))
  end do
end if
end subroutine cmd_iterations_final

```

Output.

(Commands: procedures)+≡

```

subroutine cmd_iterations_write (iterations, unit, indent)
  type(cmd_iterations_t), intent(in) :: iterations
  integer, intent(in), optional :: unit, indent
  integer :: u, i
  u = output_unit (unit); if (u < 0) return
  call write_indent (u, indent)
  write (u, "(1x,A)") "iterations ="
  do i = 1, iterations%n_pass
    call eval_tree_write (iterations%expr_n_it(i), unit)
    write (u, "(1x,A)") ":"
    call write_indent (u, indent)
    call eval_tree_write (iterations%expr_n_calls(i), unit)
    call write_indent (u, indent)
    if (i < iterations%n_pass) write (u, "(1x,A)") ":"
  end do
  write (u, "(1x,A)") ")"
end subroutine cmd_iterations_write

```

Compile. Initialize evaluation trees.

(Commands: procedures)+≡

```

subroutine cmd_iterations_compile (iterations, pn, global)
  type(cmd_iterations_t), pointer :: iterations
  type(parse_node_t), intent(in), target :: pn
  type(rt_data_t), intent(in), target :: global
  type(parse_node_t), pointer :: pn_arg, pn_pass, pn_n_it, pn_n_calls
  integer :: i
  allocate (iterations)
  pn_arg => parse_node_get_sub_ptr (pn, 3)
  if (associated (pn_arg)) then
    iterations%n_pass = parse_node_get_n_sub (pn_arg)
    allocate (iterations%expr_n_it (iterations%n_pass))
    allocate (iterations%expr_n_calls (iterations%n_pass))
    pn_pass => parse_node_get_sub_ptr (pn_arg)
    i = 1
    do while (associated (pn_pass))
      pn_n_it => parse_node_get_sub_ptr (pn_pass)
      pn_n_calls => parse_node_get_next_ptr (pn_n_it, 2)
      call eval_tree_init_expr (iterations%expr_n_it(i), &
        pn_n_it, global%var_list)
      call eval_tree_init_expr (iterations%expr_n_calls(i), &
        pn_n_calls, global%var_list)
      i = i + 1
      pn_pass => parse_node_get_next_ptr (pn_pass)
    end do
  end if
end subroutine cmd_iterations_compile

```

```

        end do
    else
        allocate (iterations%expr_n_it (0), iterations%expr_n_calls (0))
    end if
end subroutine cmd_iterations_compile

```

Execute. Evaluate the trees and add the result to the iteration list in the runtime data set.

```

<Commands: procedures>+≡
subroutine cmd_iterations_execute (iterations, global)
    type(cmd_iterations_t), intent(inout) :: iterations
    type(rt_data_t), intent(inout) :: global
    integer, dimension(iterations%n_pass) :: n_it, n_calls
    integer :: i
    do i = 1, iterations%n_pass
        call eval_tree_evaluate (iterations%expr_n_it(i))
        call eval_tree_evaluate (iterations%expr_n_calls(i))
        if (eval_tree_result_is_known (iterations%expr_n_it(i)) &
            .and. eval_tree_result_is_known (iterations%expr_n_calls(i))) then
            n_it(i) = eval_tree_get_int (iterations%expr_n_it(i))
            n_calls(i) = eval_tree_get_int (iterations%expr_n_calls(i))
        else
            call msg_error ("Undefined iterations/calls specification: ignored")
            n_it(i) = 0
            n_calls(i) = 0
        end if
    end do
    call iterations_list_init (global%it_list, n_it, n_calls)
end subroutine cmd_iterations_execute

```

Scan over parameters and other objects

```

<Commands: parameters>+≡
integer, parameter :: STEP_NONE = 0
integer, parameter :: STEP_ADD = 1
integer, parameter :: STEP_SUB = 2
integer, parameter :: STEP_MUL = 3
integer, parameter :: STEP_DIV = 4

<Commands: types>+≡
type :: cmd_scan_t
    private
    integer :: var_type = V_NONE
    type(string_t) :: var_name
    logical :: allow_steps = .false.
    integer :: n_arg = 0
    type(command_list_t), dimension(:), pointer :: cmd_var => null ()
    logical, dimension(:), allocatable :: has_range
    type(eval_tree_t), dimension(:), allocatable :: beg_expr
    type(eval_tree_t), dimension(:), allocatable :: end_expr
    integer, dimension(:), allocatable :: step_type
    type(eval_tree_t), dimension(:), allocatable :: step_expr
    type(command_list_t), pointer :: body => null ()

```

```

        type(rt_data_t) :: local
    end type cmd_scan_t

```

Finalizer.

(Commands: procedures)+≡

```

subroutine cmd_scan_final (loop)
    type(cmd_scan_t), intent(inout) :: loop
    integer :: i
    if (associated (loop%cmd_var)) then
        do i = 1, size (loop%cmd_var)
            call command_list_final (loop%cmd_var(i))
        end do
        deallocate (loop%cmd_var)
    end if
    if (allocated (loop%has_range)) deallocate (loop%has_range)
    if (allocated (loop%beg_expr)) then
        do i = 1, size (loop%beg_expr)
            call eval_tree_final (loop%beg_expr(i))
        end do
        deallocate (loop%beg_expr)
    end if
    if (allocated (loop%end_expr)) then
        do i = 1, size (loop%end_expr)
            call eval_tree_final (loop%end_expr(i))
        end do
        deallocate (loop%end_expr)
    end if
    if (allocated (loop%step_type)) deallocate (loop%step_type)
    if (allocated (loop%step_expr)) then
        do i = 1, size (loop%step_expr)
            call eval_tree_final (loop%step_expr(i))
        end do
        deallocate (loop%step_expr)
    end if
    if (associated (loop%body)) then
        call command_list_final (loop%body)
        deallocate (loop%body)
    end if
end subroutine cmd_scan_final

```

Output.

(Commands: procedures)+≡

```

subroutine cmd_scan_write (loop, unit, indent)
    type(cmd_scan_t), intent(in) :: loop
    integer, intent(in), optional :: unit, indent
    integer :: u
    u = output_unit (unit); if (u < 0) return
    call write_indent (u, indent)
    write (u, "(A)", advance="no") "scan ("
    if (associated (loop%body)) then
        write (u, "(1x,'{'")
        call command_list_write (loop%body, unit, indent)
        call write_indent (u, indent)
    end if
end subroutine cmd_scan_write

```

```

        write (u, "(1x,}')")
    else
        write (u, *)
    end if
end subroutine cmd_scan_write

```

Compile the loop, including the list of step specifications.

(*Commands: procedures*) \equiv

```

recursive subroutine cmd_scan_compile (loop, pn, global)
    type(cmd_scan_t), pointer :: loop
    type(parse_node_t), intent(in), target :: pn
    type(rt_data_t), intent(inout), target :: global
    type(parse_node_t), pointer :: pn_spec, pn_cmd, pn_list, pn_body
    integer :: i
    type(parse_tree_t) :: parse_tree
    type(parse_node_t), pointer :: pn_root, pn_init_arg, pn_arg
    type(parse_node_t), pointer :: pn_expr, pn_range, pn_range_expr
    type(parse_node_t), pointer :: pn_step, pn_step_op, pn_step_expr
    type(parse_node_t), pointer :: pn_name
    type(string_t) :: str_init
    type(lexer_t) :: lexer
    type(stream_t) :: stream
    pn_spec => parse_node_get_sub_ptr (pn)
    pn_cmd => parse_node_get_sub_ptr (pn_spec, 2)
    allocate (loop)
    call rt_data_local_init (loop%local, global)
    if (associated (pn_cmd)) then
        pn_list => parse_node_get_last_sub_ptr (pn_cmd)
        if (associated (pn_list)) then
            loop%n_arg = parse_node_get_n_sub (pn_list)
            allocate (loop%cmd_var (loop%n_arg))
            call lexer_init_cmd_list (lexer)
            select case (char (parse_node_get_rule_key (pn_cmd)))
            case ("cmd_model_list")
                str_init = 'model = ""'
            case ("cmd_library_list")
                str_init = 'library = ""'
            case ("cmd_seed_list")
                loop%var_type = V_INT
                loop%var_name = "seed"
                str_init = 'seed = 0'
                loop%allow_steps = .true.
            case ("cmd_cuts_list")
                str_init = 'cuts = true'
            case ("cmd_weight_list")
                str_init = 'weight = 0'
            case ("cmd_scale_list")
                str_init = 'scale = 0'
            case ("cmd_analysis_list")
                str_init = 'analysis = true'
            case ("log_list")
                loop%var_type = V_LOG
                pn_name => parse_node_get_sub_ptr (pn_cmd, 2)
                loop%var_name = '?' // parse_node_get_string (pn_name)
            end select
        end if
    end if
end subroutine cmd_scan_compile

```

```

        str_init = loop%var_name // ' = true'
case ("real_list")
    loop%var_type = V_REAL
    pn_name => parse_node_get_sub_ptr (pn_cmd, 2)
    loop%var_name = parse_node_get_string (pn_name)
    str_init = 'real ' // loop%var_name // ' = 0'
    loop%allow_steps = .true.
case ("int_list")
    loop%var_type = V_INT
    pn_name => parse_node_get_sub_ptr (pn_cmd, 2)
    loop%var_name = parse_node_get_string (pn_name)
    str_init = 'int ' // loop%var_name // ' = 0'
    loop%allow_steps = .true.
case ("string_list")
    loop%var_type = V_STR
    pn_name => parse_node_get_sub_ptr (pn_cmd, 2)
    loop%var_name = '$' // parse_node_get_string (pn_name)
    str_init = loop%var_name // ' = ""'
case ("alias_list")
    loop%var_type = V_PDG
    pn_name => parse_node_get_sub_ptr (pn_cmd, 2)
    loop%var_name = parse_node_get_string (pn_name)
    str_init = 'alias ' // loop%var_name // ' = PDG(0)'
case ("num_list")
    pn_name => parse_node_get_sub_ptr (pn_cmd)
    loop%var_name = parse_node_get_string (pn_name)
    if (var_list_exists (loop%local%var_list, loop%var_name)) then
        loop%var_type = var_entry_get_type (var_list_get_var_ptr &
            (loop%local%var_list, loop%var_name))
        str_init = loop%var_name // ' = 0'
    else
        call msg_error ("Loop variable '" &
            // char (loop%var_name) &
            // "' should be declared; assuming 'real'")
        loop%var_type = V_REAL
        str_init = 'real ' // loop%var_name // ' = 0'
    end if
    loop%allow_steps = .true.
end select
allocate (loop%has_range (loop%n_arg)); loop%has_range = .false.
if (loop%allow_steps) then
    allocate (loop%beg_expr (loop%n_arg))
    allocate (loop%end_expr (loop%n_arg))
    allocate (loop%step_type (loop%n_arg)); loop%step_type = STEP_NONE
    allocate (loop%step_expr (loop%n_arg))
end if
call stream_init (stream, str_init)
call parse_tree_init (parse_tree, syntax_cmd_list, lexer, stream)
pn_root => parse_tree_get_root_ptr (parse_tree)
pn_cmd => parse_node_get_sub_ptr (pn_root)
pn_init_arg => parse_node_get_last_sub_ptr (pn_cmd)
i = 0
pn_arg => parse_node_get_sub_ptr (pn_list)
do while (associated (pn_arg))

```

```

i = i + 1
select case (char (parse_node_get_rule_key (pn_arg)))
case ("num_steps")
    pn_expr => parse_node_get_sub_ptr (pn_arg)
    pn_range => parse_node_get_next_ptr (pn_expr)
    if (associated (pn_range)) then
        loop%has_range(i) = .true.
        pn_range_expr => parse_node_get_sub_ptr (pn_range, 2)
        call eval_tree_init_expr (loop%beg_expr(i), &
            pn_expr, loop%local%var_list)
        call eval_tree_init_expr (loop%end_expr(i), &
            pn_range_expr, loop%local%var_list)
        pn_step => parse_node_get_next_ptr (pn_range_expr)
        if (associated (pn_step)) then
            pn_step_op => parse_node_get_sub_ptr (pn_step)
            select case (char (parse_node_get_key (pn_step_op)))
            case ("/+"); loop%step_type(i) = STEP_ADD
            case ("/-"); loop%step_type(i) = STEP_SUB
            case ("/*"); loop%step_type(i) = STEP_MUL
            case ("///"); loop%step_type(i) = STEP_DIV
            end select
            pn_step_expr => parse_node_get_next_ptr (pn_step_op)
            call eval_tree_init_expr (loop%step_expr(i), &
                pn_step_expr, loop%local%var_list)
        end if
    end if
case default
    pn_expr => pn_arg
end select
call parse_node_replace_last_sub (pn_cmd, pn_expr)
call command_list_compile (loop%cmd_var(i), pn_root, loop%local)
pn_arg => parse_node_get_next_ptr (pn_arg)
end do
call parse_node_replace_last_sub (pn_cmd, pn_init_arg)
call parse_tree_final (parse_tree)
call stream_final (stream)
call lexer_final (lexer)
end if
pn_body => parse_node_get_next_ptr (pn_spec)
if (associated (pn_body)) then
    allocate (loop%body)
    call command_list_compile (loop%body, pn_body, loop%local)
end if
else
    loop%n_arg = 0
end if
end subroutine cmd_scan_compile

```

Execute the loop for all values in the step list.

```

<Commands: procedures>+≡
recursive subroutine cmd_scan_execute (loop, global)
    type(cmd_scan_t), intent(inout), target :: loop
    type(rt_data_t), intent(inout), target :: global
    type(string_t) :: model_name

```

```

logical :: is_seed
integer :: i, j
integer :: i1, i2, istep, ival
real(default) :: r1, r2, rstep, rval
type(var_entry_t), pointer :: var
type(var_list_t), pointer :: model_vars
call rt_data_link (loop%local, global)
if (associated (loop%local%model)) then
    model_name = model_get_name (loop%local%model)
    model_vars => model_get_var_list_ptr (loop%local%model)
else
    model_vars => null ()
end if
LOOP_LIST: do i = 1, loop%n_arg
    call command_list_execute (loop%cmd_var(i), loop%local)
    if (.not. loop%has_range(i)) then
        if (associated (loop%body)) then
            call command_list_execute (loop%body, loop%local)
            if (loop%local%quit) then
                global%quit_code = loop%local%quit_code
                global%quit = .true.
                return
            end if
        end if
    else
        call eval_tree_evaluate (loop%beg_expr(i))
        if (eval_tree_result_is_known (loop%beg_expr(i))) then
            r1 = eval_tree_get_real (loop%beg_expr(i))
            i1 = eval_tree_get_int (loop%beg_expr(i))
        else
            call msg_error ("Scan: undefined lower bound, skipping")
            cycle LOOP_LIST
        end if
        call eval_tree_evaluate (loop%end_expr(i))
        if (eval_tree_result_is_known (loop%end_expr(i))) then
            r2 = eval_tree_get_real (loop%end_expr(i))
            i2 = eval_tree_get_int (loop%end_expr(i))
        else
            call msg_error ("Scan: undefined upper bound, skipping")
            cycle LOOP_LIST
        end if
        select case (loop%step_type(i))
        case (STEP_NONE)
            rstep = 1
            istep = 1
        case default
            call eval_tree_evaluate (loop%step_expr(i))
            if (eval_tree_result_is_known (loop%step_expr(i))) then
                rstep = eval_tree_get_real (loop%step_expr(i))
                istep = eval_tree_get_int (loop%step_expr(i))
            else
                call msg_error ("Scan: undefined step size, skipping")
                cycle LOOP_LIST
            end if
        end select
    end do
end if

```

```

end select
if (bounds_check_fails (loop%step_type(i), loop%var_type)) &
    cycle LOOP_LIST
if (loop%var_name == "seed") then
    is_seed = .true.
else
    is_seed = .false.
    var => var_list_get_var_ptr (loop%local%var_list, loop%var_name)
    if (var_entry_get_type (var) /= loop%var_type) then
        call msg_fatal ("Type mismatch for loop variable '" &
            // char (loop%var_name) // "; skipping")
        exit LOOP_LIST
    end if
end if
select case (loop%var_type)
case (V_REAL)
    select case (loop%step_type(i))
    case (STEP_NONE, STEP_ADD)
        do j = 0, huge (0)
            rval = r1 + j * rstep
            if (rstep > 0) then
                if (rval > r2) exit
            else
                if (rval < r2) exit
            end if
            call set_real (rval, j/=0)
            if (associated (loop%body)) then
                call command_list_execute (loop%body, loop%local)
                if (loop%local%quit) then
                    global%quit_code = loop%local%quit_code
                    global%quit = .true.
                    return
                end if
            end if
        end do
    case (STEP_SUB)
        do j = 0, huge (0)
            rval = r1 - j * rstep
            if (rstep > 0) then
                if (rval < r2) exit
            else
                if (rval > r2) exit
            end if
            call set_real (rval, j/=0)
            if (associated (loop%body)) then
                call command_list_execute (loop%body, loop%local)
                if (loop%local%quit) then
                    global%quit_code = loop%local%quit_code
                    global%quit = .true.
                    return
                end if
            end if
        end do
    case (STEP_MUL)

```

```

    rval = r1
    do j = 0, huge (0)
        if (rstep > 1) then
            if (rval > r2) exit
        else
            if (rval < r2) exit
        end if
        call set_real (rval, j/=0)
        if (associated (loop%body)) then
            call command_list_execute (loop%body, loop%local)
            if (loop%local%quit) then
                global%quit_code = loop%local%quit_code
                global%quit = .true.
                return
            end if
        end if
        rval = rval * rstep
    end do
case (STEP_DIV)
    rval = r1
    do j = 0, huge (0)
        if (rstep > 1) then
            if (rval < r2) exit
        else
            if (rval > r2) exit
        end if
        call set_real (rval, j/=0)
        if (associated (loop%body)) then
            call command_list_execute (loop%body, loop%local)
            if (loop%local%quit) then
                global%quit_code = loop%local%quit_code
                global%quit = .true.
                return
            end if
        end if
        rval = rval / rstep
    end do
end select
case (V_INT)
select case (loop%step_type(i))
case (STEP_NONE, STEP_ADD)
    do j = 0, huge (0)
        ival = i1 + j * istep
        if (istep > 0) then
            if (ival > i2) exit
        else
            if (ival < i2) exit
        end if
        call set_int (ival, j/=0, is_seed)
        if (associated (loop%body)) then
            call command_list_execute (loop%body, loop%local)
            if (loop%local%quit) then
                global%quit_code = loop%local%quit_code
                global%quit = .true.
            end if
        end if
    end do
end select

```

```

        return
    end if
end if
end do
case (STEP_SUB)
do j = 0, huge (0)
    ival = i1 - j * istep
    if (istep > 0) then
        if (ival < i2) exit
    else
        if (ival > i2) exit
    end if
    call set_int (ival, j/=0, is_seed)
    if (associated (loop%body)) then
        call command_list_execute (loop%body, loop%local)
        if (loop%local%quit) then
            global%quit_code = loop%local%quit_code
            global%quit = .true.
            return
        end if
    end if
end do
case (STEP_MUL)
    ival = i1
do j = 0, huge (0)
    if (istep > 1) then
        if (ival > i2) exit
    else
        if (ival < i2) exit
    end if
    call set_int (ival, j/=0, is_seed)
    if (associated (loop%body)) then
        call command_list_execute (loop%body, loop%local)
        if (loop%local%quit) then
            global%quit_code = loop%local%quit_code
            global%quit = .true.
            return
        end if
    end if
    ival = ival * istep
end do
case (STEP_DIV)
    ival = i1
do j = 0, huge (0)
    if (istep > 1) then
        if (ival < i2) exit
    else
        if (ival > i2) exit
    end if
    call set_int (ival, j/=0, is_seed)
    if (associated (loop%body)) then
        call command_list_execute (loop%body, loop%local)
        if (loop%local%quit) then
            global%quit_code = loop%local%quit_code

```

```

                                global%quit = .true.
                                return
                                end if
                                end if
                                ival = ival / istep
                            end do
                        end select
                    end select
                end if
            end do LOOP_LIST
            call rt_data_restore (global, loop%local)
contains
    subroutine set_real (rval, verbose)
        real(default), intent(in) :: rval
        logical, intent(in) :: verbose
        call var_entry_set_real (var, rval, is_known=.true., verbose=verbose, &
            model_name=model_name)
        if (var_entry_is_copy (var)) then
            call model_parameters_update (loop%local%model)
            call var_list_synchronize (loop%local%var_list, model_vars)
        end if
    end subroutine set_real
    subroutine set_int (ival, verbose, is_seed)
        integer, intent(in) :: ival
        logical, intent(in) :: verbose, is_seed
        if (is_seed) then
            call set_rng_seed (loop%local%rng, loop%local%var_list, ival, &
                verbose=verbose)
        else
            call var_entry_set_int (var, ival, is_known=.true., verbose=verbose, &
                model_name=model_name)
            if (var_entry_is_copy (var)) then
                call model_parameters_update (loop%local%model)
                call var_list_synchronize (loop%local%var_list, model_vars)
            end if
        end if
    end subroutine set_int
    function bounds_check_fails (step_type, var_type) result (fails)
        logical :: fails
        integer, intent(in) :: step_type, var_type
        fails = .false.
        select case (var_type)
        case (V_REAL)
            if (rstep == 0) then
                call msg_error ("Scan: step size equals zero, skipping")
                fails = .true.; return
            end if
            select case (step_type)
            case (STEP_MUL, STEP_DIV)
                if (rstep < 0) then
                    call msg_error ("Scan: multiplicative step < 0, skipping")
                    fails = .true.; return
                else if (rstep == 1) then
                    call msg_error ("Scan: multiplicative step = 1, skipping")

```

```

        fails = .true.; return
    else if (r1 == 0 .or. r2 == 0) then
        call msg_error ("Scan: " &
            // "boundary for multiplicative step is zero, skipping")
        fails = .true.; return
    end if
end select
case (V_INT)
    if (istep == 0) then
        call msg_error ("Scan: step size equals zero, skipping")
        fails = .true.; return
    end if
    select case (step_type)
    case (STEP_MUL, STEP_DIV)
        if (istep < 0) then
            call msg_error ("Scan: multiplicative step < 0, skipping")
            fails = .true.; return
        else if (istep == 1) then
            call msg_error ("Scan: multiplicative step = 1, skipping")
            fails = .true.; return
        else if (i1 == 0 .or. i2 == 0) then
            call msg_error ("Scan: " &
                // "boundary for multiplicative step is zero, skipping")
            fails = .true.; return
        end if
    end select
end select
end function bounds_check_fails
end subroutine cmd_scan_execute

```

Conditionals

Conditionals are implemented as a list that is compiled and evaluated recursively; this allows for a straightforward representation of `else if` constructs. A `cmd_if_t` object can hold either an `else_if` clause which is another object of this type, or an `else_body`, but not both.

If- or else-bodies are no scoping units, so all data remain global and no copy-in copy-out is needed.

```

<Commands: types>+≡
    type :: cmd_if_t
    private
    type(eval_tree_t) :: if_lexpr
    type(command_list_t), pointer :: if_body => null ()
    type(cmd_if_t), dimension(:), pointer :: elsif_cond => null ()
    type(command_list_t), pointer :: else_body => null ()
end type cmd_if_t

```

Finalizer.

```

<Commands: procedures>+≡
    recursive subroutine cmd_if_final (cond)
        type(cmd_if_t), intent(inout) :: cond
        integer :: i
    end subroutine cmd_if_final

```

```

call eval_tree_final (cond%if_lexpr)
if (associated (cond%if_body)) then
  call command_list_final (cond%if_body)
  deallocate (cond%if_body)
end if
if (associated (cond%elsif_cond)) then
  do i = 1, size (cond%elsif_cond)
    call cmd_if_final (cond%elsif_cond(i))
  end do
  deallocate (cond%elsif_cond)
end if
if (associated (cond%else_body)) then
  call command_list_final (cond%else_body)
  deallocate (cond%else_body)
end if
end subroutine cmd_if_final

```

Output.

(Commands: procedures)+≡

```

recursive subroutine cmd_if_write (cond, unit, indent)
  type(cmd_if_t), intent(in) :: cond
  integer, intent(in), optional :: unit, indent
  integer :: u, ind, i
  u = output_unit (unit); if (u < 0) return
  call write_indent (u, indent)
  write (u, "(A)", advance="no") "if "
  call eval_tree_write (cond%if_lexpr, unit=unit)
  call write_indent (u, indent)
  write (u, "(A)") " then"
  ind = 2; if (present (indent)) ind = ind + indent
  if (associated (cond%if_body)) then
    call write_indent (u, ind)
    call command_list_write (cond%if_body, unit, ind)
  end if
  if (associated (cond%elsif_cond)) then
    do i = 1, size (cond%elsif_cond)
      if (associated (cond%elsif_cond(i)%if_body)) then
        call write_indent (u, indent)
        write (u, "(A)", advance="no") "elsif "
        call eval_tree_write (cond%elsif_cond(i)%if_lexpr, unit=unit)
        call write_indent (u, indent)
        write (u, "(A)") " then"
        call write_indent (u, ind)
        call command_list_write (cond%elsif_cond(i)%if_body, unit, ind)
      end if
    end do
  end if
  if (associated (cond%else_body)) then
    call write_indent (u, indent)
    write (u, "(A)", advance="no") "else"
    write (u, "(1x,A,1x)") "else"
    call write_indent (u, ind)
    call command_list_write (cond%else_body, unit, ind)
    call write_indent (u, ind)
  end if
end subroutine cmd_if_write

```

```

    else
        write (u, *)
    end if
end subroutine cmd_if_write

```

Compile the conditional.

(Commands: procedures)+≡

```

recursive subroutine cmd_if_compile (cond, pn, global)
    type(cmd_if_t), pointer :: cond
    type(parse_node_t), intent(in), target :: pn
    type(rt_data_t), intent(inout), target :: global
    type(parse_node_t), pointer :: pn_lexpr, pn_body
    type(parse_node_t), pointer :: pn_elseif_clauses, pn_cmd_elseif
    type(parse_node_t), pointer :: pn_else_clause, pn_cmd_else
    integer :: i, n_elseif
    allocate (cond)
    pn_lexpr => parse_node_get_sub_ptr (pn, 2)
    call eval_tree_init_lexpr (cond%if_lexpr, pn_lexpr, global%var_list)
    pn_body => parse_node_get_next_ptr (pn_lexpr, 2)
    select case (char (parse_node_get_rule_key (pn_body)))
    case ("command_list")
        allocate (cond%if_body)
        call command_list_compile (cond%if_body, pn_body, global)
        pn_elseif_clauses => parse_node_get_next_ptr (pn_body)
    case default
        pn_elseif_clauses => pn_body
    end select
    select case (char (parse_node_get_rule_key (pn_elseif_clauses)))
    case ("elseif_clauses")
        n_elseif = parse_node_get_n_sub (pn_elseif_clauses)
        allocate (cond%elseif_cond (n_elseif))
        pn_cmd_elseif => parse_node_get_sub_ptr (pn_elseif_clauses)
        do i = 1, n_elseif
            pn_lexpr => parse_node_get_sub_ptr (pn_cmd_elseif, 2)
            call eval_tree_init_lexpr &
                (cond%elseif_cond(i)%if_lexpr, pn_lexpr, global%var_list)
            pn_body => parse_node_get_next_ptr (pn_lexpr, 2)
            if (associated (pn_body)) then
                allocate (cond%elseif_cond(i)%if_body)
                call command_list_compile &
                    (cond%elseif_cond(i)%if_body, pn_body, global)
            end if
            pn_cmd_elseif => parse_node_get_next_ptr (pn_cmd_elseif)
        end do
        pn_else_clause => parse_node_get_next_ptr (pn_elseif_clauses)
    case default
        pn_else_clause => pn_elseif_clauses
    end select
    select case (char (parse_node_get_rule_key (pn_else_clause)))
    case ("else_clause")
        pn_cmd_else => parse_node_get_sub_ptr (pn_else_clause)
        pn_body => parse_node_get_sub_ptr (pn_cmd_else, 2)
        if (associated (pn_body)) then
            allocate (cond%else_body)

```

```

        call command_list_compile (cond%else_body, pn_body, global)
    end if
end select
end subroutine cmd_if_compile

```

(Recursively) execute the condition. Context remains global in all cases.

(Commands: procedures)+≡

```

recursive subroutine cmd_if_execute (cond, global)
    type(cmd_if_t), intent(inout), target :: cond
    type(rt_data_t), intent(inout), target :: global
    integer :: i
    call eval_tree_evaluate (cond%if_lexpr)
    if (eval_tree_result_is_known (cond%if_lexpr)) then
        if (eval_tree_get_log (cond%if_lexpr)) then
            if (associated (cond%if_body)) then
                call command_list_execute (cond%if_body, global)
            end if
            return
        end if
    else
        call error_undecided ()
        return
    end if
    if (associated (cond%elsif_cond)) then
        SCAN_ELSEIF: do i = 1, size (cond%elsif_cond)
            call eval_tree_evaluate (cond%elsif_cond(i)%if_lexpr)
            if (eval_tree_result_is_known (cond%elsif_cond(i)%if_lexpr)) then
                if (eval_tree_get_log (cond%elsif_cond(i)%if_lexpr)) then
                    if (associated (cond%elsif_cond(i)%if_body)) then
                        call command_list_execute &
                            (cond%elsif_cond(i)%if_body, global)
                    end if
                end if
            end if
        end do SCAN_ELSEIF
    end if
    if (associated (cond%else_body)) then
        call command_list_execute (cond%else_body, global)
    end if
contains
    subroutine error_undecided ()
        call msg_error ("Undefined result of conditional expression: " &
            // "neither branch will be executed")
    end subroutine error_undecided
end subroutine cmd_if_execute

```

Include another command-list file

The include command allocates a local parse tree. This must not be deleted before the command object itself is deleted, since pointers may point to subobjects of it.

```
<Commands: types>+≡
  type :: cmd_include_t
  private
  type(string_t) :: file
  type(command_list_t), pointer :: command_list => null ()
  type(parse_tree_t) :: parse_tree
end type cmd_include_t
```

Finalizer: delete the command list.

```
<Commands: procedures>+≡
  subroutine cmd_include_final (include)
    type(cmd_include_t), intent(inout) :: include
    call parse_tree_final (include%parse_tree)
    if (associated (include%command_list)) then
      call command_list_final (include%command_list)
      deallocate (include%command_list)
    end if
  end subroutine cmd_include_final
```

Output: Write file contents as if they were part of the present file (but indented).

```
<Commands: procedures>+≡
  subroutine cmd_include_write (include, unit, indent)
    type(cmd_include_t), intent(in) :: include
    integer, intent(in), optional :: unit, indent
    integer :: u
    u = output_unit (unit); if (u < 0) return
    call write_indent (u, indent)
    write (u, "(A)")  "! begin include file " &
      // '""' // char (include%file) // '""'
    call command_list_write (include%command_list, unit, indent)
    call write_indent (u, indent)
    write (u, "(A)")  "! end include file " &
      // '""' // char (include%file) // '""'
  end subroutine cmd_include_write
```

Compile file contents: First parse the file, then immediately compile its contents. Use the global data set.

```
<Commands: procedures>+≡
  subroutine cmd_include_compile (include, pn, global)
    type(cmd_include_t), pointer :: include
    type(parse_node_t), intent(in), target :: pn
    type(rt_data_t), intent(inout), target :: global
    type(parse_node_t), pointer :: pn_arg, pn_file
    type(string_t) :: file
    logical :: exist
    integer :: u
    type(stream_t) :: stream
```

```

type(lexer_t) :: lexer
pn_arg => parse_node_get_sub_ptr (pn, 2)
pn_file => parse_node_get_sub_ptr (pn_arg)
allocate (include)
file = parse_node_get_string (pn_file)
inquire (file=char(file), exist=exist)
if (exist) then
    include%file = file
else
    include%file = global%os_data%whizard_cutspath // "/" // file
    inquire (file=char(include%file), exist=exist)
    if (.not. exist) then
        call msg_error ("Include file '" // char (file) // "' not found")
        return
    end if
end if
u = free_unit ()
open (unit=u, file=char(include%file), action="read", status="old")
call lexer_init_cmd_list (lexer)
call stream_init (stream, u)
call parse_tree_init (include%parse_tree, syntax_cmd_list, lexer, stream)
call stream_final (stream)
call lexer_final (lexer)
close (u)
allocate (include%command_list)
call command_list_compile &
    (include%command_list, parse_tree_get_root_ptr (include%parse_tree), &
    global)
end subroutine cmd_include_compile

```

Execute file contents in the global context.

(Commands: procedures)+≡

```

subroutine cmd_include_execute (include, global)
    type(cmd_include_t), intent(inout), target :: include
    type(rt_data_t), intent(inout), target :: global
    if (associated (include%command_list)) then
        call msg_message &
            ("Including script file '" // char (include%file) // "'")
        call command_list_execute (include%command_list, global)
    end if
end subroutine cmd_include_execute

```

Quit command execution

The code is the return code of the whole program if it is terminated by this command.

(Commands: types)+≡

```

type :: cmd_quit_t
private
    logical :: has_code = .false.
    type(eval_tree_t) :: code_expr
end type cmd_quit_t

```

Finalizer.

```
<Commands: procedures>+≡
subroutine cmd_quit_final (quit)
  type(cmd_quit_t), intent(inout) :: quit
  call eval_tree_final (quit%code_expr)
end subroutine cmd_quit_final
```

Output.

```
<Commands: procedures>+≡
subroutine cmd_quit_write (quit, unit, indent)
  type(cmd_quit_t), intent(in) :: quit
  integer, intent(in), optional :: unit, indent
  integer :: u
  u = output_unit (unit); if (u < 0) return
  call write_indent (u, indent)
  write (u, "(A)") "quit"
end subroutine cmd_quit_write
```

Compile: allocate a quit object which serves as a placeholder.

```
<Commands: procedures>+≡
subroutine cmd_quit_compile (quit, pn, global)
  type(cmd_quit_t), pointer :: quit
  type(parse_node_t), intent(in), target :: pn
  type(rt_data_t), intent(inout), target :: global
  type(parse_node_t), pointer :: pn_arg, pn_expr
  allocate (quit)
  pn_arg => parse_node_get_sub_ptr (pn, 2)
  if (associated (pn_arg)) then
    pn_expr => parse_node_get_sub_ptr (pn_arg)
    call eval_tree_init_expr (quit%code_expr, pn_expr, global%var_list)
    quit%has_code = .true.
  end if
end subroutine cmd_quit_compile
```

Execute: The quit command does not execute anything, it just stops command execution. This is achieved by setting quit flag and quit code in the global variable list. However, the return code, if present, is an expression which has to be evaluated.

```
<Commands: procedures>+≡
subroutine cmd_quit_execute (quit, global)
  type(cmd_quit_t), intent(inout), target :: quit
  type(rt_data_t), intent(inout), target :: global
  if (quit%has_code) then
    call eval_tree_evaluate (quit%code_expr)
    if (eval_tree_result_is_known (quit%code_expr)) then
      global%quit_code = eval_tree_get_int (quit%code_expr)
    else
      call msg_error ("Undefined return code of quit/exit command")
    end if
  end if
end if
```

```

    global%quit = .true.
end subroutine cmd_quit_execute

```

17.1.8 The command list

The command list holds a list of commands and relevant global data.

```

<Commands: public>+≡
    public :: command_list_t

<Commands: types>+≡
    type :: command_list_t
    private
    type(command_t), pointer :: first => null ()
    type(command_t), pointer :: last => null ()
end type command_list_t

```

Append a new command.

```

<Commands: procedures>+≡
    subroutine command_list_append (cmd_list, command)
    type(command_list_t), intent(inout) :: cmd_list
    type(command_t), intent(in), target :: command
    if (associated (cmd_list%last)) then
        cmd_list%last%next => command
    else
        cmd_list%first => command
    end if
    cmd_list%last => command
end subroutine command_list_append

```

Finalize.

```

<Commands: public>+≡
    public :: command_list_final

<Commands: procedures>+≡
    recursive subroutine command_list_final (cmd_list)
    type(command_list_t), intent(inout) :: cmd_list
    type(command_t), pointer :: command
    do while (associated (cmd_list%first))
        command => cmd_list%first
        cmd_list%first => cmd_list%first%next
        call command_final (command)
        deallocate (command)
    end do
    cmd_list%last => null ()
end subroutine command_list_final

```

Output.

```

<Commands: public>+≡
    public :: command_list_write

```

```

<Commands: procedures>+≡
recursive subroutine command_list_write (cmd_list, unit, indent)
  type(command_list_t), intent(in) :: cmd_list
  integer, intent(in), optional :: unit, indent
  type(command_t), pointer :: command
  command => cmd_list%first
  do while (associated (command))
    if (present (indent)) then
      call command_write (command, unit, indent + 1)
    else
      call command_write (command, unit, 1)
    end if
    command => command%next
  end do
end subroutine command_list_write

```

17.1.9 Compiling the parse tree

Transform a parse tree into a command list. Initialization is assumed to be done.

```

<Commands: public>+≡
public :: command_list_compile

<Commands: procedures>+≡
recursive subroutine command_list_compile (cmd_list, pn, global)
  type(command_list_t), intent(inout), target :: cmd_list
  type(parse_node_t), intent(in), target :: pn
  type(rt_data_t), intent(inout), target :: global
  type(parse_node_t), pointer :: pn_cmd
  type(command_t), pointer :: command
  integer :: i
  pn_cmd => parse_node_get_sub_ptr (pn)
  do i = 1, parse_node_get_n_sub (pn)
    call command_compile (command, pn_cmd, global)
    call command_list_append (cmd_list, command)
    pn_cmd => parse_node_get_next_ptr (pn_cmd)
  end do
end subroutine command_list_compile

```

17.1.10 Executing the command list

```

<Commands: public>+≡
public :: command_list_execute

<Commands: procedures>+≡
recursive subroutine command_list_execute (cmd_list, global, print)
  type(command_list_t), intent(in) :: cmd_list
  type(rt_data_t), intent(inout), target :: global
  logical, intent(in), optional :: print
  type(command_t), pointer :: command
  command => cmd_list%first
  COMMAND_COND: do while (associated (command))

```

```

        call command_execute (command, global, print)
        if (global%quit) exit COMMAND_COND
        command => command%next
    end do COMMAND_COND
end subroutine command_list_execute

```

17.1.11 Command list syntax

```

<Commands: public>+≡
    public :: syntax_cmd_list

<Commands: variables>≡
    type(syntax_t), target, save :: syntax_cmd_list

<Commands: public>+≡
    public :: syntax_cmd_list_init

<Commands: procedures>+≡
    subroutine syntax_cmd_list_init ()
        type(ifile_t) :: ifile
        call define_cmd_list_syntax (ifile)
        call syntax_init (syntax_cmd_list, ifile)
        call ifile_final (ifile)
    end subroutine syntax_cmd_list_init

<Commands: public>+≡
    public :: syntax_cmd_list_final

<Commands: procedures>+≡
    subroutine syntax_cmd_list_final ()
        call syntax_final (syntax_cmd_list)
    end subroutine syntax_cmd_list_final

<Commands: procedures>+≡
    subroutine define_cmd_list_syntax (ifile)
        type(ifile_t), intent(inout) :: ifile
        call ifile_append (ifile, "SEQ command_list = command*")
        call ifile_append (ifile, "ALT command = " &
            // "cmd_model | cmd_library | cmd_iterations | cmd_seed | " &
            // "cmd_var | cmd_slha | cmd_show | cmd_expect | cmd_echo | " &
            // "cmd_cuts | cmd_weight | cmd_scale | " &
            // "cmd_beams | cmd_integrate | " &
            // "cmd_observable | cmd_histogram | cmd_plot | cmd_clear | " &
            // "cmd_analysis | cmd_write_analysis | " &
            // "cmd_unstable | cmd_simulate | " &
            // "cmd_process | cmd_compile | cmd_load | cmd_exec | " &
            // "cmd_scan | cmd_if | cmd_include | cmd_quit")
        call ifile_append (ifile, "GRO options = '{' local_command_list '}'")
        call ifile_append (ifile, "SEQ local_command_list = local_command*")
        call ifile_append (ifile, "ALT local_command = " &
            // "cmd_model | cmd_library | cmd_iterations | cmd_seed | " &
            // "cmd_var | cmd_slha | cmd_show | " &
            // "cmd_cuts | cmd_weight | cmd_scale | " &

```

```

// "cmd_beams | " &
// "cmd_observable | cmd_histogram | cmd_plot | " &
// "cmd_analysis | cmd_clear | cmd_write_analysis")
call ifile_append (ifile, "SEQ cmd_model = model '=' model_name")
call ifile_append (ifile, "KEY model")
call ifile_append (ifile, "ALT model_name = model_id | string_literal")
call ifile_append (ifile, "IDE model_id")
call ifile_append (ifile, "SEQ cmd_library = library '=' lib_name")
call ifile_append (ifile, "KEY library")
call ifile_append (ifile, "ALT lib_name = lib_id | string_literal")
call ifile_append (ifile, "IDE lib_id")
call ifile_append (ifile, "ALT cmd_var = " &
// "cmd_num | cmd_cmplx | cmd_real | cmd_int | cmd_log | cmd_string | cmd_alias")
call ifile_append (ifile, "SEQ cmd_num = var_name '=' expr")
call ifile_append (ifile, "SEQ cmd_cmplx = cmplx var_name '=' expr")
call ifile_append (ifile, "SEQ cmd_real = real var_name '=' expr")
call ifile_append (ifile, "SEQ cmd_int = int var_name '=' expr")
call ifile_append (ifile, "SEQ cmd_log = '?' var_name '=' lexpr")
call ifile_append (ifile, "SEQ cmd_string = '$' var_name '=' sexpr") ! $
call ifile_append (ifile, "SEQ cmd_alias = alias var_name '=' cexpr")
call ifile_append (ifile, "SEQ cmd_slha = slha_action slha_arg options?")
call ifile_append (ifile, "ALT slha_action = " &
// "read_slha | write_slha")
call ifile_append (ifile, "KEY read_slha")
call ifile_append (ifile, "KEY write_slha")
call ifile_append (ifile, "ARG slha_arg = ( string_literal )")
call ifile_append (ifile, "SEQ cmd_show = show show_arg?")
call ifile_append (ifile, "KEY show")
call ifile_append (ifile, "ARG show_arg = ( var_generic* )")
call ifile_append (ifile, "ALT var_generic = " &
// "model | beams | results | unstable | real | int | " &
// "cuts | weight | scale | analysis | expect | " &
// "library_spec | " &
// "intrinsic | result_var | " &
// "log_var | alias_var | string_var | num_var")
call ifile_append (ifile, "KEY results")
call ifile_append (ifile, "KEY intrinsic")
call ifile_append (ifile, "SEQ library_spec = library lib_name?")
call ifile_append (ifile, "SEQ result_var = result_key result_arg?")
call ifile_append (ifile, "SEQ log_var = '?' log_var_spec?")
call ifile_append (ifile, "ALT log_var_spec = log_val | variable")
call ifile_append (ifile, "GRO log_val = ( lexpr )")
call ifile_append (ifile, "SEQ alias_var = alias alias_var_spec?")
call ifile_append (ifile, "ALT alias_var_spec = alias_val | variable")
call ifile_append (ifile, "GRO alias_val = ( cexpr )")
call ifile_append (ifile, "SEQ string_var = '$' string_var_spec?") ! $
call ifile_append (ifile, "ALT string_var_spec = string_val | variable")
call ifile_append (ifile, "GRO string_val = ( sexpr )")
call ifile_append (ifile, "SEQ num_var = num_var_spec")
call ifile_append (ifile, "ALT num_var_spec = num_val | variable")
call ifile_append (ifile, "GRO num_val = ( expr )")
call ifile_append (ifile, "SEQ cmd_expect = expect expect_arg options?")
call ifile_append (ifile, "KEY expect")
call ifile_append (ifile, "ARG expect_arg = ( lexpr )")

```

```

call ifile_append (ifile, "SEQ cmd_cuts = cuts '=' lexpr")
call ifile_append (ifile, "SEQ cmd_echo = echo echo_arg?")
call ifile_append (ifile, "KEY echo")
call ifile_append (ifile, "ARG echo_arg = ( sexpr* )")
call ifile_append (ifile, "SEQ cmd_weight = weight '=' expr")
call ifile_append (ifile, "SEQ cmd_scale = scale '=' expr")
call ifile_append (ifile, "KEY cuts")
call ifile_append (ifile, "KEY weight")
call ifile_append (ifile, "KEY scale")
call ifile_append (ifile, "SEQ cmd_process = process process_id '=' " &
    // "prt_list '->' prt_list options?")
call ifile_append (ifile, "KEY process")
call ifile_append (ifile, "KEY '->")
call ifile_append (ifile, "LIS prt_list = cexpr+")
call ifile_append (ifile, "SEQ cmd_compile = compile_cmd options?")
call ifile_append (ifile, "SEQ compile_cmd = compile_clause compile_arg?")
call ifile_append (ifile, "SEQ compile_clause = compile_exec_name_spec?")
call ifile_append (ifile, "KEY compile")
call ifile_append (ifile, "SEQ exec_name_spec = as exec_name")
call ifile_append (ifile, "KEY as")
call ifile_append (ifile, "ALT exec_name = exec_id | string_literal")
call ifile_append (ifile, "IDE exec_id")
call ifile_append (ifile, "ARG compile_arg = ( lib_name* )")
call ifile_append (ifile, "SEQ cmd_load = load load_arg?")
call ifile_append (ifile, "KEY load")
call ifile_append (ifile, "ARG load_arg = ( lib_name* )")
call ifile_append (ifile, "SEQ cmd_exec = exec exec_arg")
call ifile_append (ifile, "KEY exec")
call ifile_append (ifile, "ARG exec_arg = ( sexpr )")
call ifile_append (ifile, "SEQ cmd_beams = beams '=' beam_def")
call ifile_append (ifile, "KEY beams")
call ifile_append (ifile, "SEQ beam_def = beam_spec strfun_seq*")
call ifile_append (ifile, "SEQ beam_spec = beam_list options?")
call ifile_append (ifile, "LIS beam_list = cexpr, cexpr?")
call ifile_append (ifile, "SEQ strfun_seq = '->' strfun_pair")
call ifile_append (ifile, "LIS strfun_pair = strfun_def, strfun_def?")
call ifile_append (ifile, "SEQ strfun_def = strfun_id options?")
call ifile_append (ifile, "ALT strfun_id = none | lhpdf | isr | epa")
call ifile_append (ifile, "KEY none")
call ifile_append (ifile, "KEY lhpdf")
call ifile_append (ifile, "KEY isr")
call ifile_append (ifile, "KEY epa")
call ifile_append (ifile, "SEQ cmd_integrate = " &
    // "integrate proc_arg options?")
call ifile_append (ifile, "KEY integrate")
call ifile_append (ifile, "ARG proc_arg = ( proc_id* )")
call ifile_append (ifile, "IDE proc_id")
call ifile_append (ifile, "SEQ cmd_seed = seed '=' expr")
call ifile_append (ifile, "KEY seed")
call ifile_append (ifile, "SEQ cmd_iterations = " &
    // "iterations '=' iterations_list")
call ifile_append (ifile, "KEY iterations")
call ifile_append (ifile, "LIS iterations_list = iterations_spec+")
call ifile_append (ifile, "SEQ iterations_spec = expr ':' expr")

```

```

call ifile_append (ifile, "SEQ cmd_observable = observable analysis_tag")
call ifile_append (ifile, "KEY observable")
call ifile_append (ifile, "SEQ cmd_histogram = " &
// "histogram analysis_tag histogram_arg")
call ifile_append (ifile, "KEY histogram")
call ifile_append (ifile, "ARG histogram_arg = (expr, expr, expr)")
call ifile_append (ifile, "SEQ cmd_plot = " &
// "plot analysis_tag plot_arg")
call ifile_append (ifile, "KEY plot")
call ifile_append (ifile, "ARG plot_arg = (expr, expr)")
call ifile_append (ifile, "SEQ cmd_analysis = analysis '=' lexpr")
call ifile_append (ifile, "KEY analysis")
call ifile_append (ifile, "SEQ cmd_write_analysis = " &
// "write_analysis write_analysis_arg?")
call ifile_append (ifile, "KEY write_analysis")
call ifile_append (ifile, "ARG write_analysis_arg = ( analysis_tag* )")
call ifile_append (ifile, "SEQ cmd_clear = clear clear_arg?")
call ifile_append (ifile, "KEY clear")
call ifile_append (ifile, "ARG clear_arg = ( clear_obj* )")
call ifile_append (ifile, "ALT clear_obj = " &
// "iterations | cuts | weight | scale | analysis | expect | " &
// "analysis_tag")
call ifile_append (ifile, "SEQ cmd_unstable = unstable cexpr unstable_arg")
call ifile_append (ifile, "KEY unstable")
call ifile_append (ifile, "ARG unstable_arg = ( proc_id+ )")
call ifile_append (ifile, "SEQ cmd_simulate = " &
// "simulate proc_arg options?")
call ifile_append (ifile, "KEY simulate")
call ifile_append (ifile, "SEQ cmd_scan = scan_spec scan_body?")
call ifile_append (ifile, "SEQ scan_spec = scan scan_command?")
call ifile_append (ifile, "KEY scan")
call ifile_append (ifile, "ALT scan_command = " &
// "cmd_model_list | cmd_library_list | " &
// "cmd_seed_list | " &
// "cmd_cuts_list | cmd_weight_list | cmd_scale_list | " &
// "cmd_analysis_list | " &
// "cmd_var_list")
call ifile_append (ifile, "SEQ cmd_model_list = model model_list_arg")
call ifile_append (ifile, "ARG model_list_arg = ( model_name* )")
call ifile_append (ifile, "SEQ cmd_library_list = library library_list_arg")
call ifile_append (ifile, "ARG library_list_arg = ( lib_name* )")
call ifile_append (ifile, "SEQ cmd_seed_list = seed num_step_list_arg")
call ifile_append (ifile, "ARG num_step_list_arg = ( num_steps* )")
call ifile_append (ifile, "SEQ num_steps = expr range_spec?")
call ifile_append (ifile, "SEQ range_spec = '->' expr step_spec?")
call ifile_append (ifile, "SEQ step_spec = step_op expr")
call ifile_append (ifile, "ALT step_op = '/+' | '/-' | '/*' | '//")
call ifile_append (ifile, "KEY '/+'")
call ifile_append (ifile, "KEY '/-'")
call ifile_append (ifile, "KEY '/*'")
! call ifile_append (ifile, "KEY '//")
call ifile_append (ifile, "ALT cmd_var_list = " &
// "log_list | real_list | int_list | string_list | " &
// "alias_list | num_list")

```

```

call ifile_append (ifile, "SEQ log_list = '?' variable log_list_arg")
call ifile_append (ifile, "ARG log_list_arg = ( lexpr* )")
call ifile_append (ifile, "SEQ real_list = real variable num_step_list_arg")
call ifile_append (ifile, "SEQ int_list = int variable num_step_list_arg")
call ifile_append (ifile, "SEQ string_list = '$' variable " &
// "string_list_arg") !$
call ifile_append (ifile, "ARG string_list_arg = ( sexpr* )")
call ifile_append (ifile, "SEQ alias_list = alias variable alias_list_arg")
call ifile_append (ifile, "ARG alias_list_arg = ( cexpr* )")
call ifile_append (ifile, "SEQ num_list = variable num_step_list_arg")
call ifile_append (ifile, "SEQ cmd_cuts_list = cuts log_list_arg")
call ifile_append (ifile, "SEQ cmd_weight_list = weight num_list_arg")
call ifile_append (ifile, "SEQ cmd_scale_list = scale num_list_arg")
call ifile_append (ifile, "ARG num_list_arg = ( expr* )")
call ifile_append (ifile, "SEQ cmd_analysis_list = analysis log_list_arg")
call ifile_append (ifile, "GRO scan_body = '{' command_list '}'")
call ifile_append (ifile, "SEQ cmd_if = " &
// "if lexpr then command_list elsif_clauses else_clause endif")
call ifile_append (ifile, "SEQ elsif_clauses = cmd_elseif*")
call ifile_append (ifile, "SEQ cmd_elseif = elsif lexpr then command_list")
call ifile_append (ifile, "KEY elsif")
call ifile_append (ifile, "SEQ else_clause = cmd_else?")
call ifile_append (ifile, "SEQ cmd_else = else command_list")
call ifile_append (ifile, "SEQ cmd_include = include include_arg")
call ifile_append (ifile, "KEY include")
call ifile_append (ifile, "ARG include_arg = ( string_literal )")
call ifile_append (ifile, "SEQ cmd_quit = quit_cmd quit_arg?")
call ifile_append (ifile, "ALT quit_cmd = quit | exit")
call ifile_append (ifile, "KEY quit")
call ifile_append (ifile, "KEY exit")
call ifile_append (ifile, "ARG quit_arg = ( expr )")
call define_expr_syntax (ifile, particles=.true., analysis=.true.)
end subroutine define_cmd_list_syntax

```

<Commands: public>+≡

```
public :: lexer_init_cmd_list
```

<Commands: procedures>+≡

```

subroutine lexer_init_cmd_list (lexer)
  type(lexer_t), intent(out) :: lexer
  call lexer_init (lexer, &
    comment_chars = "#!", &
    quote_chars = "'", &
    quote_match = "'", &
    single_chars = "()[]{},:&%?@$@", &
    special_class = (/ "+-*/^<>=~" /) , &
    keyword_list = syntax_get_keyword_list_ptr (syntax_cmd_list))
end subroutine lexer_init_cmd_list

```

17.1.12 Test

<Commands: public>+≡

```
public :: command_test
```

```

<Commands: procedures>+≡
subroutine command_test ()
  integer :: u
  type(stream_t) :: stream
  type(lexer_t) :: lexer
  type(parse_tree_t) :: parse_tree
  type(command_list_t), target :: command_list
  type(rt_data_t), target :: global
  print *, "* Initialization"
  call os_data_init (global%os_data)
  global%os_data%fcflags = "-gline -C=all"
  allocate (global%rng)
  call tao_random_create (global%rng, 0)
  call syntax_model_file_init ()
  call syntax_phs_forest_init ()
  call syntax_pexpr_init ()
  call syntax_cmd_list_init ()
  call lexer_init_cmd_list (lexer)
  print *, "* Open 'whizard.sin'"
  u = free_unit ()
  open (unit=u, file="whizard.sin")
  call stream_init (stream, u)
  print *, "* Parse"
  call parse_tree_init (parse_tree, syntax_cmd_list, lexer, stream)
  call stream_final (stream)
  close (u)
  call parse_tree_write (parse_tree)
  print *
  print *, "* Compile command list"
  if (associated (parse_tree_get_root_ptr (parse_tree))) then
    call command_list_compile &
      (command_list, parse_tree_get_root_ptr (parse_tree), global)
  end if
  print *, "* Command list:"
  call command_list_write (command_list)
  print *
  print *, "* Execute command list"
  call command_list_execute (command_list, global, print=.true.)
  print *
  print *, "* Cleanup"
  call command_list_final (command_list)
  call process_store_final ()
  call model_list_final ()
  call syntax_cmd_list_final ()
  call syntax_pexpr_final ()
  call syntax_phs_forest_final ()
  call syntax_model_file_final ()
end subroutine command_test

```

17.2 Toplevel module WHIZARD

<whizard.f90>≡

```

<File header>

module whizard

<Use file utils>
<Use strings>
  use limits, only: EOF, BACKSLASH !NODEP!
  use diagnostics !NODEP!
  use md5
  use os_interface
  use lexers
  use parser
  use colors
  use state_matrices
  use analysis
  use variables
  use expressions
  use models
  use evaluators
  use pbs_forests
  use hard_interactions
  use processes
  use decays
  use process_libraries
  use slha_interface
  use commands
  use vamp !NODEP!

<Standard module head>

<WHIZARD: public>

<WHIZARD: variables>

  save

contains

<WHIZARD: procedures>

end module whizard

```

17.2.1 Initialization and finalization

These procedures initialize and finalize global variables. Most of them are collected in the `global` data record located here, the others are syntax tables located in various modules, which do not change during program execution. Furthermore, there is a global model list and a global process store, which get filled during program execution but are finalized here.

During initialization, we can preload a default model and initialize a default library for setting up processes. The default library is loaded if requested by the setup. Further libraries can be loaded as specified by command-line flags.

<WHIZARD: variables>≡

```

    type(rt_data_t), target :: global
<WHIZARD: public>≡
    public :: whizard_init
<WHIZARD: procedures>≡
    subroutine whizard_init &
        (preload_model, preload_libs, default_lib, &
         rebuild_library, rebuild_phs, rebuild_grids, recompile_library)
    type(string_t), intent(in) :: preload_model, preload_libs
    type(string_t), intent(in) :: default_lib
    logical, intent(in) :: rebuild_library, rebuild_phs, rebuild_grids
    logical, intent(in) :: recompile_library
    type(string_t) :: filename, libname, libs
    type(var_list_t), pointer :: model_vars
    call rt_data_global_init (global)
    call var_list_append_log &
        (global%var_list, var_str ("?rebuild_library"), rebuild_library, &
         intrinsic=.true.)
    call var_list_append_log &
        (global%var_list, var_str ("?rebuild_phase_space"), rebuild_phs, &
         intrinsic=.true.)
    call var_list_append_log &
        (global%var_list, var_str ("?rebuild_grids"), rebuild_grids, &
         intrinsic=.true.)
    call var_list_append_log &
        (global%var_list, var_str ("?recompile_library"), recompile_library, &
         intrinsic=.true.)
    call syntax_model_file_init ()
    call syntax_phs_forest_init ()
    call syntax_pexpr_init ()
    call syntax_slha_init ()
    call syntax_cmd_list_init ()
    call process_library_store_load_static &
        (global%os_data, global%prc_lib, global%model, global%var_list)
    libs = adjustl (preload_libs)
    SCAN_LIBS: do while (libs /= "")
        call split (libs, libname, " ")
        call process_library_store_append &
            (libname, global%os_data, global%prc_lib)
        call process_library_load &
            (global%prc_lib, global%os_data, global%model, global%var_list, &
             ignore=.true.)
    end do SCAN_LIBS
    if (.not. associated (global%prc_lib)) then
        call process_library_store_append &
            (default_lib, global%os_data, global%prc_lib)
        if (.not. (rebuild_library .or. recompile_library)) then
            call process_library_load (global%prc_lib, &
                global%os_data, global%model, global%var_list, ignore=.true.)
        else
            call var_list_set_string (global%var_list, &
                var_str ("$_library_name"), &
                process_library_get_name (global%prc_lib), is_known=.true.)
        end if
    end if

```

```

end if
if (.not. associated (global%model)) then
    filename = preload_model // ".mdl"
    call model_list_read_model &
        (preload_model, filename, global%os_data, global%model)
end if
if (associated (global%model)) then
    model_vars => model_get_var_list_ptr (global%model)
    call var_list_init_copies (global%var_list, model_vars)
    call var_list_synchronize &
        (global%var_list, model_vars, reset_pointers = .true.)
    call msg_message ("Using model: " &
        // char (model_get_name (global%model)))
    call var_list_set_string (global%var_list, var_str ("$model_name"), &
        model_get_name (global%model), is_known=.true.)
end if
end subroutine whizard_init

```

Apart from the global data which have been initialized above, the process and model lists need to be finalized.

```

<WHIZARD: public>+≡
    public :: whizard_final
<WHIZARD: procedures>+≡
    subroutine whizard_final ()
        call rt_data_global_final (global)
        call decay_store_final ()
        call process_store_final ()
        call model_list_final ()
        call syntax_cmd_list_final ()
        call syntax_slha_final ()
        call syntax_pexpr_final ()
        call syntax_phs_forest_final ()
        call syntax_model_file_final ()
    end subroutine whizard_final

```

17.2.2 Execute command lists

Process standard input as a command list. The whole input is read, compiled and executed as a whole.

```

<WHIZARD: public>+≡
    public :: whizard_process_stdin
<WHIZARD: procedures>+≡
    subroutine whizard_process_stdin (quit, quit_code)
        logical, intent(out) :: quit
        integer, intent(out) :: quit_code
        type(lexer_t) :: lexer
        type(stream_t) :: stream
        call msg_message ("Reading commands from standard input")
        call lexer_init_cmd_list (lexer)
        call stream_init (stream, 5)
    end subroutine whizard_process_stdin

```

```

    call whizard_process_stream (stream, lexer, quit, quit_code)
    call stream_final (stream)
    call lexer_final (lexer)
end subroutine whizard_process_stdin

```

Process a file as a command list.

```

<WHIZARD: public>+≡
    public :: whizard_process_file

<WHIZARD: procedures>+≡
    subroutine whizard_process_file (file, quit, quit_code)
        type(string_t), intent(in) :: file
        logical, intent(out) :: quit
        integer, intent(out) :: quit_code
        integer :: u
        type(lexer_t) :: lexer
        type(stream_t) :: stream
        logical :: exist
        call msg_message ("Reading commands from file '" // char (file) // "'")
        inquire (file=char(file), exist=exist)
        if (exist) then
            u = free_unit ()
            open (unit=u, file=char(file))
            call lexer_init_cmd_list (lexer)
            call stream_init (stream, u)
            call whizard_process_stream (stream, lexer, quit, quit_code)
            call stream_final (stream)
            call lexer_final (lexer)
            close (u)
        else
            call msg_error ("File '" // char (file) // "' not found")
        end if
    end subroutine whizard_process_file

```

```

<WHIZARD: procedures>+≡
    subroutine whizard_process_stream (stream, lexer, quit, quit_code)
        type(stream_t), intent(inout) :: stream
        type(lexer_t), intent(inout) :: lexer
        logical, intent(out) :: quit
        integer, intent(out) :: quit_code
        type(parse_tree_t) :: parse_tree
        type(command_list_t), target :: command_list
        call parse_tree_init (parse_tree, syntax_cmd_list, lexer, stream)
        ! call parse_tree_write (parse_tree)
        if (associated (parse_tree_get_root_ptr (parse_tree))) then
            call command_list_compile &
                (command_list, parse_tree_get_root_ptr (parse_tree), global)
        end if
        ! call command_list_write (command_list)
        ! call command_list_execute (command_list, global, print=.true.)
        call command_list_execute (command_list, global)
        call command_list_final (command_list)
        quit = global%quit
        quit_code = global%quit_code
    end subroutine whizard_process_stream

```

```
end subroutine whizard_process_stream
```

17.2.3 The WHIZARD shell

This procedure implements interactive mode. One line is processed at a time.

```
<WHIZARD: public>+≡
  public :: whizard_shell

<WHIZARD: procedures>+≡
  subroutine whizard_shell (quit_code)
    integer, intent(out) :: quit_code
    type(lexer_t) :: lexer
    type(stream_t) :: stream
    type(string_t) :: prompt1
    type(string_t) :: prompt2
    type(string_t) :: input
    type(string_t) :: extra
    integer :: last
    integer :: iostat
    logical :: mask_tmp
    logical :: quit
    call msg_message ("Launching interactive shell")
    call lexer_init_cmd_list (lexer)
    prompt1 = "whish? "
    prompt2 = "      > "
    COMMAND_LOOP: do
      call put (6, prompt1)
      call get (5, input, iostat=iostat)
      if (iostat > 0 .or. iostat == EOF) exit COMMAND_LOOP
      CONTINUE_INPUT: do
        last = len_trim (input)
        if (extract (input, last, last) /= BACKSLASH) exit CONTINUE_INPUT
        call put (6, prompt2)
        call get (5, extra, iostat=iostat)
        if (iostat > 0) exit COMMAND_LOOP
        input = replace (input, last, extra)
      end do CONTINUE_INPUT
      call stream_init (stream, input)
      mask_tmp = mask_fatal_errors
      mask_fatal_errors = .true.
      call whizard_process_stream (stream, lexer, quit, quit_code)
      msg_count = 0
      mask_fatal_errors = mask_tmp
      call stream_final (stream)
      if (quit) exit COMMAND_LOOP
    end do COMMAND_LOOP
    print *
    call lexer_final (lexer)
  end subroutine whizard_shell
```

17.2.4 Self-tests

This is for developers only, but needs a well-defined interface.

```
<WHIZARD: public>+≡
    public :: whizard_check
<WHIZARD: procedures>+≡
    subroutine whizard_check (check)
        type(string_t), intent(in) :: check
        call msg_message (repeat ('=', 76), 0)
        call msg_message ("Running self-test: " // char (check), 0)
        call msg_message (repeat ('-', 76), 0)
        select case (char (check))
            case ("md5"); call md5_test ()
            case ("colors"); call color_test ()
            case ("state_matrices"); call state_matrix_test ()
            case ("analysis"); call analysis_test ()
            case ("expressions"); call expressions_test ()
            case ("hard_interactions"); call hard_interaction_test (global%model)
            case ("evaluators"); call evaluator_test (global%model)
            case ("slha_interface"); call slha_test ()
            case default
                call msg_error ("Self-test '" // char (check) // "' not implemented.")
            end select
        end subroutine whizard_check
```

17.3 Driver program

The main program handles command options, initializes the environment, and runs WHIZARD in a particular mode (interactive, file, standard input).

```
<Limits: public parameters>+≡
    integer, parameter, public :: CMDLINE_ARG_LEN = 1000
<main.f90>≡
<File header>

    program main

<Use strings>
        use system_dependencies !NODEP!
        use limits, only: CMDLINE_ARG_LEN !NODEP!
        use diagnostics !NODEP!
        use whizard

        implicit none

        ! Main program variable declarations
        character(CMDLINE_ARG_LEN) :: arg
        character(2) :: option
        integer :: i, j, arg_len, arg_status
        logical :: look_for_options
        logical :: interactive
        type(string_t) :: files, this, model, libname, library, libraries, logfile
```

```

type(string_t) :: check, checks
logical :: rebuild_library, rebuild_phs, rebuild_grids
logical :: recompile_library

! Exit status
logical :: quit = .false.
integer :: quit_code = 0

! Initial values
look_for_options = .true.
interactive = .false.
files = ""
model = "SM"
libname = "processes"
library = ""
logfile = "whizard.log"
libraries = ""
check = ""
checks = ""
rebuild_library = .false.
rebuild_phs = .false.
rebuild_grids = .false.
recompile_library = .false.

! Read and process options
i = 0
SCAN_CMDLINE: do
  i = i + 1
  call get_command_argument (i, arg, arg_len, arg_status)
  select case (arg_status)
    case (0)
    case (-1)
      call msg_error (" Command argument truncated: '" // arg // "'")
    case default
      exit SCAN_CMDLINE
  end select
  if (look_for_options) then
    select case (arg(1:2))
      case ("--")
        select case (trim (arg))
          case ("--version")
            call print_version (); stop
          case ("--help")
            call print_usage (); stop
          case ("--check")
            check = get_option_value (i, trim (arg))
            checks = checks // " " // check
            cycle SCAN_CMDLINE
          case ("--interactive")
            interactive = .true.
            cycle SCAN_CMDLINE
          case ("--library")
            library = get_option_value (i, trim (arg))
            libraries = libraries // " " // library
        end select
      end select
    end if
  end do

```

```

        cycle SCAN_CMDLINE
    case ("--logfile")
        logfile = get_option_value (i, trim (arg))
        cycle SCAN_CMDLINE
    case ("--no-logfile")
        logfile = ""
        cycle SCAN_CMDLINE
    case ("--model")
        model = get_option_value (i, trim (arg))
        cycle SCAN_CMDLINE
    case ("--rebuild")
        rebuild_library = .true.
        rebuild_phs = .true.
        rebuild_grids = .true.
        cycle SCAN_CMDLINE
    case ("--rebuild-library")
        rebuild_library = .true.
        cycle SCAN_CMDLINE
    case ("--rebuild-phase-space")
        rebuild_phs = .true.
        cycle SCAN_CMDLINE
    case ("--rebuild-grids")
        rebuild_grids = .true.
        cycle SCAN_CMDLINE
    case ("--recompile")
        recompile_library = .true.
        cycle SCAN_CMDLINE
    case default
        call print_usage ()
        call msg_fatal ("Option '" // trim (arg) // "' not recognized")
    end select
end select
select case (arg(1:1))
case ("-")
    j = 1
    if (len_trim (arg) == 1) then
        look_for_options = .false.
    else
        SCAN_SHORT_OPTIONS: do
            j = j + 1
            if (j > len_trim (arg)) exit SCAN_SHORT_OPTIONS
            option = "-" // arg(j:j)
            select case (option)
            case ("-V")
                call print_version (); stop
            case ("-?", "-h")
                call print_usage (); stop
            case ("-i")
                interactive = .true.
                cycle SCAN_SHORT_OPTIONS
            case ("-l")
                if (j == len_trim (arg)) then
                    library = get_option_value (i, option)
                else

```

```

        library = trim (arg(j+1:))
    end if
    libraries = libraries // " " // library
    cycle SCAN_CMDLINE
case ("-L")
    if (j == len_trim (arg)) then
        logfile = get_option_value (i, option)
    else
        logfile = trim (arg(j+1:))
    end if
    cycle SCAN_CMDLINE
case ("-m")
    if (j < len_trim (arg)) call msg_fatal &
        ("Option '" // option // "' needs a value")
    model = get_option_value (i, option)
    cycle SCAN_CMDLINE
case ("-r")
    rebuild_library = .true.
    rebuild_phs = .true.
    rebuild_grids = .true.
    cycle SCAN_SHORT_OPTIONS
case default
    call print_usage ()
    call msg_fatal &
        ("Option '" // option // "' not recognized")
end select
end do SCAN_SHORT_OPTIONS
end if
case default
    files = files // " " // trim (arg)
end select
else
    files = files // " " // trim (arg)
end if
end do SCAN_CMDLINE

! Overall initialization
if (logfile /= "") call logfile_init (logfile)
call msg_banner ()
call whizard_init &
    (preload_model=model, preload_libs=libraries, default_lib=libname, &
    rebuild_library=rebuild_library, &
    rebuild_phs=rebuild_phs, &
    rebuild_grids=rebuild_grids, &
    recompile_library=recompile_library)

! Run any self-checks (and no commands)
if (checks /= "") then

    checks = trim (adjustl (checks))
    RUN_CHECKS: do while (checks /= "")
        call split (checks, check, " ")
        call whizard_check (check)
    end do RUN_CHECKS

```

```

! Process commands from standard input
else if (.not. interactive .and. files == "") then
    call whizard_process_stdin (quit, quit_code)

! Process commands from file
else
    files = trim (adjustl (files))
    SCAN_FILES: do while (files /= "")
        call split (files, this, " ")
        call whizard_process_file (this, quit, quit_code)
        if (quit) exit SCAN_FILES
    end do SCAN_FILES

end if

! Enter an interactive shell if requested
if (.not. quit .and. interactive) then
    call whizard_shell (quit_code)
end if

! Overall finalization
call whizard_final ()
call msg_terminate (quit_code = quit_code)

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
contains

function get_option_value (i, option) result (string)
    type(string_t) :: string
    integer, intent(inout) :: i
    character(*), intent(in) :: option
    character(CMDLINE_ARG_LEN) :: arg
    character(CMDLINE_ARG_LEN) :: arg_value
    integer :: arg_len, arg_status
    i = i + 1
    call get_command_argument (i, arg_value, arg_len, arg_status)
    select case (arg_status)
    case (0)
    case (-1)
        call msg_error (" Option value truncated: '" // arg // "'")
    case default
        call print_usage ()
        call msg_fatal (" Option '" // trim (option) // "' needs a value")
    end select
    select case (arg(1:1))
    case ("-")
        call print_usage ()
        call msg_fatal (" Option '" // trim (option) // "' needs a value")
    end select
    string = trim (arg_value)
end function get_option_value

subroutine print_version ()

```

```

    print "(A)", "WHIZARD " // WHIZARD_VERSION
    print "(A)", "Copyright (C) 1999-2010 Wolfgang Kilian, Thorsten Ohl, Juergen Reuter"
    print "(A)", "This is free software; see the source for copying conditions. There is NO"
    print "(A)", "warranty; not even for MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE."
    print *
end subroutine print_version

subroutine print_usage ()
    print "(A)", "WHIZARD " // WHIZARD_VERSION
    print "(A)", "Usage: whizard [OPTIONS] [FILE]"
    print "(A)", "Run WHIZARD with the command list taken from FILE(s)"
    print "(A)", "Options:"
    print "(A)", "-h, --help           display this help and exit"
    print "(A)", "-i, --interactive       run interactively after reading FILE(s)"
    print "(A)", "-l, --library           preload process library NAME"
    print "(A)", "-L, --logfile FILE      write log to FILE (default: 'whizard.log')"
    print "(A)", "-m, --model NAME        preload model NAME (default: 'SM')"
    print "(A)", "    --no-logfile        do not write a logfile"
    print "(A)", "-r, --rebuild           rebuild process code, phase space and integration grids"
    print "(A)", "    --rebuild-grids     rebuild integration grids"
    print "(A)", "    --rebuild-library   rebuild process code library"
    print "(A)", "    --rebuild-phase-space rebuild phase-space configuration"
    print "(A)", "    --recompile         recompile process code, ignoring any existing library"
    print "(A)", "-V, --version          output version information and exit"
    print "(A)", "-                        further options are taken as filenames"
    print *
    print "(A)", "With no FILE, read standard input."
end subroutine print_usage

end program main

```

Chapter 18

Cross References

18.1 Identifiers

18.2 Chunks