

# O'Mega: Optimal Monte-Carlo Event Generation Amplitudes

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as well as Christian Schwinn et al.

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## Abstract

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## *Revision Control*

# CONTENTS

1	INTRODUCTION	1
1.1	<i>Complexity</i>	1
1.2	<i>Ancestors</i>	2
1.3	<i>Architecture</i>	2
1.3.1	<i>General purpose libraries</i>	2
1.3.2	<i>O'Mega</i>	2
1.3.3	<i>Abstract interfaces</i>	3
1.3.4	<i>Models</i>	3
1.3.5	<i>Targets</i>	4
1.3.6	<i>Applications</i>	4
1.4	<i>The Big To Do Lists</i>	4
1.4.1	<i>Required</i>	4
1.4.2	<i>Useful</i>	4
1.4.3	<i>Future Features</i>	4
1.4.4	<i>Science Fiction</i>	5
2	TUPLES AND POLYTUPLES	6
2.1	<i>Interface of Tuple</i>	6
2.2	<i>Implementation of Tuple</i>	9
2.2.1	<i>Typesafe Combinatorics</i>	10
2.2.2	<i>Pairs</i>	10
2.2.3	<i>Triples</i>	12
2.2.4	<i>Pairs and Triples</i>	13
2.2.5	<i>... and All The Rest</i>	15
3	TOPOLOGIES	18
3.1	<i>Interface of Topology</i>	18
3.1.1	<i>Diagnostics: Counting Diagrams and Factorizations for <math>\sum_n \lambda_n \phi^n</math></i>	19
3.1.2	<i>Emulating HELAC</i>	20
3.2	<i>Implementation of Topology</i>	20
3.2.1	<i>Factorizing Diagrams for <math>\phi^3</math></i>	21
3.2.2	<i>Factorizing Diagrams for <math>\sum_n \lambda_n \phi^n</math></i>	24
3.2.3	<i>Factorizing Diagrams for <math>\phi^4</math></i>	26
3.2.4	<i>Factorizing Diagrams for <math>\phi^3 + \phi^4</math></i>	26
3.2.5	<i>Diagnostics: Counting Diagrams and Factorizations for <math>\sum_n \lambda_n \phi^n</math></i>	27
3.2.6	<i>Emulating HELAC</i>	33

4	DIRECTED ACYCLICAL GRAPHS	35
4.1	<i>Interface of DAG</i>	35
4.1.1	<i>Forests</i>	35
4.1.2	<i>DAGs</i>	37
4.1.3	<i>Graded Sets, Forests &amp; DAGs</i>	39
4.2	<i>Implementation of DAG</i>	40
4.2.1	<i>The Forest Functor</i>	42
4.2.2	<i>Gradings</i>	43
4.2.3	<i>The DAG Functor</i>	45
5	MOMENTA	50
5.1	<i>Interface of Momentum</i>	50
5.1.1	<i>Scattering Kinematics</i>	52
5.1.2	<i>Decay Kinematics</i>	53
5.2	<i>Implementation of Momentum</i>	54
5.2.1	<i>Lists of Integers</i>	55
5.2.2	<i>Bit Fiddlings</i>	61
5.2.3	<i>Whizard</i>	66
5.2.4	<i>Suggesting a Default Implementation</i>	67
6	CASCADES	68
6.1	<i>Interface of Cascade_syntax</i>	68
6.2	<i>Implementation of Cascade_syntax</i>	68
6.3	<i>Lexer</i>	70
6.4	<i>Parser</i>	71
6.5	<i>Interface of Cascade</i>	72
6.6	<i>Implementation of Cascade</i>	73
7	COLOR	80
7.1	<i>Interface of Color</i>	80
7.1.1	<i>Quantum Numbers</i>	80
7.1.2	<i>Color Flows</i>	80
7.2	<i>Implementation of Color</i>	81
7.2.1	<i>Quantum Numbers</i>	81
7.2.2	<i>Color Flows</i>	83
8	FUSIONS	88
8.1	<i>Interface of Fusion</i>	88
8.1.1	<i>Multiple Amplitudes</i>	91
8.1.2	<i>Tags</i>	93
8.2	<i>Implementation of Fusion</i>	93
8.2.1	<i>Fermi Statistics</i>	95
8.2.2	<i>Dirac Fermions</i>	95
8.2.3	<i>Tags</i>	97
8.2.4	<i>Tagged, the Fusion.Make Functor</i>	98
8.2.5	<i>Fusions with Majorana Fermions</i>	125
8.2.6	<i>Multiple Amplitudes</i>	127

9	LORENTZ REPRESENTATIONS, COUPLINGS, MODELS AND TARGETS	135
9.1	<i>Interface of Coupling</i>	135
9.1.1	<i>Propagators</i>	135
9.1.2	<i>Vertices</i>	137
9.1.3	<i>Gauge Couplings</i>	140
9.1.4	<i>SU(2) Gauge Bosons</i>	150
9.1.5	<i>Quartic Couplings and Auxiliary Fields</i>	152
9.1.6	<i>Gravitinos and supersymmetric currents</i>	154
9.1.7	<i>Perturbative Quantum Gravity and Kaluza-Klein Interactions</i>	154
9.1.8	<i>Dependent Parameters</i>	166
9.1.9	<i>More Exotic Couplings</i>	172
9.2	<i>Interface of Model</i>	172
9.2.1	<i>General Quantum Field Theories</i>	172
9.2.2	<i>Mutable Quantum Field Theories</i>	175
9.2.3	<i>Gauge Field Theories</i>	176
9.2.4	<i>Gauge Field Theories with Broken Gauge Symmetries</i>	177
9.3	<i>Interface of Target</i>	178
10	CONSERVED QUANTUM NUMBERS	180
10.1	<i>Interface of Charges</i>	180
10.1.1	<i>Abstract Type</i>	180
10.1.2	<i>Trivial Realisation</i>	180
10.1.3	<i>Nontrivial Realisations</i>	180
10.2	<i>Implementation of Charges</i>	181
11	COLORIZATION	183
11.1	<i>Interface of Colorize</i>	183
11.1.1	<i>...</i>	183
11.2	<i>Implementation of Colorize</i>	183
11.2.1	<i>Colorizing a Monochrome Model</i>	183
11.2.2	<i>Colorizing a Monochrome Gauge Model</i>	207
12	PROCESSES	209
12.1	<i>Interface of Process</i>	209
12.2	<i>Implementation of Process</i>	210
12.2.1	<i>Select Charge Conserving Processes</i>	211
12.2.2	<i>Parsing Process Descriptions</i>	211
12.2.3	<i>Remove Duplicate Final States</i>	213
13	HARDCODED MODELS	217
13.1	<i>Interface of Modeltools</i>	217
13.1.1	<i>Compilation</i>	217
13.1.2	<i>Mutable Models</i>	217
13.2	<i>Implementation of Modeltools</i>	218
13.2.1	<i>Compilation</i>	218
13.2.2	<i>Mutable Models</i>	222
13.3	<i>Interface of Modellib_SM</i>	224
13.3.1	<i>Hardcoded Models</i>	224
13.4	<i>Implementation of Modellib_SM</i>	224

13.4.1	$\phi^3$	225
13.4.2	$\lambda_3\phi^3 + \lambda_4\phi^4$	226
13.4.3	Quantum Electro Dynamics	227
13.4.4	Quantum Chromo Dynamics	230
13.4.5	Complete Minimal Standard Model (Unitarity Gauge)	234
13.4.6	Complete Minimal Standard Model (including some extensions)	236
13.4.7	Incomplete Standard Model in $R_\xi$ Gauge	265
13.4.8	Groves	267
13.4.9	MSM With Cloned Families	272
13.5	Interface of Modellib_BSM	272
13.5.1	More Hardcoded BSM Models	272
13.6	Implementation of Modellib_BSM	273
13.6.1	Littlest Higgs Model	273
13.6.2	Three-Site Higgsless Model	395
13.6.3	2HDM with and without non-trivial flavor structure	410
13.6.4	Complete Minimal Standard Model including additional Resonances	428
13.7	Interface of Modellib_MSSM	443
13.7.1	More Hardcoded Models	443
13.8	Implementation of Modellib_MSSM	444
13.8.1	Minimal Supersymmetric Standard Model	444
13.9	Interface of Modellib_NMSSM	495
13.9.1	Extended Supersymmetric Models	495
13.10	Implementation of Modellib_NMSSM	495
13.10.1	Next-to-Minimal Supersymmetric Standard Model	495
13.11	Interface of Modellib_PSSSM	525
13.11.1	Extended Supersymmetric Models	525
13.12	Implementation of Modellib_PSSSM	526
13.12.1	Extended Supersymmetric Standard Model(s)	526
14	COMPHEP MODELS	564
14.1	Interface of Comphep_syntax	564
14.2	Implementation of Comphep_syntax	564
14.3	Lexer	566
14.4	Parser	567
14.5	Interface of Comphep	568
14.6	Implementation of Comphep	568
15	HARDCODED TARGETS	578
15.1	Interface of Targets	578
15.1.1	Supported Targets	578
15.1.2	Potential Targets	578
15.2	Implementation of Targets	578
15.2.1	O'Mega Virtual Machine with Fortran 90/95	579
15.2.2	Fortran 90/95	608
15.2.3	C	678
15.2.4	O'Caml	678
15.2.5	L <sup>A</sup> T <sub>E</sub> X	678
15.3	Interface of Targets_Kmatrix	678

15.4	<i>Implementation of Targets_Kmatrix</i>	678
16	PHASE SPACE	691
16.1	<i>Interface of Phasespace</i>	691
16.2	<i>Implementation of Phasespace</i>	692
16.2.1	<i>Tools</i>	692
16.2.2	<i>Phase Space Parameterization Trees</i>	692
17	WHIZARD	698
17.1	<i>Interface of Whizard</i>	698
17.2	<i>Implementation of Whizard</i>	698
17.2.1	<i>Building Trees</i>	699
17.2.2	<i>Merging Homomorphic Trees</i>	700
17.2.3	<i>Printing Trees</i>	701
17.2.4	<i>Process Dispatcher</i>	703
17.2.5	<i>Makefile</i>	705
18	APPLICATIONS	707
18.1	<i>Sample</i>	707
18.2	<i>Interface of Omega</i>	707
18.3	<i>Implementation of Omega</i>	707
18.3.1	<i>Main Program</i>	713
18.4	<i>Implementation of Omega_QED</i>	718
18.5	<i>Implementation of Omega_SM</i>	718
18.6	<i>Implementation of Omega_SYM</i>	718
A	REVISION CONTROL	726
A.1	<i>Interface of RCS</i>	726
A.2	<i>Implementation of RCS</i>	727
B	AUTOTOOLS	729
B.1	<i>Interface of Config</i>	729
B.2	<i>Implementation of Config</i>	729
C	TEXTUAL OPTIONS	730
C.1	<i>Interface of Options</i>	730
C.2	<i>Implementation of Options</i>	730
D	PROGRESS REPORTS	732
D.1	<i>Interface of Progress</i>	732
D.2	<i>Implementation of Progress</i>	732
E	MORE ON FILENAMES	735
E.1	<i>Interface of ThoFilename</i>	735
E.2	<i>Implementation of ThoFilename</i>	735
F	CACHE FILES	736
F.1	<i>Interface of Cache</i>	736
F.2	<i>Implementation of Cache</i>	737

G	MORE ON LISTS	740
	<i>G.1 Interface of ThoList</i>	740
	<i>G.2 Implementation of ThoList</i>	742
H	MORE ON ARRAYS	748
	<i>H.1 Interface of ThoArray</i>	748
	<i>H.2 Implementation of ThoArray</i>	748
I	MORE ON STRINGS	751
	<i>I.1 Interface of ThoString</i>	751
	<i>I.2 Implementation of ThoString</i>	751
J	POLYMORPHIC MAPS	754
	<i>J.1 Interface of Pmap</i>	754
	<i>J.2 Implementation of Pmap</i>	755
	<i>J.3 Interface of Partial</i>	764
	<i>J.4 Implementation of Partial</i>	765
K	TRIES	767
	<i>K.1 Interface of Trie</i>	767
	<i>K.1.1 Monomorphically</i>	767
	<i>K.1.2 New in O'Caml 3.08</i>	767
	<i>K.1.3 O'Mega customization</i>	768
	<i>K.1.4 Polymorphically</i>	768
	<i>K.1.5 O'Mega customization</i>	769
	<i>K.2 Implementation of Trie</i>	769
	<i>K.2.1 Monomorphically</i>	769
	<i>K.2.2 O'Mega customization</i>	772
	<i>K.2.3 Polymorphically</i>	772
	<i>K.2.4 O'Mega customization</i>	774
L	TENSOR PRODUCTS	776
	<i>L.1 Interface of Product</i>	776
	<i>L.1.1 Lists</i>	776
	<i>L.1.2 Sets</i>	776
	<i>L.2 Implementation of Product</i>	777
	<i>L.2.1 Lists</i>	777
	<i>L.2.2 Sets</i>	778
M	(FIBER) BUNDLES	779
	<i>M.1 Interface of Bundle</i>	779
	<i>M.2 Implementation of Bundle</i>	780
N	POWER SETS	783
	<i>N.1 Interface of PowSet</i>	783
	<i>N.2 Implementation of PowSet</i>	784



O	COMBINATORICS	787
O.1	<i>Interface of Combinatorics</i>	787
O.1.1	<i>Simple Combinatorial Functions</i>	787
O.1.2	<i>Partitions</i>	787
O.1.3	<i>Choices</i>	789
O.1.4	<i>Permutations</i>	789
O.2	<i>Implementation of Combinatorics</i>	789
O.2.1	<i>Simple Combinatorial Functions</i>	789
O.2.2	<i>Partitions</i>	791
O.2.3	<i>Choices</i>	794
O.2.4	<i>Permutations</i>	795
O.3	<i>Interface of Permutation</i>	796
O.4	<i>Implementation of Permutation</i>	796
P	PARTITIONS	802
P.1	<i>Interface of Partition</i>	802
P.2	<i>Implementation of Partition</i>	802
Q	TREES	804
Q.1	<i>Interface of Tree</i>	805
Q.1.1	<i>Abstract Data Type</i>	805
Q.1.2	<i>Homomorphisms</i>	806
Q.1.3	<i>Output</i>	806
Q.2	<i>Implementation of Tree</i>	808
Q.2.1	<i>Abstract Data Type</i>	808
Q.2.2	<i>Homomorphisms</i>	810
Q.2.3	<i>Output</i>	810
Q.2.4	<i>Least Squares Layout</i>	815
R	DEPENDENCY TREES	820
R.1	<i>Interface of Tree2</i>	820
R.2	<i>Implementation of Tree2</i>	820
S	CONSISTENCY CHECKS	821
T	COMPLEX NUMBERS	822
U	ALGEBRA	823
U.1	<i>Interface of Algebra</i>	823
U.1.1	<i>Coefficients</i>	823
U.1.2	<i>Naive Rational Arithmetic</i>	823
U.1.3	<i>Expressions: Terms, Rings and Linear Combinations</i>	824
U.2	<i>Implementation of Algebra</i>	826
U.2.1	<i>Coefficients</i>	826
U.2.2	<i>Naive Rational Arithmetic</i>	826
U.2.3	<i>Expressions: Terms, Rings and Linear Combinations</i>	827
V	SIMPLE LINEAR ALGEBRA	833
V.1	<i>Interface of Linalg</i>	833
V.2	<i>Implementation of Linalg</i>	833
V.2.1	<i>LU Decomposition</i>	834

W TALK TO THE WHIZARD . . .	838
X FORTRAN LIBRARIES	839
X.1 Trivia . . . . .	839
X.1.1 Inner Product . . . . .	840
X.1.2 Spinor Vector Space . . . . .	840
X.1.3 Norm . . . . .	844
X.2 Spinors Revisited . . . . .	844
X.2.1 Spinor Vector Space . . . . .	845
X.2.2 Norm . . . . .	848
X.3 Vectorspinors . . . . .	848
X.3.1 Vectorspinor Vector Space . . . . .	849
X.3.2 Norm . . . . .	853
X.4 Vectors and Tensors . . . . .	853
X.4.1 Constructors . . . . .	854
X.4.2 Inner Products . . . . .	855
X.4.3 Not Entirely Inner Products . . . . .	856
X.4.4 Outer Products . . . . .	857
X.4.5 Vector Space . . . . .	858
X.4.6 Norm . . . . .	865
X.4.7 Conjugation . . . . .	865
X.4.8 $\epsilon$ -Tensors . . . . .	866
X.4.9 Utilities . . . . .	869
X.5 Polarization vectors . . . . .	869
X.6 Polarization vectors revisited . . . . .	872
X.7 Symmetric Tensors . . . . .	874
X.7.1 Vector Space . . . . .	875
X.8 Symmetric Polarization Tensors . . . . .	879
X.9 Couplings . . . . .	881
X.9.1 Triple Gauge Couplings . . . . .	885
X.9.2 Quadruple Gauge Couplings . . . . .	885
X.9.3 Scalar Current . . . . .	886
X.9.4 Transversal Scalar-Vector Coupling . . . . .	886
X.9.5 Triple Vector Couplings . . . . .	887
X.10 Graviton Couplings . . . . .	890
X.11 Tensor Couplings . . . . .	892
X.12 Scalar-Vector Dim-5 Couplings . . . . .	892
X.13 Spinor Couplings . . . . .	896
X.13.1 Fermionic Vector and Axial Couplings . . . . .	896
X.13.2 Fermionic Scalar and Pseudo Scalar Couplings . . . . .	910
X.13.3 On Shell Wave Functions . . . . .	914
X.13.4 Off Shell Wave Functions . . . . .	917
X.13.5 Propagators . . . . .	919
X.14 Spinor Couplings Revisited . . . . .	922
X.14.1 Fermionic Vector and Axial Couplings . . . . .	922
X.14.2 Fermionic Scalar and Pseudo Scalar Couplings . . . . .	928
X.14.3 Couplings for BRST Transformations . . . . .	930
X.14.4 Gravitino Couplings . . . . .	937
X.14.5 Gravitino 4-Couplings . . . . .	959
X.14.6 On Shell Wave Functions . . . . .	970

<i>X.14.7 Off Shell Wave Functions</i>	972
<i>X.14.8 Propagators</i>	973
<i>X.15 Polarization vectorspinors</i>	975
<i>X.16 Color</i>	979
<i>X.16.1 Color Sum</i>	979
<i>X.17 Utilities</i>	980
<i>X.17.1 Helicity Selection Rule Heuristics</i>	980
<i>X.17.2 Diagnostics</i>	981
<i>X.17.3 Obsolete Summation</i>	986
<i>X.18 omega95</i>	988
<i>X.19 omega95 Revisited</i>	989
<i>X.20 Testing</i>	989
<i>X.21 O'Mega Virtual Machine</i>	1014
<i>X.21.1 Memory Layout</i>	1017
<i>X.21.2 Controlling the VM</i>	1020
<i>X.21.3 Reading the bytecode</i>	1026
<i>X.21.4 Main Decode Function</i>	1032
<i>X.21.5 Helper functions</i>	1043
<i>X.21.6 O'Mega Interface</i>	1050
 Y INDEX	 1054

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# —1—

## INTRODUCTION

### 1.1 Complexity

There are

$$P(n) = \frac{2^n - 2}{2} - n = 2^{n-1} - n - 1 \quad (1.1)$$

independent internal momenta in a  $n$ -particle scattering amplitude [1]. This grows much slower than the number

$$F(n) = (2n - 5)!! = (2n - 5) \cdot (2n - 7) \cdot \dots \cdot 3 \cdot 1 \quad (1.2)$$

of tree Feynman diagrams in vanilla  $\phi^3$  (see table 1.1). There are no known corresponding expressions for theories with more than one particle type. However, empirical evidence from numerical studies [1, 2] as well as explicit counting results from O’Mega suggest

$$P^*(n) \propto 10^{n/2} \quad (1.3)$$

while the factorial growth of the number of Feynman diagrams remains unchecked, of course.

$n$	$P(n)$	$F(n)$
4	3	3
5	10	15
6	25	105
7	56	945
8	119	10395
9	246	135135
10	501	2027025
11	1012	34459425
12	2035	654729075
13	4082	13749310575
14	8177	316234143225
15	16368	7905853580625
16	32751	213458046676875

Table 1.1: The number of  $\phi^3$  Feynman diagrams  $F(n)$  and independent poles  $P(n)$ .

The number of independent momenta in an amplitude is a better measure for the complexity of the amplitude than the number of Feynman diagrams, since there can be substantial cancellations among the latter. Therefore it should be possible to express the scattering amplitude more compactly than by a sum over Feynman diagrams.

## 1.2 *Ancestors*

Some of the ideas that O’Mega is based on can be traced back to HELAS [5]. HELAS builds Feynman amplitudes by recursively forming off-shell ‘wave functions’ from joining external lines with other external lines or off-shell ‘wave functions’.

The program Madgraph [6] automatically generates Feynman diagrams and writes a Fortran program corresponding to their sum. The amplitudes are calculated by calls to HELAS [5]. Madgraph uses one straightforward optimization: no statement is written more than once. Since each statement corresponds to a collection of trees, this optimization is very effective for up to four particles in the final state. However, since the amplitudes are given as a sum of Feynman diagrams, this optimization can, by design, *not* remove the factorial growth and is substantially weaker than the algorithms of [1, 2] and the algorithm of O’Mega for more particles in the final state.

Then ALPHA [1] (see also the slightly modified variant [2]) provided a numerical algorithm for calculating scattering amplitudes and it could be shown empirically, that the calculational costs are rising with a power instead of factorially.

## 1.3 *Architecture*

### 1.3.1 *General purpose libraries*

Functions that are not specific to O’Mega and could be part of the O’Caml standard library

*ThoList* : (mostly) simple convenience functions for lists that are missing from the standard library module *List* (section G, p. 740)

*Product* : efficient tensor products for lists and sets (section L, p. 776)

*Combinatorics* : combinatorical formulae, sets of subsets, etc. (section O, p. 787)

### 1.3.2 *O’Mega*

The non-trivial algorithms that constitute O’Mega:

*DAG* : Directed Acyclical Graphs (section 4, p. 35)

*Topology* : unusual enumerations of unflavored tree diagrams (section 3, p. 18)

*Momentum* : finite sums of external momenta (section 5, p. 50)

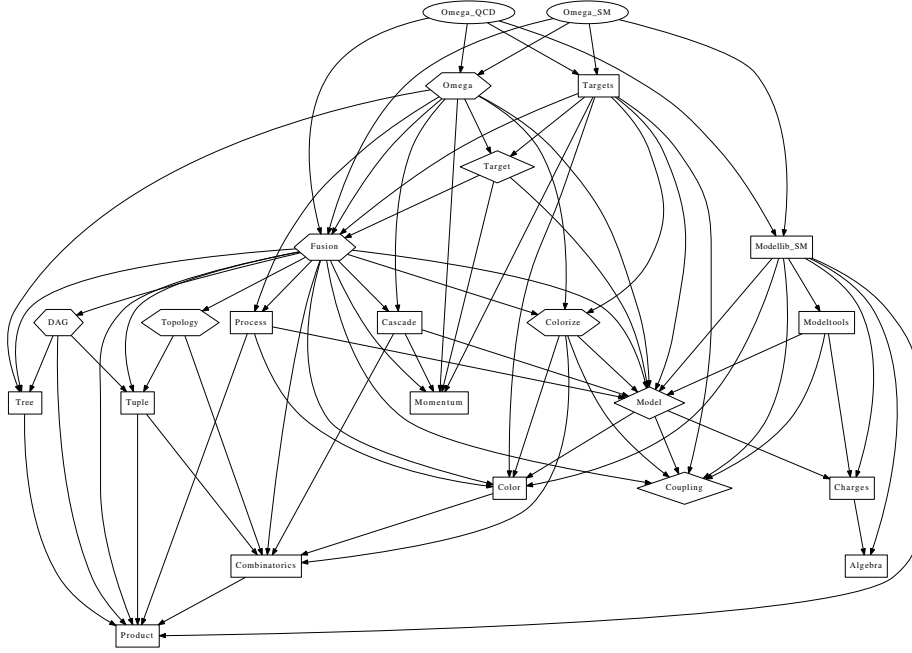


Figure 1.1: Module dependencies in O'Mega.

*Fusion* : off shell wave functions (section 8, p. 88)

*Omega* : functor constructing an application from a model and a target (section 18, p. 707)

### 1.3.3 Abstract interfaces

The domains and co-domains of functors (section 9, p. 135)

*Coupling* : all possible couplings (not comprehensive yet)

*Model* : physical models

*Target* : target programming languages

### 1.3.4 Models

(section 13, p. 217)

*Modellib<sub>S</sub>.QED* : Quantum Electrodynamics

*Modellib<sub>S</sub>.QCD* : Quantum Chromodynamics (not complete yet)

*Modellib<sub>S</sub>.SM* : Minimal Standard Model (not complete yet)

etc.

### 1.3.5 *Targets*

Any programming language that supports arithmetic and a textual representation of programs can be targeted by O’Caml. The implementations translate the abstract expressions derived by *Fusion* to expressions in the target (section 15, p. 578).

*Targets.Fortran* : Fortran95 language implementation, calling subroutines

Other targets could come in the future: C, C++, O’Caml itself, symbolic manipulation languages, etc.

### 1.3.6 *Applications*

(section 18, p. 707)

## 1.4 *The Big To Do Lists*

### 1.4.1 *Required*

All features required for leading order physics applications are in place.

### 1.4.2 *Useful*

1. select allowed helicity combinations for massless fermions
2. Weyl-Van der Waerden spinors
3. speed up helicity sums by using discrete symmetries
4. general triple and quartic vector couplings
5. diagnostics: count corresponding Feynman diagrams more efficiently for more than ten external lines
6. recognize potential cascade decays ( $\tau$ ,  $b$ , etc.)
  - warn the user to add additional
  - kill fusions (at runtime), that contribute to a cascade
7. complete standard model in  $R_\xi$ -gauge
8. groves (the simple method of cloned generations works)

### 1.4.3 *Future Features*

1. investigate if unpolarized squared matrix elements can be calculated faster as traces of density matrices. Unfortunately, the answer appears to be *no* for fermions and *up to a constant factor* for massive vectors. Since the number of fusions in the amplitude grows like  $10^{n/2}$ , the number of fusions in the squared matrix element grows like  $10^n$ . On the other hand, there are  $2^{\text{\#fermions} + \text{\#massless vectors}} \cdot 3^{\text{\#massive vectors}}$  terms in the helicity sum,

which grows *slower* than  $10^{n/2}$ . The constant factor is probably also not favorable. However, there will certainly be asymptotic gains for sums over gauge (and other) multiplets, like color sums.

2. compile Feynman rules from Lagrangians
3. evaluate amplitudes in O'Caml by compiling it to three address code for a virtual machine

```

type mem = scalar array × spinor array × spinor array × vector array
type instr =
  — VSS of int × int × int
  — SVS of int × int × int
  — AVA of int × int × int
  ...

```

this could be as fast as [1] or [2].

4. a virtual machine will be useful for other target as well, because native code appears to become too large for most compilers for more than ten external particles. Bytecode might even be faster due to improved cache locality.
5. use the virtual machine in O'Giga

#### 1.4.4 *Science Fiction*

1. numerical and symbolical loop calculations with O'TERA: O'MEGA TOOL FOR EVALUATING RENORMALIZED AMPLITUDES



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## —2—

# TUPLES AND POLYTUPLES

### 2.1 Interface of Tuple

The *Tuple.Poly* interface abstracts the notion of tuples with variable arity. Simple cases are binary polytuples, which are simply pairs and indefinite polytuples, which are nothing but lists. Another example is the union of pairs and triples. The interface is very similar to *List* from the O’Caml standard library, but the *Tuple.Poly* signature allows a more fine grained control of arities. The latter provides typesafe linking of models, targets and topologies.

```
module type Mono =
sig
  type  $\alpha$  t

  val arity :  $\alpha$  t  $\rightarrow$  int
  val max_arity : int

  val compare : ( $\alpha \rightarrow \alpha \rightarrow$  int)  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\alpha$  t  $\rightarrow$  int

  val for_all : ( $\alpha \rightarrow$  bool)  $\rightarrow$   $\alpha$  t  $\rightarrow$  bool

  val map : ( $\alpha \rightarrow \beta$ )  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\beta$  t
  val iter : ( $\alpha \rightarrow$  unit)  $\rightarrow$   $\alpha$  t  $\rightarrow$  unit
  val fold_left : ( $\alpha \rightarrow \beta \rightarrow \alpha$ )  $\rightarrow$   $\alpha \rightarrow \beta$  t  $\rightarrow$   $\alpha$ 
  val fold_right : ( $\alpha \rightarrow \beta \rightarrow \beta$ )  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\beta \rightarrow \beta$ 
```

We have applications, where no sensible initial value can be defined:

```
val fold_left_internal : ( $\alpha \rightarrow \alpha \rightarrow \alpha$ )  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\alpha$ 
val fold_right_internal : ( $\alpha \rightarrow \alpha \rightarrow \alpha$ )  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\alpha$ 

val map2 : ( $\alpha \rightarrow \beta \rightarrow \gamma$ )  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\beta$  t  $\rightarrow$   $\gamma$  t
val split : ( $\alpha \times \beta$ ) t  $\rightarrow$   $\alpha$  t  $\times$   $\beta$  t
```

The distributive tensor product expands a tuple of lists into list of tuples, e. g. for binary tuples:

$$\text{product}([x_1; x_2], [y_1; y_2]) = [(x_1, y_1); (x_1, y_2); (x_2, y_1); (x_2, y_2)] \quad (2.1)$$

NB: *product\_fold* is usually much more memory efficient than the combination of *product* and *List.fold\_right* for large sets.

```
val product :  $\alpha$  list t  $\rightarrow$   $\alpha$  t list
```

```
val product_fold : ( $\alpha$   $t \rightarrow \beta \rightarrow \beta$ )  $\rightarrow$   $\alpha$  list  $t \rightarrow \beta \rightarrow \beta$ 
```

For homogeneous tuples the *power* function could trivially be built from *product*, e. g.:

$$power\ [x_1; x_2] = product\ ([x_1; x_2], [x_1; x_2]) = [(x_1, x_1); (x_1, x_2); (x_2, x_1); (x_2, x_2)] \quad (2.2)$$

but it is also well defined for polytuples, e. g. for pairs and triples

$$power\ [x_1; x_2] = product\ ([x_1; x_2], [x_1; x_2]) \cup product\ ([x_1; x_2], [x_1; x_2], [x_1; x_2]) \quad (2.3)$$

For tuples and polytuples with bounded arity, the *power* and *power\_fold* functions terminate. In polytuples with unbounded arity, the *power* function always raises *No\_termination*. *power\_fold* also raises *No\_termination*, but could be changed to run until the argument function raises an exception. However, if we need this behaviour, we should implemente *power\_iter* instead.

```
val power :  $\alpha$  list  $\rightarrow$   $\alpha$   $t$  list
val power_fold : ( $\alpha$   $t \rightarrow \beta \rightarrow \beta$ )  $\rightarrow$   $\alpha$  list  $\rightarrow \beta \rightarrow \beta$ 
```

We can also identify all (poly)tuples with permuted elements and return only one representative, e. g.:

$$sym\_power\ [x_1; x_2] = [(x_1, x_1); (x_1, x_2); (x_2, x_2)] \quad (2.4)$$

NB: this function has not yet been implemented, because O'Mega only needs the more efficient special case *graded\_sym\_power*.

If a set  $X$  is graded (i. e. there is a map  $\phi : X \rightarrow \mathbf{N}$ , called *rank* below), the results of *power* or *sym\_power* can canonically be filtered by requiring that the sum of the ranks in each (poly)tuples has one chosen value. Implementing such a function directly is much more efficient than constructing and subsequently disregarding many (poly)tuples. The elements of rank  $n$  are at offset  $(n - 1)$  in the array. The array is assumed to be *immutable*, even if O'Cam1 doesn't support immutable arrays. NB: *graded\_power* has not yet been implemented, because O'Mega only needs *graded\_sym\_power*.

```
type  $\alpha$  graded =  $\alpha$  list array
val graded_sym_power : int  $\rightarrow$   $\alpha$  graded  $\rightarrow$   $\alpha$   $t$  list
val graded_sym_power_fold : int  $\rightarrow$  ( $\alpha$   $t \rightarrow \beta \rightarrow \beta$ )  $\rightarrow$   $\alpha$  graded  $\rightarrow$ 
   $\beta \rightarrow \beta$ 
```



We hope to be able to avoid the next one in the long run, because it mildly breaks typesafety for arities. Unfortunately, we're still working on it ...

```
val to_list :  $\alpha$   $t \rightarrow$   $\alpha$  list
```



The next one is only used for Fermi statistics below, but can not be implemented if there are no binary tuples. It must be retired as soon as possible.

```
val of2_kludge :  $\alpha \rightarrow \alpha \rightarrow \alpha$   $t$ 
val rcs : RCS. $t$ 
end
```

```

module type Poly =
  sig
    include Mono
    exception Mismatched_arity
    exception No_termination
  end

module type Binary =
  sig
    include Poly (* should become Mono! *)
    val of2 :  $\alpha \rightarrow \alpha \rightarrow \alpha\ t$ 
  end

module Binary : Binary

module type Ternary =
  sig
    include Mono
    val of3 :  $\alpha \rightarrow \alpha \rightarrow \alpha \rightarrow \alpha\ t$ 
  end

module Ternary : Ternary

type  $\alpha\ pair\_or\_triple = T2\ of\ \alpha \times \alpha \mid T3\ of\ \alpha \times \alpha \times \alpha$ 

module type Mixed23 =
  sig
    include Poly
    val of2 :  $\alpha \rightarrow \alpha \rightarrow \alpha\ t$ 
    val of3 :  $\alpha \rightarrow \alpha \rightarrow \alpha \rightarrow \alpha\ t$ 
  end

module Mixed23 : Mixed23

module type Nary =
  sig
    include Poly
    val of2 :  $\alpha \rightarrow \alpha \rightarrow \alpha\ t$ 
    val of3 :  $\alpha \rightarrow \alpha \rightarrow \alpha \rightarrow \alpha\ t$ 
    val of_list :  $\alpha\ list \rightarrow \alpha\ t$ 
  end

module Unbounded_Nary : Nary

module type Bound = sig val max_arity : int end
module Nary (B : Bound) : Nary

```



For completeness sake, we could add most of the *List* signature

- val *length* :  $\alpha\ t \rightarrow int$
- val *hd* :  $\alpha\ t \rightarrow \alpha$
- val *nth* :  $\alpha\ t \rightarrow int \rightarrow \alpha$
- val *rev* :  $\alpha\ t \rightarrow \alpha\ t$
- val *rev\_map* :  $(\alpha \rightarrow \beta) \rightarrow \alpha\ t \rightarrow \beta\ t$
- val *iter2* :  $(\alpha \rightarrow \beta \rightarrow unit) \rightarrow \alpha\ t \rightarrow \beta\ t \rightarrow unit$

- `val rev_map2 : ( $\alpha \rightarrow \beta \rightarrow \gamma$ )  $\rightarrow \alpha\ t \rightarrow \beta\ t \rightarrow \gamma\ t$`
- `val fold_left2 : ( $\alpha \rightarrow \beta \rightarrow \gamma \rightarrow \alpha$ )  $\rightarrow \alpha \rightarrow \beta\ t \rightarrow \gamma\ t \rightarrow \alpha$`
- `val fold_right2 : ( $\alpha \rightarrow \beta \rightarrow \gamma \rightarrow \gamma$ )  $\rightarrow \alpha\ t \rightarrow \beta\ t \rightarrow \gamma \rightarrow \gamma$`
- `val exists : ( $\alpha \rightarrow \text{bool}$ )  $\rightarrow \alpha\ t \rightarrow \text{bool}$`
- `val for_all2 : ( $\alpha \rightarrow \beta \rightarrow \text{bool}$ )  $\rightarrow \alpha\ t \rightarrow \beta\ t \rightarrow \text{bool}$`
- `val exists2 : ( $\alpha \rightarrow \beta \rightarrow \text{bool}$ )  $\rightarrow \alpha\ t \rightarrow \beta\ t \rightarrow \text{bool}$`
- `val mem :  $\alpha \rightarrow \alpha\ t \rightarrow \text{bool}$`
- `val memq :  $\alpha \rightarrow \alpha\ t \rightarrow \text{bool}$`
- `val find : ( $\alpha \rightarrow \text{bool}$ )  $\rightarrow \alpha\ t \rightarrow \alpha$`
- `val find_all : ( $\alpha \rightarrow \text{bool}$ )  $\rightarrow \alpha\ t \rightarrow \alpha\ \text{list}$`
- `val assoc :  $\alpha \rightarrow (\alpha \times \beta)\ t \rightarrow \beta$`
- `val assq :  $\alpha \rightarrow (\alpha \times \beta)\ t \rightarrow \beta$`
- `val mem_assoc :  $\alpha \rightarrow (\alpha \times \beta)\ t \rightarrow \text{bool}$`
- `val mem_assq :  $\alpha \rightarrow (\alpha \times \beta)\ t \rightarrow \text{bool}$`
- `val combine :  $\alpha\ t \rightarrow \beta\ t \rightarrow (\alpha \times \beta)\ t$`
- `val sort : ( $\alpha \rightarrow \alpha \rightarrow \text{int}$ )  $\rightarrow \alpha\ t \rightarrow \alpha\ t$`
- `val stable_sort : ( $\alpha \rightarrow \alpha \rightarrow \text{int}$ )  $\rightarrow \alpha\ t \rightarrow \alpha\ t$`

but only if we ever have too much time on our hand ...

## 2.2 Implementation of *Tuple*

```
let rcs_file = RCS.parse "Tuple" ["Tuples of fixed and indefinite arity"]
{ RCS.revision = "$Revision: 4926$";
  RCS.date = "$Date: 2013-12-04 13:35:06 +0100 (Wed, 04 Dec 2013)$";
  RCS.author = "$Author: jr-reuter$";
  RCS.source
    = "$URL: svn+ssh://jr-reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/sig";
module type Mono =
sig
  type  $\alpha\ t$ 
  val arity :  $\alpha\ t \rightarrow \text{int}$ 
  val max_arity :  $\text{int}$ 
  val compare : ( $\alpha \rightarrow \alpha \rightarrow \text{int}$ )  $\rightarrow \alpha\ t \rightarrow \alpha\ t \rightarrow \text{int}$ 
  val for_all : ( $\alpha \rightarrow \text{bool}$ )  $\rightarrow \alpha\ t \rightarrow \text{bool}$ 
  val map : ( $\alpha \rightarrow \beta$ )  $\rightarrow \alpha\ t \rightarrow \beta\ t$ 
  val iter : ( $\alpha \rightarrow \text{unit}$ )  $\rightarrow \alpha\ t \rightarrow \text{unit}$ 
  val fold_left : ( $\alpha \rightarrow \beta \rightarrow \alpha$ )  $\rightarrow \alpha \rightarrow \beta\ t \rightarrow \alpha$ 
  val fold_right : ( $\alpha \rightarrow \beta \rightarrow \beta$ )  $\rightarrow \alpha\ t \rightarrow \beta \rightarrow \beta$ 
  val fold_left_internal : ( $\alpha \rightarrow \alpha \rightarrow \alpha$ )  $\rightarrow \alpha\ t \rightarrow \alpha$ 
  val fold_right_internal : ( $\alpha \rightarrow \alpha \rightarrow \alpha$ )  $\rightarrow \alpha\ t \rightarrow \alpha$ 
  val map2 : ( $\alpha \rightarrow \beta \rightarrow \gamma$ )  $\rightarrow \alpha\ t \rightarrow \beta\ t \rightarrow \gamma\ t$ 
  val split : ( $\alpha \times \beta$ )  $t \rightarrow \alpha\ t \times \beta\ t$ 
```

```

val product :  $\alpha$  list  $t \rightarrow \alpha$   $t$  list
val product_fold : ( $\alpha$   $t \rightarrow \beta \rightarrow \beta$ )  $\rightarrow \alpha$  list  $t \rightarrow \beta \rightarrow \beta$ 
val power :  $\alpha$  list  $\rightarrow \alpha$   $t$  list
val power_fold : ( $\alpha$   $t \rightarrow \beta \rightarrow \beta$ )  $\rightarrow \alpha$  list  $\rightarrow \beta \rightarrow \beta$ 
type  $\alpha$  graded =  $\alpha$  list array
val graded_sym_power : int  $\rightarrow \alpha$  graded  $\rightarrow \alpha$   $t$  list
val graded_sym_power_fold : int  $\rightarrow (\alpha$   $t \rightarrow \beta \rightarrow \beta)$   $\rightarrow \alpha$  graded  $\rightarrow \beta \rightarrow \beta$ 
val to_list :  $\alpha$   $t \rightarrow \alpha$  list
val of2_kludge :  $\alpha \rightarrow \alpha \rightarrow \alpha$   $t$ 
val rcs : RCS. $t$ 
end

module type Poly =
sig
  include Mono
  exception Mismatched_arity
  exception No_termination
end

```

### 2.2.1 Typesafe Combinatorics

Wrap the combinatorial functions with varying arities into typesafe functions with fixed arities. We could provide specialized implementations, but since we *know* that *Impossible* is *never* raised, the present approach is just as good (except for a tiny inefficiency).

```

exception Impossible of string
let impossible name = raise (Impossible name)

let choose2 set =
  List.map (function [x; y]  $\rightarrow (x, y)$  | _  $\rightarrow$  impossible "choose2")
    (Combinatorics.choose 2 set)

let choose3 set =
  List.map (function [x; y; z]  $\rightarrow (x, y, z)$  | _  $\rightarrow$  impossible "choose3")
    (Combinatorics.choose 3 set)

```

### 2.2.2 Pairs

```

module type Binary =
sig
  include Poly (* should become Mono! *)
  val of2 :  $\alpha \rightarrow \alpha \rightarrow \alpha$   $t$ 
end

module Binary =
struct
  let rcs = RCS.rename rcs_file "Tuple.Binary" ["Pairs"]

  type  $\alpha$   $t$  =  $\alpha \times \alpha$ 

```

```

let arity _ = 2
let max_arity = 2

let of2 x y = (x, y)

let compare cmp (x1, y1) (x2, y2) =
  let cx = cmp x1 x2 in
  if cx ≠ 0 then
    cx
  else
    cmp y1 y2

let for_all p (x, y) = p x ∧ p y

let map f (x, y) = (f x, f y)
let iter f (x, y) = f x; f y
let fold_left f init (x, y) = f (f init x) y
let fold_right f (x, y) init = f x (f y init)
let fold_left_internal f (x, y) = f x y
let fold_right_internal f (x, y) = f x y

exception Mismatched_arity
let map2 f (x1, y1) (x2, y2) = (f x1 x2, f y1 y2)
let split ((x1, x2), (y1, y2)) = ((x1, y1), (x2, y2))

let product (lx, ly) =
  Product.list2 (fun x y → (x, y)) lx ly
let product_fold f (lx, ly) init =
  Product.fold2 (fun x y → f (x, y)) lx ly init

let power l = product (l, l)
let power_fold f l = product_fold f (l, l)

```

In the special case of binary fusions, the implementation is very concise.

```

type α graded = α list array

let fuse2 f set (i, j) acc =
  if i = j then
    List.fold_right (fun (x, y) → f x y) (choose2 set.(pred i)) acc
  else
    Product.fold2 f set.(pred i) set.(pred j) acc

let graded_sym_power_fold rank f set acc =
  let max_rank = Array.length set in
  List.fold_right (fuse2 (fun x y → f (of2 x y)) set)
    (Partition.pairs rank 1 max_rank) acc

let graded_sym_power rank set =
  graded_sym_power_fold rank (fun pair acc → pair :: acc) set []

let to_list (x, y) = [x; y]
let of2_kludge = of2

exception No_termination
end

```

2.2.3 *Triples*

```

module type Ternary =
  sig
    include Mono
    val of3 :  $\alpha \rightarrow \alpha \rightarrow \alpha \rightarrow \alpha t$ 
  end

module Ternary =
  struct
    let rcs = RCS.rename rcs_file "Tuple.Ternary" ["Triples"]

    type  $\alpha t = \alpha \times \alpha \times \alpha$ 

    let arity _ = 3
    let max_arity = 3

    let of3 x y z = (x, y, z)

    let compare cmp (x1, y1, z1) (x2, y2, z2) =
      let cx = cmp x1 x2 in
      if cx  $\neq$  0 then
        cx
      else
        let cy = cmp y1 y2 in
        if cy  $\neq$  0 then
          cy
        else
          cmp z1 z2

    let for_all p (x, y, z) = p x  $\wedge$  p y  $\wedge$  p z

    let map f (x, y, z) = (f x, f y, f z)
    let iter f (x, y, z) = f x; f y; f z
    let fold_left f init (x, y, z) = f (f (f init x) y) z
    let fold_right f (x, y, z) init = f x (f y (f z init))
    let fold_left_internal f (x, y, z) = f (f x y) z
    let fold_right_internal f (x, y, z) = f x (f y z)

    exception Mismatched_arity

    let map2 f (x1, y1, z1) (x2, y2, z2) = (f x1 x2, f y1 y2, f z1 z2)

    let split ((x1, x2), (y1, y2), (z1, z2)) = ((x1, y1, z1), (x2, y2, z2))

    let product (lx, ly, lz) =
      Product.list3 (fun x y z  $\rightarrow$  (x, y, z)) lx ly lz
    let product_fold f (lx, ly, lz) init =
      Product.fold3 (fun x y z  $\rightarrow$  f (x, y, z)) lx ly lz init

    let power l = product (l, l, l)
    let power_fold f l = product_fold f (l, l, l)

    type  $\alpha$  graded =  $\alpha$  list array

    let fuse3 f set (i, j, k) acc =
      if i = j then begin
        if j = k then

```

```

      List.fold_right (fun (x, y, z) → f x y z) (choose3 set.(pred i)) acc
    else
      Product.fold2 (fun (x, y) z → f x y z)
        (choose2 set.(pred i)) set.(pred k) acc
    end else begin
      if j = k then
        Product.fold2 (fun x (y, z) → f x y z)
          set.(pred i) (choose2 set.(pred j)) acc
      else
        Product.fold3 (fun x y z → f x y z)
          set.(pred i) set.(pred j) set.(pred k) acc
      end
    end

let graded_sym_power_fold rank f set acc =
  let max_rank = Array.length set in
  List.fold_right (fuse3 (fun x y z → f (of3 x y z)) set)
    (Partition.triples rank 1 max_rank) acc

let graded_sym_power rank set =
  graded_sym_power_fold rank (fun pair acc → pair :: acc) set []

let of2_kludge _ = failwith "Tuple.Ternary.of2_kludge"

let to_list (x, y, z) = [x; y; z]

end

```

#### 2.2.4 Pairs and Triples

```

type  $\alpha$  pair_or_triple = T2 of  $\alpha \times \alpha$  | T3 of  $\alpha \times \alpha \times \alpha$ 

module type Mixed23 =
  sig
    include Poly
    val of2 :  $\alpha \rightarrow \alpha \rightarrow \alpha t$ 
    val of3 :  $\alpha \rightarrow \alpha \rightarrow \alpha \rightarrow \alpha t$ 
  end

module Mixed23 =
  struct
    let rcs = RCS.rename rcs_file "Tuple.Mixed23"
      ["Mixed_pairs_and_triples"]

    type  $\alpha t = \alpha$  pair_or_triple

    let arity = function
      | T2 _ → 2
      | T3 _ → 3

    let max_arity = 3

    let of2 x y = T2 (x, y)
    let of3 x y z = T3 (x, y, z)

    let compare cmp m1 m2 =
      match m1, m2 with

```



---

```

| T2 -, T3 - → - 1
| T3 -, T2 - → 1
| T2 (x1, y1), T2 (x2, y2) →
    let cx = cmp x1 x2 in
    if cx ≠ 0 then
        cx
    else
        cmp y1 y2
| T3 (x1, y1, z1), T3 (x2, y2, z2) →
    let cx = cmp x1 x2 in
    if cx ≠ 0 then
        cx
    else
        let cy = cmp y1 y2 in
        if cy ≠ 0 then
            cy
        else
            cmp z1 z2

let for_all p = function
| T2 (x, y) → p x ∧ p y
| T3 (x, y, z) → p x ∧ p y ∧ p z

let map f = function
| T2 (x, y) → T2 (f x, f y)
| T3 (x, y, z) → T3 (f x, f y, f z)

let iter f = function
| T2 (x, y) → f x; f y
| T3 (x, y, z) → f x; f y; f z

let fold_left f init = function
| T2 (x, y) → f (f init x) y
| T3 (x, y, z) → f (f (f init x) y) z

let fold_right f m init =
    match m with
    | T2 (x, y) → f x (f y init)
    | T3 (x, y, z) → f x (f y (f z init))

let fold_left_internal f m =
    match m with
    | T2 (x, y) → f x y
    | T3 (x, y, z) → f (f x y) z

let fold_right_internal f m =
    match m with
    | T2 (x, y) → f x y
    | T3 (x, y, z) → f x (f y z)

exception Mismatched_arity
let map2 f m1 m2 =
    match m1, m2 with
    | T2 (x1, y1), T2 (x2, y2) → T2 (f x1 x2, f y1 y2)

```

```

    | T3 (x1, y1, z1), T3 (x2, y2, z2) → T3 (f x1 x2, f y1 y2, f z1 z2)
    | T2 -, T3 - | T3 -, T2 - → raise Mismatched_arity

let split = function
  | T2 ((x1, x2), (y1, y2)) → (T2 (x1, y1), T2 (x2, y2))
  | T3 ((x1, x2), (y1, y2), (z1, z2)) → (T3 (x1, y1, z1), T3 (x2, y2, z2))

let product = function
  | T2 (lx, ly) → Product.list2 (fun x y → T2 (x, y)) lx ly
  | T3 (lx, ly, lz) → Product.list3 (fun x y z → T3 (x, y, z)) lx ly lz
let product_fold f m init =
  match m with
  | T2 (lx, ly) → Product.fold2 (fun x y → f (T2 (x, y))) lx ly init
  | T3 (lx, ly, lz) →
      Product.fold3 (fun x y z → f (T3 (x, y, z))) lx ly lz init

exception No_termination

let power_fold f l init =
  product_fold f (T2 (l, l)) (product_fold f (T3 (l, l, l)) init)
let power l =
  power_fold (fun m acc → m :: acc) l []

type α graded = α list array

let graded_sym_power_fold rank f set acc =
  let max_rank = Array.length set in
  List.fold_right (Binary.fuse2 (fun x y → f (of2 x y)) set)
    (Partition.pairs rank 1 max_rank)
    (List.fold_right (Ternary.fuse3 (fun x y z → f (of3 x y z)) set)
      (Partition.triples rank 1 max_rank) acc)

let graded_sym_power rank set =
  graded_sym_power_fold rank (fun pair acc → pair :: acc) set []

let to_list = function
  | T2 (x, y) → [x; y]
  | T3 (x, y, z) → [x; y; z]

let of2_kludge = of2

end

```

### 2.2.5 ... and All The Rest

```

module type Nary =
  sig
    include Poly
    val of2 : α → α → α t
    val of3 : α → α → α → α t
    val of_list : α list → α t
  end

module Nary (A : sig val max_arity : int end) =
  struct

```

---

```

let rcs = RCS.rename rcs_file "Tuple.Nary"
    ["Tuples_of_indefinite_arity"]

type  $\alpha$  t =  $\alpha \times \alpha$  list

let arity (_, y) = succ (List.length y)
let max_arity = A.max_arity

let of2 x y = (x, [y])
let of3 x y z = (x, [y; z])

let of_list = function
| x :: y → (x, y)
| [] → invalid_arg "Tuple.Nary.of_list: empty"

let compare cmp (x1, y1) (x2, y2) =
    let c = cmp x1 x2 in
    if c ≠ 0 then
        c
    else
        ThoList.compare ~cmp y1 y2

let for_all p (x, y) = p x ∧ List.for_all p y

let map f (x, y) = (f x, List.map f y)
let iter f (x, y) = f x; List.iter f y
let fold_left f init (x, y) = List.fold_left f (f init x) y
let fold_right f (x, y) init = f x (List.fold_right f y init)
let fold_left_internal f (x, y) = List.fold_left f x y
let fold_right_internal f (x, y) =
    match List.rev y with
    | [] → x
    | y0 :: y_sans_y0 →
        f x (List.fold_right f (List.rev y_sans_y0) y0)

exception Mismatched_arity
let map2 f (x1, y1) (x2, y2) =
    try (f x1 x2, List.map2 f y1 y2) with
    | Invalid_argument _ → raise Mismatched_arity

let split ((x1, x2), y12) =
    let y1, y2 = List.split y12 in
    ((x1, y1), (x2, y2))

let product (xl, yl) =
    Product.list (function
    | x :: y → (x, y)
    | [] → failwith "Tuple.Nary.product") (xl :: yl)

let product_fold f (xl, yl) init =
    Product.fold (function
    | x :: y → f (x, y)
    | [] → failwith "Tuple.Nary.product_fold") (xl :: yl) init

let bounded_power_fold f l init =
    List.fold_right (fun n → product_fold f (l, ThoList.clone (pred n) l))
        (ThoList.range 2 A.max_arity) init

```

```

let bounded_power l =
  bounded_power_fold (fun t acc → t :: acc) l []

exception No_termination
let unbounded_power_fold f l init = raise No_termination
let unbounded_power l = raise No_termination

let power_fold, power =
  if A.max_arity > 0 then
    (bounded_power_fold, bounded_power)
  else
    (unbounded_power_fold, unbounded_power)

type  $\alpha$  graded =  $\alpha$  list array

let fuse_n f set partition acc =
  let choose (n, r) =
    Printf.printf "chose: n=%d r=%d len=%d\n"
      n r (List.length set.(pred r));
    Combinatorics.choose n set.(pred r) in
  Product.fold (fun wfs → f (List.concat wfs))
    (List.map choose (ThoList.classify partition)) acc

let fuse_n f set partition acc =
  let choose (n, r) = Combinatorics.choose n set.(pred r) in
  Product.fold (fun wfs → f (List.concat wfs))
    (List.map choose (ThoList.classify partition)) acc

```



*graded\_sym\_power\_fold* is well defined for unbounded arities as well: derive a reasonable replacement from *set*. The length of the flattened *set* is an upper limit, of course, but too pessimistic in most cases.

```

let graded_sym_power_fold rank f set acc =
  let max_rank = Array.length set in
  let degrees = ThoList.range 2 max_arity in
  let partitions =
    ThoList.flatmap
      (fun deg → Partition.tuples deg rank 1 max_rank) degrees in
  List.fold_right (fuse_n (fun wfs → f (of_list wfs)) set) partitions acc

let graded_sym_power rank set =
  graded_sym_power_fold rank (fun pair acc → pair :: acc) set []

let to_list (x, y) = x :: y
let of2_kludge = of2

end

```

```

module type Bound = sig val max_arity : int end
module Unbounded_Nary = Nary (struct let max_arity = -1 end)

```

---

## —3— TOPOLOGIES

### 3.1 Interface of Topology

module type  $T =$   
 sig

*partition* is a collection of integers, with arity one larger than the arity of  $\alpha$  *children* below. These arities can one fixed number corresponding to homogeneous tuples or a collection of tuples or lists.

type *partition*

*partitions*  $n$  returns the union of all  $[n_1; n_2; \dots; n_d]$  with  $1 \leq n_1 \leq n_2 \leq \dots \leq n_d \leq \lfloor n/2 \rfloor$  and

$$\sum_{i=1}^d n_i = n \quad (3.1)$$

for  $d$  from 3 to  $d_{\max}$ , where  $d_{\max}$  is a fixed number for each module implementing  $T$ . In particular, if `type partition = int × int × int`, then *partitions*  $n$  returns all  $(n_1, n_2, n_3)$  with  $n_1 \leq n_2 \leq n_3$  and  $n_1 + n_2 + n_3 = n$ .

val *partitions* : int → partition list

A (poly)tuple as implemented by the modules in *Tuple*:

type  $\alpha$  *children*

*keystones externals* returns all keystones for the amplitude with external states *externals* in the vanilla scalar theory with a

$$\sum_{3 \leq k \leq d_{\max}} \lambda_k \phi^k \quad (3.2)$$

interaction. One factor of the products is factorized. In particular, if

$$\text{type } \alpha \text{ children} = \alpha \text{ Tuple.Binary.t} = \alpha \times \alpha,$$

then *keystones externals* returns all keystones for the amplitude with external states *externals* in the vanilla scalar  $\lambda\phi^3$ -theory.

val *keystones* :  $\alpha$  list → ( $\alpha$  list ×  $\alpha$  list children list) list

The maximal depth of subtrees for a given number of external lines.

```
val max_subtree : int → int
```

Only for diagnostics:

```
val inspect_partition : partition → int list
val rcs : RCS.t
```

```
end
```

```
module Binary : T with type α children = α Tuple.Binary.t
module Ternary : T with type α children = α Tuple.Ternary.t
module Mixed23 : T with type α children = α Tuple.Mixed23.t
module Nary : functor (B : Tuple.Bound) →
  (T with type α children = α Tuple.Nary(B).t)
```

### 3.1.1 Diagnostics: Counting Diagrams and Factorizations for $\sum_n \lambda_n \phi^n$

The number of diagrams for many particles can easily exceed the range of native integers. Even if we can not calculate the corresponding amplitudes, we want to check combinatorial factors. Therefore we code a functor that can use arbitrary implementations of integers.

```
module type Integer =
sig
  type t
  val zero : t
  val one : t
  val ( + ) : t → t → t
  val ( - ) : t → t → t
  val ( × ) : t → t → t
  val ( / ) : t → t → t
  val pred : t → t
  val succ : t → t
  val ( = ) : t → t → bool
  val ( ≠ ) : t → t → bool
  val ( < ) : t → t → bool
  val ( ≤ ) : t → t → bool
  val ( > ) : t → t → bool
  val ( ≥ ) : t → t → bool
  val of_int : int → t
  val to_int : t → int
  val to_string : t → string
  val compare : t → t → int
  val factorial : t → t
end
```

Of course, native integers will provide the fastest implementation:

```
module Int : Integer
```

```
module type Count =
```

```
sig
  type integer
```

*diagrams f d n* returns the number of tree diagrams contributing to the  $n$ -point amplitude in vanilla scalar theory with

$$\sum_{3 \leq k \leq d \wedge f(k)} \lambda_k \phi^k \quad (3.3)$$

interaction. The default value of  $f$  returns `true` for all arguments.

```
val diagrams : ?f : (integer → bool) → integer → integer → integer
val diagrams_via_keystones : integer → integer → integer
```

$$\frac{1}{S(n_k, n - n_k)} \frac{1}{S(n_1, n_2, \dots, n_k)} \binom{n_1 + n_2 + \dots + n_k}{n_1, n_2, \dots, n_k} \quad (3.4)$$

```
val keystones : integer list → integer
```

*diagrams\_via\_keystones d n* must produce the same results as *diagrams d n*. This is shown explicitly in tables 3.2, 3.3 and 3.4 for small values of  $d$  and  $n$ . The test program in appendix S can be used to verify this relation for larger values.

```
val diagrams_per_keystone : integer → integer list → integer
```

```
end
```

```
module Count : functor (I : Integer) → Count with type integer = I.t
```

### 3.1.2 Emulating HELAC

We can also proceed á la [2].

```
module Helac : functor (B : Tuple.Bound) →
  (T with type α children = α Tuple.Nary(B).t)
```



The following has never been tested, but it is no rocket science and should work anyway ...

```
module Helac_Binary : T with type α children = α Tuple.Binary.t
```

## 3.2 Implementation of Topology

```
let rcs_file = RCS.parse "Topology" ["Topologies"]
{ RCS.revision = "$Revision: 6222$";
  RCS.date = "$Date: 2014-10-13 10:40:53 +0200 (Mon, 13 Oct 2014)$";
  RCS.author = "$Author: ohl$";
  RCS.source
    = "$URL: svn+ssh://jr_reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/s";
module type T =
sig
  type partition
  val partitions : int → partition list
```

$n$	$partitions\ n$
4	(1,1,2)
5	(1,2,2)
6	(1,2,3), (2,2,2)
7	(1,3,3), (2,2,3)
8	(1,3,4), (2,2,4), (2,3,3)
9	(1,4,4), (2,3,4), (3,3,3)
10	(1,4,5), (2,3,5), (2,4,4), (3,3,4)
11	(1,5,5), (2,4,5), (3,3,5), (3,4,4)
12	(1,5,6), (2,4,6), (2,5,5), (3,3,6), (3,4,5), (4,4,4)
13	(1,6,6), (2,5,6), (3,4,6), (3,5,5), (4,4,5)
14	(1,6,7), (2,5,7), (2,6,6), (3,4,7), (3,5,6), (4,4,6), (4,5,5)
15	(1,7,7), (2,6,7), (3,5,7), (3,6,6), (4,4,7), (4,5,6), (5,5,5)
16	(1,7,8), (2,6,8), (2,7,7), (3,5,8), (3,6,7), (4,4,8), (4,5,7), (4,6,6), (5,5,6)

Table 3.1:  $partitions\ n$  for moderate values of  $n$ .

```

type  $\alpha$  children
val keystones :  $\alpha$  list  $\rightarrow$  ( $\alpha$  list  $\times$   $\alpha$  list children list) list
val max_subtree : int  $\rightarrow$  int
val inspect_partition : partition  $\rightarrow$  int list
val rcs : RCS.t
end

```

### 3.2.1 Factorizing Diagrams for $\phi^3$

```

module Binary =
struct
  let rcs = RCS.rename rcs_file "Topology.Binary"
    ["phi**3_topology"]

  type partition = int  $\times$  int  $\times$  int
  let inspect_partition (n1, n2, n3) = [n1; n2; n3]

```

One way [1] to lift the degeneracy is to select the vertex that is closest to the center (see table 3.1):

$$partitions : n \rightarrow \{(n_1, n_2, n_3) \mid n_1 + n_2 + n_3 = n \wedge n_1 \leq n_2 \leq n_3 \leq \lfloor n/2 \rfloor\} \quad (3.5)$$

Other, less symmetric, approaches are possible. The simplest of these is: choose the vertex adjacent to a fixed external line [2]. They will be made available for comparison in the future.

An obvious consequence of  $n_1 + n_2 + n_3 = n$  and  $n_1 \leq n_2 \leq n_3$  is  $n_1 \leq \lfloor n/3 \rfloor$ :

```

let rec partitions' n n1 =
  if n1 > n / 3 then
    []
  else
    List.map (fun (n2, n3)  $\rightarrow$  (n1, n2, n3))

```



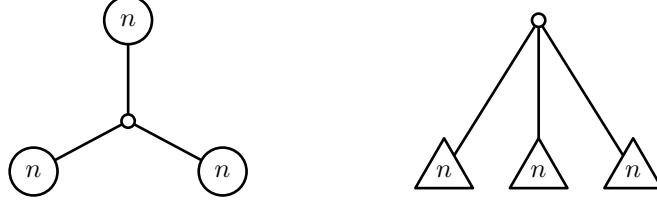


Figure 3.1: Topologies with a blatant three-fold permutation symmetry, if the number of external lines is a multiple of three

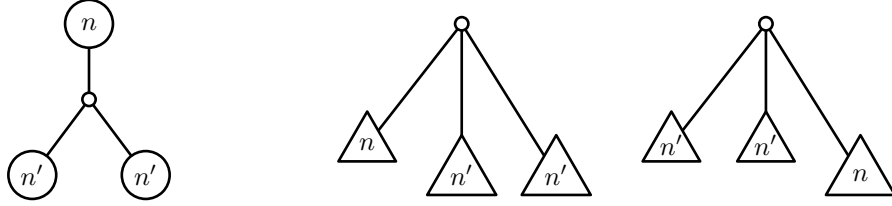


Figure 3.2: Topologies with a blatant two-fold symmetry.

```
(Partition.pairs (n - n1) n1 (n / 2)) @ partitions' n (succ n1)
let partitions n = partitions' n 1
```

```
type α children = α Tuple.Binary.t
```

There remains one peculiar case, when the number of external lines is even and  $n_3 = n_1 + n_2$  (cf. figure 3.3). Unfortunately, this reflection symmetry is not respected by the equivalence classes. E. g.

$$\{1\}\{2, 3\}\{4, 5, 6\} \mapsto \{\{4\}\{5, 6\}\{1, 2, 3\}; \{5\}\{4, 6\}\{1, 2, 3\}; \{6\}\{4, 5\}\{1, 2, 3\}\} \quad (3.6)$$

However, these reflections will always exchange the two halves and a representative can be chosen by requiring that one fixed momentum remains in one half. We choose to filter out the half of the partitions where the element  $p$  appears in the second half, i. e. the list of length  $n_3$ .

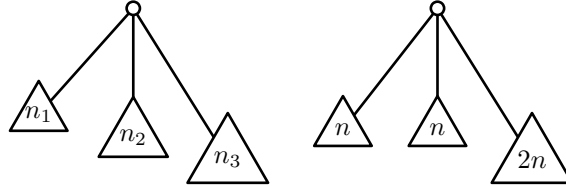


Figure 3.3: If  $n_3 = n_1 + n_2$ , the apparently asymmetric topologies on the left hand side have a non obvious two-fold symmetry, that exchanges the two halves. Therefore, the topologies on the right hand side have a four fold symmetry.

$n$	$(2n - 5)!!$	$\sum N(n_1, n_2, n_3)$
4	3	$3 \cdot (1, 1, 2)$
5	15	$15 \cdot (1, 2, 2)$
6	105	$90 \cdot (1, 2, 3) + 15 \cdot (2, 2, 2)$
7	945	$630 \cdot (1, 3, 3) + 315 \cdot (2, 2, 3)$
8	10395	$6300 \cdot (1, 3, 4) + 1575 \cdot (2, 2, 4) + 2520 \cdot (2, 3, 3)$
9	135135	$70875 \cdot (1, 4, 4) + 56700 \cdot (2, 3, 4) + 7560 \cdot (3, 3, 3)$
10	2027025	$992250 \cdot (1, 4, 5) + 396900 \cdot (2, 3, 5)$ $+ 354375 \cdot (2, 4, 4) + 283500 \cdot (3, 3, 4)$
11	34459425	$15280650 \cdot (1, 5, 5) + 10914750 \cdot (2, 4, 5)$ $+ 4365900 \cdot (3, 3, 5) + 3898125 \cdot (3, 4, 4)$
12	654729075	$275051700 \cdot (1, 5, 6) + 98232750 \cdot (2, 4, 6)$ $+ 91683900 \cdot (2, 5, 5) + 39293100 \cdot (3, 3, 6)$ $+ 130977000 \cdot (3, 4, 5) + 19490625 \cdot (4, 4, 4)$

Table 3.2: Equation (3.9) for small values of  $n$ .

Finally, a closed expression for the number of Feynman diagrams in the equivalence class  $(n_1, n_2, n_3)$  is

$$N(n_1, n_2, n_3) = \frac{(n_1 + n_2 + n_3)!}{S(n_1, n_2, n_3)} \prod_{i=1}^3 \frac{(2n_i - 3)!!}{n_i!} \quad (3.7)$$

where the symmetry factor from the above arguments is

$$S(n_1, n_2, n_3) = \begin{cases} 3! & \text{for } n_1 = n_2 = n_3 \\ 2 \cdot 2 & \text{for } n_3 = 2n_1 = 2n_2 \\ 2 & \text{for } n_1 = n_2 \vee n_2 = n_3 \\ 2 & \text{for } n_1 + n_2 = n_3 \end{cases} \quad (3.8)$$

Indeed, the sum of all Feynman diagrams

$$\sum_{\substack{n_1 + n_2 + n_3 = n \\ 1 \leq n_1 \leq n_2 \leq n_3 \leq \lfloor n/2 \rfloor}} N(n_1, n_2, n_3) = (2n - 5)!! \quad (3.9)$$

can be checked numerically for large values of  $n = n_1 + n_2 + n_3$ , verifying the symmetry factor (see table 3.2).



P. M. claims to have seen similar formulae in the context of Young tableaux. That's a good occasion to read the new edition of Howard's book ...

Return a list of all inequivalent partitions of the list  $l$  in three lists of length  $n1$ ,  $n2$  and  $n3$ , respectively. Common first lists are factored. This is nothing more than a typedafe wrapper around *Combinatorics.factorized\_keystones*.

```
exception Impossible of string
let tuple_of_list2 = function
| [x1; x2] → Tuple.Binary.of2 x1 x2
| - → raise (Impossible "Topology.tuple_of_list")
```

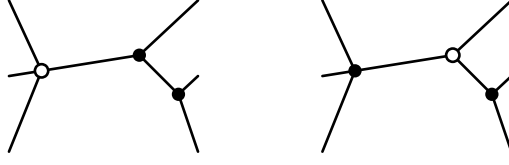


Figure 3.4: Degenerate (1, 1, 1, 3) and (1, 2, 3).

```

let keystone (n1, n2, n3) l =
  List.map (fun (p1, p23) → (p1, List.rev_map tuple_of_list2 p23))
    (Combinatorics.factorized_keystones [n1; n2; n3] l)

let keystones l =
  ThoList.flatmap (fun n123 → keystone n123 l) (partitions (List.length l))

let max_subtree n = n / 2
end

```

### 3.2.2 Factorizing Diagrams for $\sum_n \lambda_n \phi^n$

Mixed  $\phi^n$  adds new degeneracies, as in figure 3.4. They appear if and only if one part takes exactly half of the external lines and can relate central vertices of different arity.

```

module Nary (B : Tuple.Bound) =
struct
  let rcs = RCS.rename rcs_file "Topology.Nary"
    ["phi**n_topology"]

  type partition = int list
  let inspect_partition p = p

  let partition d sum =
    Partition.tuples d sum 1 (sum / 2)

  let rec partitions' d sum =
    if d < 3 then
      []
    else
      partition d sum @ partitions' (pred d) sum

  let partitions sum = partitions' (succ B.max_arity) sum

module Tuple = Tuple.Nary(B)
type  $\alpha$  children =  $\alpha$  Tuple.t

let keystones' l =
  let n = List.length l in
  ThoList.flatmap (fun p → Combinatorics.factorized_keystones p l)

```

$n$	$\Sigma$	$\Sigma$
4	4	$1 \cdot (1, 1, 1, 1) + 3 \cdot (1, 1, 2)$
5	25	$10 \cdot (1, 1, 1, 2) + 15 \cdot (1, 2, 2)$
6	220	$40 \cdot (1, 1, 1, 3) + 45 \cdot (1, 1, 2, 2) + 120 \cdot (1, 2, 3) + 15 \cdot (2, 2, 2)$
7	2485	$840 \cdot (1, 1, 2, 3) + 105 \cdot (1, 2, 2, 2) + 1120 \cdot (1, 3, 3) + 420 \cdot (2, 2, 3)$
8	34300	$5250 \cdot (1, 1, 2, 4) + 4480 \cdot (1, 1, 3, 3) + 3360 \cdot (1, 2, 2, 3)$ $+ 105 \cdot (2, 2, 2, 2) + 14000 \cdot (1, 3, 4)$ $+ 2625 \cdot (2, 2, 4) + 4480 \cdot (2, 3, 3)$
9	559405	$126000 \cdot (1, 1, 3, 4) + 47250 \cdot (1, 2, 2, 4) + 40320 \cdot (1, 2, 3, 3)$ $+ 5040 \cdot (2, 2, 2, 3) + 196875 \cdot (1, 4, 4)$ $+ 126000 \cdot (2, 3, 4) + 17920 \cdot (3, 3, 3)$
10	10525900	$1108800 \cdot (1, 1, 3, 5) + 984375 \cdot (1, 1, 4, 4) + 415800 \cdot (1, 2, 2, 5)$ $+ 1260000 \cdot (1, 2, 3, 4) + 179200 \cdot (1, 3, 3, 3) + 78750 \cdot (2, 2, 2, 4)$ $+ 100800 \cdot (2, 2, 3, 3) + 3465000 \cdot (1, 4, 5) + 1108800 \cdot (2, 3, 5)$ $+ 984375 \cdot (2, 4, 4) + 840000 \cdot (3, 3, 4)$

Table 3.3:  $\mathcal{L} = \lambda_3\phi^3 + \lambda_4\phi^4$

$n$	$\Sigma$	$\Sigma$
4	4	$1 \cdot (1, 1, 1, 1) + 3 \cdot (1, 1, 2)$
5	26	$1 \cdot (1, 1, 1, 1, 1) + 10 \cdot (1, 1, 1, 2) + 15 \cdot (1, 2, 2)$
6	236	$1 \cdot (1, 1, 1, 1, 1, 1) + 15 \cdot (1, 1, 1, 1, 2) + 40 \cdot (1, 1, 1, 3)$ $+ 45 \cdot (1, 1, 2, 2) + 120 \cdot (1, 2, 3) + 15 \cdot (2, 2, 2)$
7	2751	$21 \cdot (1, 1, 1, 1, 1, 2) + 140 \cdot (1, 1, 1, 1, 3) + 105 \cdot (1, 1, 1, 2, 2)$ $+ 840 \cdot (1, 1, 2, 3) + 105 \cdot (1, 2, 2, 2) + 1120 \cdot (1, 3, 3) + 420 \cdot (2, 2, 3)$
8	39179	$224 \cdot (1, 1, 1, 1, 1, 3) + 210 \cdot (1, 1, 1, 1, 2, 2) + 910 \cdot (1, 1, 1, 1, 4)$ $+ 2240 \cdot (1, 1, 1, 2, 3) + 420 \cdot (1, 1, 2, 2, 2) + 5460 \cdot (1, 1, 2, 4)$ $+ 4480 \cdot (1, 1, 3, 3) + 3360 \cdot (1, 2, 2, 3) + 105 \cdot (2, 2, 2, 2)$ $+ 14560 \cdot (1, 3, 4) + 2730 \cdot (2, 2, 4) + 4480 \cdot (2, 3, 3)$

Table 3.4:  $\mathcal{L} = \lambda_3\phi^3 + \lambda_4\phi^4 + \lambda_5\phi^5 + \lambda_6\phi^6$

```

    (partitions n)
  let keystones l =
    List.map (fun (bra, kets) → (bra, List.map Tuple.of_list kets))
      (keystones' l)
  let max_subtree n = n / 2
end
module Nary4 = Nary (struct let max_arity = 3 end)

```

### 3.2.3 Factorizing Diagrams for $\phi^4$

```

module Ternary =
  struct
    let rcs = RCS.rename rcs_file "Topology.Ternary"
      ["phi**4_⊔topology"]
    let rcs = rcs_file
    type partition = int × int × int × int
    let inspect_partition (n1, n2, n3, n4) = [n1; n2; n3; n4]
    type α children = α Tuple.Ternary.t
    let collect4 acc = function
      | [x; y; z; u] → (x, y, z, u) :: acc
      | _ → acc
    let partitions n =
      List.fold_left collect4 [] (Nary4.partitions n)
    let collect3 acc = function
      | [x; y; z] → Tuple.Ternary.of3 x y z :: acc
      | _ → acc
    let keystones l =
      List.map (fun (bra, kets) → (bra, List.fold_left collect3 [] kets))
        (Nary4.keystones' l)
    let max_subtree = Nary4.max_subtree
  end

```

### 3.2.4 Factorizing Diagrams for $\phi^3 + \phi^4$

```

module Mixed23 =
  struct
    let rcs = RCS.rename rcs_file "Topology.Mixed23"
      ["phi**3_⊔+⊔phi**4_⊔topology"]
    type partition =
      | P3 of int × int × int
      | P4 of int × int × int × int
    let inspect_partition = function
      | P3 (n1, n2, n3) → [n1; n2; n3]
      | P4 (n1, n2, n3, n4) → [n1; n2; n3; n4]
    type α children = α Tuple.Mixed23.t
    let collect34 acc = function

```

```

| [x; y; z] → P3 (x, y, z) :: acc
| [x; y; z; u] → P4 (x, y, z, u) :: acc
| _ → acc
let partitions n =
  List.fold_left collect34 [] (Nary4.partitions n)
let collect23 acc = function
| [x; y] → Tuple.Mixed23.of2 x y :: acc
| [x; y; z] → Tuple.Mixed23.of3 x y z :: acc
| _ → acc
let keystones l =
  List.map (fun (bra, kets) → (bra, List.fold_left collect23 [] kets))
    (Nary4.keystones' l)
let max_subtree = Nary4.max_subtree
end

```

### 3.2.5 Diagnostics: Counting Diagrams and Factorizations for $\sum_n \lambda_n \phi^n$

```

module type Integer =
sig
  type t
  val zero : t
  val one : t
  val ( + ) : t → t → t
  val ( - ) : t → t → t
  val ( × ) : t → t → t
  val ( / ) : t → t → t
  val pred : t → t
  val succ : t → t
  val ( = ) : t → t → bool
  val ( ≠ ) : t → t → bool
  val ( < ) : t → t → bool
  val ( ≤ ) : t → t → bool
  val ( > ) : t → t → bool
  val ( ≥ ) : t → t → bool
  val of_int : int → t
  val to_int : t → int
  val to_string : t → string
  val compare : t → t → int
  val factorial : t → t
end

```

O’Caml’s native integers suffice for all applications, but in appendix [S](#), we want to use big integers for numeric checks in high orders:

```

module Int : Integer =
struct
  type t = int
  let zero = 0
  let one = 1

```

```

let ( + ) = ( + )
let ( - ) = ( - )
let ( × ) = ( × )
let ( / ) = ( / )
let pred = pred
let succ = succ
let ( = ) = ( = )
let ( ≠ ) = ( ≠ )
let ( < ) = ( < )
let ( ≤ ) = ( ≤ )
let ( > ) = ( > )
let ( ≥ ) = ( ≥ )
let of_int n = n
let to_int n = n
let to_string = string_of_int
let compare = compare
let factorial = Combinatorics.factorial
end

module type Count =
sig
  type integer
  val diagrams : ?f : (integer → bool) → integer → integer → integer
  val diagrams_via_keystones : integer → integer → integer
  val keystones : integer list → integer
  val diagrams_per_keystone : integer → integer list → integer
end

module Count (I : Integer) =
struct
  let rcs = rcs_file
  let description = ["(still_inoperational)_phi^n_topology"]

  type integer = I.t
  open I
  let two = of_int 2
  let three = of_int 3

```

If *I.t* is an abstract datatype, the polymorphic *Pervasives.min* can fail. Provide our own version using the specific comparison “(*≤*)”.

```

let min x y =
  if x ≤ y then
    x
  else
    y

```

### Counting Diagrams for $\sum_n \lambda_n \phi^n$

Classes of diagrams are defined by the number of vertices and their degrees. We could use fixed size arrays, but we will use a map instead. For efficiency, we also maintain the number of external lines and the total number of propagators.

```

module IMap = Map.Make (struct type t = integer let compare = compare end)
type diagram_class = { ext : integer; prop : integer; v : integer IMap.t }

```

The numbers of external lines, propagators and vertices are determined by the degrees and multiplicities of vertices:

$$E(\{n_3, n_4, \dots\}) = 2 + \sum_{d=3}^{\infty} (d-2)n_d \quad (3.10a)$$

$$P(\{n_3, n_4, \dots\}) = \sum_{d=3}^{\infty} n_d - 1 = V(\{n_3, n_4, \dots\}) - 1 \quad (3.10b)$$

$$V(\{n_3, n_4, \dots\}) = \sum_{d=3}^{\infty} n_d \quad (3.10c)$$

```

let num_ext v =
  List.fold_left (fun sum (d, n) → sum + (d - two) × n) two v
let num_prop v =
  List.fold_left (fun sum (_, n) → sum + n) (zero - one) v

```

The sum of all vertex degrees must be equal to the number of propagator end points. This can be verified easily:

$$2P(\{n_3, n_4, \dots\}) + E(\{n_3, n_4, \dots\}) = \sum_{d=3}^{\infty} dn_d \quad (3.11)$$

```

let add_degree map (d, n) =
  if d < three then
    invalid_arg "add_degree: d < 3"
  else if n < zero then
    invalid_arg "add_degree: n <= 0"
  else if n = zero then
    map
  else
    IMap.add d n map
let create_class v =
  { ext = num_ext v;
    prop = num_prop v;
    v = List.fold_left add_degree IMap.empty v }
let multiplicity cl d =
  if d ≥ three then
    try
      IMap.find d cl.v
    with
    | Not_found → zero
  else
    invalid_arg "multiplicity: d < 3"

```

Remove one vertex of degree  $d$ , maintaining the invariants. Raises *Zero* if all vertices of degree  $d$  are exhausted.



```

exception Zero

let remove cl d =
  let n = pred (multiplicity cl d) in
  if n < zero then
    raise Zero
  else
    { ext = cl.ext - (d - two);
      prop = pred cl.prop;
      v = if n = zero then
        IMap.remove d cl.v
      else
        IMap.add d n cl.v }

```

Add one vertex of degree  $d$ , maintaining the invariants.

```

let add cl d =
  { ext = cl.ext + (d - two);
    prop = succ cl.prop;
    v = IMap.add d (succ (multiplicity cl d)) cl.v }

```

Count the number of diagrams. Any diagram can be obtained recursively either from a diagram with one ternary vertex less by insertion of a ternary vertex in an internal or external propagator or from a diagram with a higher order vertex that has its degree reduced by one:

$$\begin{aligned}
D(\{n_3, n_4, \dots\}) = & \\
& (P(\{n_3 - 1, n_4, \dots\}) + E(\{n_3 - 1, n_4, \dots\})) D(\{n_3 - 1, n_4, \dots\}) \\
& + \sum_{d=4}^{\infty} (n_{d-1} + 1) D(\{n_3, n_4, \dots, n_{d-1} + 1, n_d - 1, \dots\}) \quad (3.12)
\end{aligned}$$

```

let rec class_size cl =
  if cl.ext = two ∨ cl.prop = zero then
    one
  else
    IMap.fold (fun d _ s → class_size_n cl d + s) cl.v (class_size_3 cl)

```

Purely ternary vertices recurse among themselves:

```

and class_size_3 cl =
  try
    let d' = remove cl three in
    (d'.ext + d'.prop) × class_size d'
  with
  | Zero → zero

```

Vertices of higher degree recurse one step towards lower degrees:

```

and class_size_n cl d =
  if d > three then begin
    try
      let d' = pred d in
      let cl' = add (remove cl d) d' in

```

```

      multiplicity cl' d' × class_size cl'
    with
    | Zero → zero
  end else
    zero

```

Find all  $\{n_3, n_4, \dots, n_d\}$  with

$$E(\{n_3, n_4, \dots, n_d\}) - 2 = \sum_{i=3}^c l(i-2)n_i = \text{sum} \quad (3.13)$$

The implementation is a variant of *tuples* above.

```

let rec distribute_degrees' d sum =
  if d < three then
    invalid_arg "distribute_degrees"
  else if d = three then
    [[(d, sum)]]
  else
    distribute_degrees'' d sum (sum / (d - two))
and distribute_degrees'' d sum n =
  if n < zero then
    []
  else
    List.fold_left (fun ll l → ((d, n) :: l) :: ll)
      (distribute_degrees'' d sum (pred n))
      (distribute_degrees' (pred d) (sum - (d - two) × n))

```

Actually, we need to find all  $\{n_3, n_4, \dots, n_d\}$  with

$$E(\{n_3, n_4, \dots, n_d\}) = \text{sum} \quad (3.14)$$

```

let distribute_degrees d sum = distribute_degrees' d (sum - two)

```

Finally we can count all diagrams by adding all possible ways of splitting the degrees of vertices. We can also count diagrams where *all* degrees satisfy a predicate *f*:

```

let diagrams ?(f = fun _ → true) deg n =
  List.fold_left (fun s d →
    if List.for_all (fun (d', n') → f d' ∨ n' = zero) d then
      s + class_size (create_class d)
    else
      s)
    zero (distribute_degrees deg n)

```

The next two are duplicated from *ThoList* and *Combinatorics*, in order to use the specific comparison functions.

```

let classify l =
  let rec add_to_class a = function
    | [] → [of_int 1, a]
    | (n, a') :: rest →

```

```

      if  $a = a'$  then
        ( $\text{succ } n, a$ ) ::  $\text{rest}$ 
      else
        ( $n, a'$ ) ::  $\text{add\_to\_class } a \text{ rest}$ 
    in
    let rec  $\text{classify}' \text{ cl} = \text{function}$ 
      | []  $\rightarrow \text{cl}$ 
      |  $a :: \text{rest} \rightarrow \text{classify}' (\text{add\_to\_class } a \text{ cl}) \text{ rest}$ 
    in
     $\text{classify}' [] l$ 

let  $\text{permutation\_symmetry } l =$ 
   $\text{List.fold\_left } (\text{fun } s (n, -) \rightarrow \text{factorial } n \times s) \text{ one } (\text{classify } l)$ 

let  $\text{symmetry } l =$ 
  let  $\text{sum} = \text{List.fold\_left } (+) \text{ zero } l$  in
  if  $\text{List.exists } (\text{fun } x \rightarrow \text{two} \times x = \text{sum}) l$  then
     $\text{two} \times \text{permutation\_symmetry } l$ 
  else
     $\text{permutation\_symmetry } l$ 

```

The number of Feynman diagrams built of vertices with maximum degree  $d_{\max}$  in a partition  $N_{d,n} = \{n_1, n_2, \dots, n_d\}$  with  $n = n_1 + n_2 + \dots + n_d$  and

$$\tilde{F}(d_{\max}, N_{d,n}) = \frac{n!}{|\mathcal{S}(N_{d,n})| \sigma(n_d, n)} \prod_{i=1}^d \frac{F(d_{\max}, n_i + 1)}{n_i!} \quad (3.15)$$

with  $|\mathcal{S}(N)|$  the size of the symmetric group of  $N$ ,  $\sigma(n, 2n) = 2$  and  $\sigma(n, m) = 1$  otherwise.

```

let  $\text{keystones } p =$ 
  let  $\text{sum} = \text{List.fold\_left } (+) \text{ zero } p$  in
   $\text{List.fold\_left } (\text{fun } \text{acc } n \rightarrow \text{acc} / (\text{factorial } n)) (\text{factorial } \text{sum}) p$ 
  /  $\text{symmetry } p$ 

let  $\text{diagrams\_per\_keystone } \text{deg } p =$ 
   $\text{List.fold\_left } (\text{fun } \text{acc } n \rightarrow \text{acc} \times \text{diagrams } \text{deg } (\text{succ } n)) \text{ one } p$ 

```

We must find

$$F(d_{\max}, n) = \sum_{d=3}^{d_{\max}} \sum_{\substack{N=\{n_1, n_2, \dots, n_d\} \\ n_1 + n_2 + \dots + n_d = n \\ 1 \leq n_1 \leq n_2 \leq \dots \leq n_d \leq \lfloor n/2 \rfloor}} \tilde{F}(d_{\max}, N) \quad (3.16)$$

```

let  $\text{diagrams\_via\_keystones } \text{deg } n =$ 
  let module  $N = \text{Nary } (\text{struct let } \text{max\_arity} = \text{to\_int } (\text{pred } \text{deg}) \text{ end})$  in
   $\text{List.fold\_left}$ 
    ( $\text{fun } \text{acc } p \rightarrow \text{acc} + \text{diagrams\_per\_keystone } \text{deg } p \times \text{keystones } p$ )
    zero ( $\text{List.map } (\text{List.map of\_int}) (N.\text{partitions } (\text{to\_int } n))$ )

```

end

## 3.2.6 Emulating HELAC

In [2], one leg is singled out:

```

module Helac (B : Tuple.Bound) =
  struct
    let rcs = RCS.rename rcs_file "Topology.Helac"
      ["phi**n_topology, Helac_style"]
    module Tuple = Tuple.Nary(B)

    type partition = int list
    let inspect_partition p = p

    let partition d sum =
      Partition.tuples d sum 1 (sum - d + 1)

    let rec partitions' d sum =
      let d' = pred d in
      if d' < 2 then
        []
      else
        List.map (fun p → 1 :: p) (partition d' (pred sum)) @ partitions' d' sum

    let partitions sum = partitions' (succ B.max_arity) sum

    type α children = α Tuple.t

    let keystones' l =
      match l with
      | [] → []
      | head :: tail →
        [[head],
         ThoList.flatmap (fun p → Combinatorics.partitions (List.tl p) tail)
           (partitions (List.length l))]]

    let keystones l =
      List.map (fun (bra, kets) → (bra, List.map Tuple.of_list kets))
        (keystones' l)

    let max_subtree n = pred n
  end

```



The following is not tested, but it is no rocket science either ...

```

module Helac_Binary =
  struct
    let rcs = RCS.rename rcs_file "Topology.Helac_Binary"
      ["phi**3_topology, Helac_style"]

    type partition = int × int × int
    let inspect_partition (n1, n2, n3) = [n1; n2; n3]

    let partitions sum =
      List.map (fun (n2, n3) → (1, n2, n3))
        (Partition.pairs (sum - 1) 1 (sum - 2))
  end

```

```

type  $\alpha$  children =  $\alpha$  Tuple.Binary.t

let keystones' l =
  match l with
  | []  $\rightarrow$  []
  | head :: tail  $\rightarrow$ 
    [[head],
     ThoList.flatmap (fun (_, p2, _)  $\rightarrow$  Combinatorics.split p2 tail)
     (partitions (List.length l))]]

let keystones l =
  List.map (fun (bra, kets)  $\rightarrow$ 
    (bra, List.map (fun (x, y)  $\rightarrow$  Tuple.Binary.of2 x y) kets))
    (keystones' l)

let max_subtree n = pred n
end

```

---

# —4—

## DIRECTED ACYCLICAL GRAPHS

### 4.1 Interface of DAG

This datastructure describes large collections of trees with many shared nodes. The sharing of nodes is semantically irrelevant, but can turn a factorial complexity to exponential complexity. Note that *DAG* implements only a very specialized subset of Directed Acyclical Graphs (DAGs).

If  $T(n, D)$  denotes the set of all binary trees with root  $n$  encoded in  $D$ , while

$$O(n, D) = \{(e_1, n_1, n'_1), \dots, (e_k, n_k, n'_k)\} \quad (4.1)$$

denotes the set of all *offspring* of  $n$  in  $D$ , and  $\text{tree}(e, t, t')$  denotes the binary tree formed by joining the binary trees  $t$  and  $t'$  with the label  $e$ , then

$$T(n, D) = \{\text{tree}(e_i, t_i, t'_i) \mid (e_i, t_i, t'_i) \in \{e_1\} \times T(n_1, D) \times T(n'_1, D) \cup \dots \cup \{e_k\} \times T(n_k, D) \times T(n'_k, D)\} \quad (4.2)$$

is the recursive definition of the binary trees encoded in  $D$ . It is obvious how this definitions translates to  $n$ -ary trees (including trees with mixed arity).

#### 4.1.1 Forests

We require edges and nodes to be members of ordered sets. The semantics of *compare* are compatible with *Pervasives.compare*:

$$\text{compare}(x, y) = \begin{cases} -1 & \text{for } x < y \\ 0 & \text{for } x = y \\ 1 & \text{for } x > y \end{cases} \quad (4.3)$$

Note that this requirement does *not* exclude any trees. Even if we consider only topological equivalence classes with anonymous nodes, we can always construct a canonical labeling and order from the children of the nodes. However, in practical applications, we will often have more efficient labelings and orders at our disposal.

```
module type Ord =
  sig
    type t
    val compare : t → t → int
```

end

A forest  $F$  over a set of nodes and a set of edges is a map from the set of nodes  $N$ , to the direct product of the set of edges  $E$  and the power set  $2^N$  of  $N$  augmented by a special element  $\perp$  (“bottom”).

$$F : N \rightarrow (E \times 2^N) \cup \{\perp\}$$

$$n \mapsto \begin{cases} (e, \{n'_1, n'_2, \dots\}) \\ \perp \end{cases} \quad (4.4)$$

The nodes are ordered so that cycles can be detected

$$\forall n \in N : F(n) = (e, x) \Rightarrow \forall n' \in x : n > n' \quad (4.5)$$

A suitable function that exists for *all* forests is the depth of the tree beneath a node.

Nodes that are mapped to  $\perp$  are called *leaf* nodes and nodes that do not appear in any  $F(n)$  are called *root* nodes. There are as many trees in the forest as there are root nodes.

```
module type Forest =
  sig
    module Nodes : Ord
    type node = Nodes.t
    type edge
```

A subset  $X \subset 2^N$  of the powerset of the set of nodes. The members of  $X$  can be characterized by a fixed number of members (e.g. two for binary trees, as in QED). We can also have mixed arities (e.g. two and three for QCD) or even arbitrary arities. However, in most cases, the members of  $X$  will have at least two members.

```
type children
```

This type abbreviation and order allow to apply the *Set.Make* functor to  $E \times X$ .

```
type t = edge × children
val compare : t → t → int
```

Test a predicate for *all* children.

```
val for_all : (node → bool) → t → bool
```

*fold*  $f$   $(-, children)$  *acc* will calculate

$$f(x_1, f(x_2, \dots f(x_n, acc))) \quad (4.6)$$

where the *children* are  $\{x_1, x_2, \dots, x_n\}$ . There are slightly more efficient alternatives for fixed arity (in particular binary), but we want to be general.

```
val fold : (node → α → α) → t → α → α
```

end

```
module Forest : functor (PT : Tuple.Poly) →
  functor (N : Ord) → functor (E : Ord) →
    Forest with module Nodes = N and type edge = E.t
    and type node = N.t and type children = N.t PT.t
```

## 4.1.2 DAGs

```

module type T =
  sig
    type node
    type edge

```

In the description of the function we assume for definiteness DAGs of binary trees with `type children = node × node`. However, we will also have implementations with `type children = node list` below.

Other possibilities include `type children = V3 of node × node | V4 of node × node × node`. There's probably never a need to use sets with logarithmic access, but it is easy to add.

```

    type children
    type t

```

The empty DAG.

```

    val empty : t

```

`add_node n dag` returns the DAG `dag` with the node `n`. If the node `n` already exists in `dag`, it is returned unchanged. Otherwise `n` is added without offspring.

```

    val add_node : node → t → t

```

`add_offspring n (e, (n1, n2)) dag` returns the DAG `dag` with the node `n` and its offspring `n1` and `n2` with edge label `e`. Each node can have an arbitrary number of offspring, but identical offspring are added only once. In order to prevent cycles, `add_offspring` requires both `n > n1` and `n > n2` in the given ordering. The nodes `n1` and `n2` are added as by `add_node`. NB: Adding all nodes `n1` and `n2`, even if they are sterile, is not strictly necessary for our applications. It even slows down the code by a few percent. But it is desirable for consistency and allows much more efficient `iter_nodes` and `fold_nodes` below.

```

    val add_offspring : node → edge × children → t → t
    exception Cycle

```

Just like `add_offspring`, but does not check for potential cycles.

```

    val add_offspring_unsafe : node → edge × children → t → t

```

`is_node n dag` returns `true` iff `n` is a node in `dag`.

```

    val is_node : node → t → bool

```

`is_sterile n dag` returns `true` iff `n` is a node in `dag` and boasts no offspring.

```

    val is_sterile : node → t → bool

```

`is_offspring n (e, (n1, n2)) dag` returns `true` iff `n1` and `n2` are offspring of `n` with label `e` in `dag`.

```

    val is_offspring : node → edge × children → t → bool

```

Note that the following functions can run into infinite recursion if the DAG given as argument contains cycles.

The usual functionals for processing all nodes (including sterile) ...



```

val iter_nodes : (node → unit) → t → unit
val map_nodes : (node → node) → t → t
val fold_nodes : (node → α → α) → t → α → α

```

... and all parent/offspring relations. Note that *map* requires *two* functions: one for the nodes and one for the edges and children. This is so because a change in the definition of node is *not* propagated automatically to where it is used as a child.

```

val iter : (node → edge × children → unit) → t → unit
val map : (node → node) →
  (node → edge × children → edge × children) → t → t
val fold : (node → edge × children → α → α) → t → α → α

```



Note that in it's current incarnation, *fold add\_offspring dag empty* copies *only* the fertile nodes, while *fold add\_offspring dag (fold\_nodes add\_node dag empty)* includes sterile ones, as does *map (fun n → n) (fun n ec → ec) dag*.

Return the DAG as a list of lists.

```
val lists : t → (node × (edge × children) list) list
```

*dependencies dag node* returns a canonically sorted *Tree2.t* of all nodes reachable from *node*.

```
val dependencies : t → node → (node, edge) Tree2.t
```

*harvest dag n roots* returns the DAG *roots* enlarged by all nodes in *dag* reachable from *n*.

```
val harvest : t → node → t → t
```

*harvest\_list dag nlist* returns the part of the DAG *dag* that is reachable from the nodes in *nlist*.

```
val harvest_list : t → node list → t
```

*size dag* returns the number of nodes in the DAG *dag*.

```
val size : t → int
```

*eval f mul\_edge mul\_nodes add null unit root dag* interprets the part of *dag* beneath *root* as an algebraic expression:

- each node is evaluated by  $f : \text{node} \rightarrow \alpha$
- each set of children is evaluated by iterating the binary  $\text{mul\_nodes} : \alpha \rightarrow \gamma \rightarrow \gamma$  on the values of the nodes, starting from *unit*:  $\gamma$
- each offspring relation  $(\text{node}, (\text{edge}, \text{children}))$  is evaluated by applying  $\text{mul\_edge} : \text{node} \rightarrow \text{edge} \rightarrow \gamma \rightarrow \delta$  to *node*, *edge* and the evaluation of *children*.
- all offspring relations of a *node* are combined by iterating the binary  $\text{add} : \delta \rightarrow \alpha \rightarrow \alpha$  starting from *null*:  $\alpha$

In our applications, we will always have  $\alpha = \gamma = \delta$ , but the more general type is useful for documenting the relationships. The memoizing variant *eval\_memoized* *f* *mul\_edge* *mul\_nodes* *add null unit root dag* requires some overhead, but can be more efficient for complex operations.

```
val eval : (node → α) → (node → edge → γ → δ) →
  (α → γ → γ) → (δ → α → α) → α → γ → node → t → α
val eval_memoized : (node → α) → (node → edge → γ → δ) →
  (α → γ → γ) → (δ → α → α) → α → γ → node → t → α
```

*forest root dag* expands the *dag* beneath *root* into the equivalent list of trees *Tree.t*. *children* are represented as list of nodes.



A sterile node *n* is represented as *Tree.Leaf* ((*n*, *None*), *n*), cf. page 806. There might be a better way, but we need to change the interface and semantics of *Tree* for this.

```
val forest : node → t → (node × edge option, node) Tree.t list
val forest_memoized : node → t → (node × edge option, node) Tree.t list
```

*count\_trees n dag* returns the number of trees with root *n* encoded in the DAG *dag*, i.e.  $|T(n, D)|$ . NB: the current implementation is very naive and can take a *very* long time for moderately sized DAGs that encode a large set of trees.

```
val count_trees : node → t → int
```

```
val rcs : RCS.t
```

```
end
```

```
module Make (F : Forest) :
```

```
  T with type node = F.node and type edge = F.edge
```

```
  and type children = F.children
```

### 4.1.3 Graded Sets, Forests & DAGs

A graded ordered<sup>1</sup> set is an ordered set with a map into another ordered set (often the non-negative integers). The grading does not necessarily respect the ordering.

```
module type Graded_Ord =
```

```
  sig
```

```
    include Ord
```

```
    module G : Ord
```

```
    val rank : t → G.t
```

```
  end
```

For all ordered sets, there are two canonical gradings: a *Chaotic* grading that assigns the same rank (e.g. *unit*) to all elements and the *Discrete* grading that uses the identity map as grading.

```
module type Grader = functor (O : Ord) → Graded_Ord with type t = O.t
```

```
module Chaotic : Grader
```

```
module Discrete : Grader
```

A graded forest is just a forest in which the nodes form a graded ordered set.

<sup>1</sup>We don't appear to have use for graded unordered sets.



There doesn't appear to be a nice syntax for avoiding the repetition here.  
Fortunately, the signature is short ...

```

module type Graded_Forest =
sig
  module Nodes : Graded_Ord
  type node = Nodes.t
  type edge
  type children
  type t = edge × children
  val compare : t → t → int
  val for_all : (node → bool) → t → bool
  val fold : (node → α → α) → t → α → α
end

module type Forest_Grader = functor (G : Grader) → functor (F : Forest) →

  Graded_Forest with type Nodes.t = F.node
  and type node = F.node
  and type edge = F.edge
  and type children = F.children
  and type t = F.t

module Grade_Forest : Forest_Grader

Finally, a graded DAG is a DAG in which the nodes form a graded ordered set
and the subsets with a given rank can be accessed cheaply.

module type Graded =
sig
  include T
  type rank
  val rank : node → rank
  val ranks : t → rank list
  val min_max_rank : t → rank × rank
  val ranked : rank → t → node list
end

module Graded (F : Graded_Forest) :
  Graded with type node = F.node and type edge = F.edge
  and type children = F.children and type rank = F.Nodes.G.t

```

## 4.2 Implementation of DAG

```

let rcs_file = RCS.parse "DAG" ["Directed_Acyclical_Graph"]
{ RCS.revision = "$Revision: 4983$";
  RCS.date = "$Date: 2013-12-11 17:46:32 +0100 (Wed, 11 Dec 2013)$";
  RCS.author = "$Author: ohl$";
  RCS.source
    = "$URL: svn+ssh://jr_reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/s";
module type Ord =

```

```

sig
  type t
  val compare : t → t → int
end

module type Forest =
sig
  module Nodes : Ord
  type node = Nodes.t
  type edge
  type children
  type t = edge × children
  val compare : t → t → int
  val for_all : (node → bool) → t → bool
  val fold : (node → α → α) → t → α → α
end

module type T =
sig
  type node
  type edge
  type children
  type t
  val empty : t
  val add_node : node → t → t
  val add_offspring : node → edge × children → t → t
  exception Cycle
  val add_offspring_unsafe : node → edge × children → t → t
  val is_node : node → t → bool
  val is_sterile : node → t → bool
  val is_offspring : node → edge × children → t → bool
  val iter_nodes : (node → unit) → t → unit
  val map_nodes : (node → node) → t → t
  val fold_nodes : (node → α → α) → t → α → α
  val iter : (node → edge × children → unit) → t → unit
  val map : (node → node) →
    (node → edge × children → edge × children) → t → t
  val fold : (node → edge × children → α → α) → t → α → α
  val lists : t → (node × (edge × children) list) list
  val dependencies : t → node → (node, edge) Tree2.t
  val harvest : t → node → t → t
  val harvest_list : t → node list → t
  val size : t → int
  val eval : (node → α) → (node → edge → γ → δ) →
    (α → γ → γ) → (δ → α → α) → α → γ → node → t → α
  val eval_memoized : (node → α) → (node → edge → γ → δ) →
    (α → γ → γ) → (δ → α → α) → α → γ → node → t → α
  val forest : node → t → (node × edge option, node) Tree.t list
  val forest_memoized : node → t → (node × edge option, node) Tree.t list
  val count_trees : node → t → int
  val rcs : RCS.t

```

```

end

module type Graded_Ord =
sig
  include Ord
  module G : Ord
  val rank : t → G.t
end

module type Grader = functor (O : Ord) → Graded_Ord with type t = O.t

module type Graded_Forest =
sig
  module Nodes : Graded_Ord
  type node = Nodes.t
  type edge
  type children
  type t = edge × children
  val compare : t → t → int
  val for_all : (node → bool) → t → bool
  val fold : (node → α → α) → t → α → α
end

module type Forest_Grader = functor (G : Grader) → functor (F : Forest) →

  Graded_Forest with type Nodes.t = F.node
  and type node = F.node
  and type edge = F.edge
  and type children = F.children
  and type t = F.t

```

#### 4.2.1 The Forest Functor

```

module Forest (PT : Tuple.Poly) (N : Ord) (E : Ord) :
  Forest with module Nodes = N and type edge = E.t
  and type node = N.t and type children = N.t PT.t =
struct
  module Nodes = N
  type edge = E.t
  type node = N.t
  type children = node PT.t
  type t = edge × children

  let compare (e1, n1) (e2, n2) =
    let c = PT.compare N.compare n1 n2 in
    if c ≠ 0 then
      c
    else
      E.compare e1 e2

  let for_all f (_, nodes) = PT.for_all f nodes
  let fold f (_, nodes) acc = PT.fold_right f nodes acc

```

end

### 4.2.2 Gradings

```

module Chaotic (O : Ord) =
  struct
    include O
    module G =
      struct
        type t = unit
        let compare _ _ = 0
      end
    let rank _ = ()
  end

module Discrete (O : Ord) =
  struct
    include O
    module G = O
    let rank x = x
  end

module Fake_Grading (O : Ord) =
  struct
    include O
    exception Impossible of string
    module G =
      struct
        type t = unit
        let compare _ _ = raise (Impossible "G.compare")
      end
    let rank _ = raise (Impossible "G.compare")
  end

module Grade_Forest (G : Grader) (F : Forest) =
  struct
    module Nodes = G(F.Nodes)
    type node = Nodes.t
    type edge = F.edge
    type children = F.children
    type t = F.t
    let compare = F.compare
    let for_all = F.for_all
    let fold = F.fold
  end

```



The following can easily be extended to *Map.S* in its full glory, if we ever need it.

```

module type Graded_Map =

```

```

sig
  type key
  type rank
  type  $\alpha$  t
  val empty :  $\alpha$  t
  val add : key  $\rightarrow$   $\alpha$   $\rightarrow$   $\alpha$  t  $\rightarrow$   $\alpha$  t
  val find : key  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\alpha$ 
  val mem : key  $\rightarrow$   $\alpha$  t  $\rightarrow$  bool
  val iter : (key  $\rightarrow$   $\alpha$   $\rightarrow$  unit)  $\rightarrow$   $\alpha$  t  $\rightarrow$  unit
  val fold : (key  $\rightarrow$   $\alpha$   $\rightarrow$   $\beta$   $\rightarrow$   $\beta$ )  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\beta$   $\rightarrow$   $\beta$ 
  val ranks :  $\alpha$  t  $\rightarrow$  rank list
  val min_max_rank :  $\alpha$  t  $\rightarrow$  rank  $\times$  rank
  val ranked : rank  $\rightarrow$   $\alpha$  t  $\rightarrow$  key list
end

module type Graded_Map_Maker = functor (O : Graded_Ord)  $\rightarrow$ 
  Graded_Map with type key = O.t and type rank = O.G.t

module Graded_Map (O : Graded_Ord) :
  Graded_Map with type key = O.t and type rank = O.G.t =
struct
  module M1 = Map.Make(O.G)
  module M2 = Map.Make(O)

  type key = O.t
  type rank = O.G.t

  type (+ $\alpha$ ) t =  $\alpha$  M2.t M1.t

  let empty = M1.empty
  let add key data map1 =
    let rank = O.rank key in
    let map2 = try M1.find rank map1 with Not_found  $\rightarrow$  M2.empty in
    M1.add rank (M2.add key data map2) map1
  let find key map = M2.find key (M1.find (O.rank key) map)
  let mem key map =
    M2.mem key (try M1.find (O.rank key) map with Not_found  $\rightarrow$  M2.empty)
  let iter f map1 = M1.iter (fun rank  $\rightarrow$  M2.iter f) map1
  let fold f map1 acc1 = M1.fold (fun rank  $\rightarrow$  M2.fold f) map1 acc1

```



The set of ranks and its minimum and maximum should be maintained explicitly!

```

module S1 = Set.Make(O.G)
let ranks map = M1.fold (fun key data acc  $\rightarrow$  key :: acc) map []
let rank_set map = M1.fold (fun key data  $\rightarrow$  S1.add key) map S1.empty
let min_max_rank map =
  let s = rank_set map in
  (S1.min_elt s, S1.max_elt s)

module S2 = Set.Make(O)
let keys map = M2.fold (fun key data acc  $\rightarrow$  key :: acc) map []
let sorted_keys map =

```

```

    S2.elements (M2.fold (fun key data → S2.add key) map S2.empty)
  let ranked rank map =
    keys (try M1.find rank map with Not_found → M2.empty)
end

```

### 4.2.3 The DAG Functor

```

module Maybe_Graded (GMM : Graded_Map_Maker) (F : Graded_Forest) =
struct
  let rcs = RCS.rename rcs_file "DAG.Graded()"
    ["Graded_directed_Acyclical_Graph";
     "representing_binary_or_n-ary_trees"]

  module G = F.Nodes.G

  type node = F.node
  type rank = G.t
  type edge = F.edge
  type children = F.children

```

If we get tired of graded DAGs, we just have to replace *Graded\_Map* by *Map* here and remove *ranked* below and gain a tiny amount of simplicity and efficiency.

```

  module Parents = GMM(F.Nodes)
  module Offspring = Set.Make(F)

  type t = Offspring.t Parents.t

  let rank = F.Nodes.rank
  let ranks = Parents.ranks
  let min_max_rank = Parents.min_max_rank
  let ranked = Parents.ranked

  let empty = Parents.empty

  let add_node node dag =
    if Parents.mem node dag then
      dag
    else
      Parents.add node Offspring.empty dag

  let add_offspring_unsafe node offspring dag =
    let offsprings =
      try Parents.find node dag with Not_found → Offspring.empty in
    Parents.add node (Offspring.add offspring offsprings)
    (F.fold add_node offspring dag)

  exception Cycle

  let add_offspring node offspring dag =
    if F.for_all (fun n → F.Nodes.compare n node < 0) offspring then
      add_offspring_unsafe node offspring dag
    else
      raise Cycle

```



```

let is_node node dag =
  Parents.mem node dag

let is_sterile node dag =
  try
    Offspring.is_empty (Parents.find node dag)
  with
  | Not_found → false

let is_offspring node offspring dag =
  try
    Offspring.mem offspring (Parents.find node dag)
  with
  | Not_found → false

let iter_nodes f dag =
  Parents.iter (fun n _ → f n) dag

let iter f dag =
  Parents.iter (fun node _ → Offspring.iter (f node)) dag

let map_nodes f dag =
  Parents.fold (fun n _ → Parents.add (f n)) dag Parents.empty

let map fn fo dag =
  Parents.fold (fun node offspring _ →
    Parents.add (fn node)
    (Offspring.fold (fun o _ → Offspring.add (fo node o))
      offspring Offspring.empty)) dag Parents.empty

let fold_nodes f dag acc =
  Parents.fold (fun n _ → f n) dag acc

let fold f dag acc =
  Parents.fold (fun node _ → Offspring.fold (f node)) dag acc

```



Note that in it's current incarnation, `fold add_offspring dag empty` copies *only* the fertile nodes, while `fold add_offspring dag (fold_nodes add_node dag empty)` includes sterile ones, as does `map (fun n → n) (fun n ec → ec) dag`.

```

let dependencies dag node =
  let rec dependencies' node' =
    let offspring = Parents.find node' dag in
    if Offspring.is_empty offspring then
      Tree2.leaf node'
    else
      Tree2.cons
        (Offspring.fold
          (fun o acc _ →
            (fst o,
             node',
             F.fold (fun wf acc' → dependencies' wf :: acc') o [] :: acc)
            offspring []))
  in

```

```

dependencies' node

let lists dag =
  Sort.list (fun (n1, _) (n2, _) → F.Nodes.compare n1 n2 ≤ 0)
    (Parents.fold (fun node offspring l →
      (node, Offspring.elements offspring) :: l) dag [])

let size dag =
  Parents.fold (fun _ _ n → succ n) dag 0

let rec harvest dag node roots =
  Offspring.fold
    (fun offspring roots' →
      if is_offspring node offspring roots' then
        roots'
      else
        F.fold (harvest dag)
          offspring (add_offspring_unsafe node offspring roots'))
    (Parents.find node dag) (add_node node roots)

let harvest_list dag nodes =
  List.fold_left (fun roots node → harvest dag node roots) empty nodes

```

Build a closure once, so that we can recurse faster:

```

let eval f mule muln add null unit node dag =
  let rec eval' n =
    if is_sterile n dag then
      f n
    else
      Offspring.fold
        (fun (e, _ as offspring) v0 →
          add (mule n e (F.fold muln' offspring unit)) v0)
        (Parents.find n dag) null
    and muln' n = muln (eval' n) in
  eval' node

let count_trees node dag =
  eval (fun _ → 1) (fun _ _ p → p) ( × ) (+) 0 1 node dag

let build_forest evaluator node dag =
  evaluator (fun n → [Tree.leaf (n, None) n])
    (fun n e p → List.map (fun p' → Tree.cons (n, Some e) p') p)
    (fun p1 p2 → Product.fold2 (fun n nl pl → (n :: nl) :: pl) p1 p2 [])
    (@) [] [[]] node dag

let forest = build_forest eval

```

At least for `count_trees`, the memoizing variant `eval_memoized` is considerably slower than direct recursive evaluation with `eval`.

```

let eval_offspring f mule muln add null unit dag values (node, offspring) =
  let muln' n = muln (Parents.find n values) in
  let v =
    if is_sterile node dag then
      f node

```

```

    else
      Offspring.fold
        (fun (e, _ as offspring) v0 →
          add (mule node e (F.fold muln' offspring unit)) v0)
        offspring null
    in
      (v, Parents.add node v values)
let eval_memoized' f mule muln add null unit dag =
  let result, _ =
    List.fold_left
      (fun (v, values) → eval_offspring f mule muln add null unit dag values)
      (null, Parents.empty)
      (Sort.list (fun (n1, _) (n2, _) → F.Nodes.compare n1 n2 ≤ 0)
        (Parents.fold
          (fun node offspring l → (node, offspring) :: l) dag [])) in
    result
let eval_memoized f mule muln add null unit node dag =
  eval_memoized' f mule muln add null unit
  (harvest dag node empty)
let forest_memoized = build_forest eval_memoized
end

module type Graded =
sig
  include T
  type rank
  val rank : node → rank
  val ranks : t → rank list
  val min_max_rank : t → rank × rank
  val ranked : rank → t → node list
end

module Graded (F : Graded_Forest) = Maybe_Graded(Graded_Map)(F)

The following is not a graded map, obviously. But it can pass as one by the
typechecker for constructing non-graded DAGs.

module Fake_Graded_Map (O : Graded_Ord) :
  Graded_Map with type key = O.t and type rank = O.G.t =
struct
  module M = Map.Make(O)
  type key = O.t
  type (+α) t = α M.t
  let empty = M.empty
  let add = M.add
  let find = M.find
  let mem = M.mem
  let iter = M.iter
  let fold = M.fold

```

We make sure that the remaining three are never called inside *DAG* and are not visible outside.

```

type rank = O.G.t
exception Impossible of string
let ranks _ = raise (Impossible "ranks")
let min_max_rank _ = raise (Impossible "min_max_rank")
let ranked _ _ = raise (Impossible "ranked")
end

```

We could also have used signature projection with a chaotic or discrete grading, but the *Graded\_Map* can cost some efficiency. This is probably not the case for the current simple implementation, but future embellishment can change this. Therefore, the ungraded DAG uses *Map* directly, without overhead.

```

module Make (F : Forest) =
  Maybe_Graded(Fake_Graded_Map)(Grade_Forest(Fake_Grading)(F))

```



If O'Cam1 had *polymorphic recursion*, we could think of even more elegant implementations unifying nodes and offspring (cf. the generalized tries in [4]).

---

# —5—

## MOMENTA

### 5.1 Interface of Momentum

Model the finite combinations

$$p = \sum_{n=1}^k c_k \bar{p}_n, \quad (\text{with } c_k \in \{0, 1\}) \quad (5.1)$$

of  $n_{\text{in}}$  incoming and  $k - n_{\text{in}}$  outgoing momenta  $p_n$

$$\bar{p}_n = \begin{cases} -p_n & \text{for } 1 \leq n \leq n_{\text{in}} \\ p_n & \text{for } n_{\text{in}} + 1 \leq n \leq k \end{cases} \quad (5.2)$$

where momentum is conserved

$$\sum_{n=1}^k \bar{p}_n = 0 \quad (5.3)$$

below, we need the notion of ‘rank’ and ‘dimension’:

$$\dim(p) = k \quad (5.4a)$$

$$\text{rank}(p) = \sum_{n=1}^k c_k \quad (5.4b)$$

where ‘dimension’ is *not* the dimension of the underlying space-time, of course.

module type  $T =$

sig  
type  $t$

Constructor:  $(k, N) \rightarrow p = \sum_{n \in N} \bar{p}_n$  and  $k = \dim(p)$  is the *overall* number of independent momenta, while  $\text{rank}(p) = |N|$  is the number of momenta in  $p$ . It would be possible to fix  $\dim$  as a functor argument instead. This might be slightly faster and allow a few more compile time checks, but would be much more tedious to use, since the number of particles will be chosen at runtime.

val  $of\_ints : int \rightarrow int\ list \rightarrow t$

No two indices may be the same. Implementations of  $of\_ints$  can either raise the exception *Duplicate* or ignore the duplicate, but implementations of  $add$  are required to raise *Duplicate*.

exception *Duplicate* of *int*

Raise *Range* iff  $n > k$ :

exception *Range* of *int*

Binary operations require that both momenta have the same dimension. *Mismatch* is raised if this condition is violated.

exception *Mismatch* of  $string \times t \times t$

*Negative* is raised if the result of *sub* is undefined.

exception *Negative*

The inverses of the constructor (we have  $rank\ p = List.length\ (to\_ints\ p)$ , but *rank* might be more efficient):

```
val to_ints : t → int list
val dim   : t → int
val rank  : t → int
```

Shortcuts:  $singleton\ d\ p = of\_ints\ d\ [p]$  and  $zero\ d = of\_ints\ d\ []$ :

```
val singleton : int → int → t
val zero      : int → t
```

An arbitrary total order, with the condition  $rank(p_1) < rank(p_2) \Rightarrow p_1 < p_2$ .

```
val compare : t → t → int
```

Use momentum conservation to construct the negative momentum with positive coefficients:

```
val neg : t → t
```

Return the momentum or its negative, whichever has the lower rank. NB: the present implementation does *not* guarantee that

$$abs\ p = abs\ q \iff p = p \vee p = -q \quad (5.5)$$

for momenta with  $rank = dim/2$ .

```
val abs : t → t
```

Add and subtract momenta. This can fail, since the coefficients  $c_k$  must be either 0 or 1.

```
val add : t → t → t
val sub : t → t → t
```

Once more, but not raising exceptions this time:

```
val try_add : t → t → t option
val try_sub : t → t → t option
```

*Not* the total order provided by *compare*, but set inclusion of non-zero coefficients instead:

```
val less : t → t → bool
val lesseq : t → t → bool
```

$$p_1 + (\pm p_2) + (\pm p_3) = 0$$

$$\text{val } \text{try\_fusion} : t \rightarrow t \rightarrow t \rightarrow (bool \times bool) \text{ option}$$

A textual representation for debugging:

$$\text{val } \text{to\_string} : t \rightarrow \text{string}$$

*split i n p* splits  $\bar{p}_i$  into  $n$  momenta  $\bar{p}_i \rightarrow \bar{p}_i + \bar{p}_{i+1} + \dots + \bar{p}_{i+n-1}$  and makes room via  $\bar{p}_{j>i} \rightarrow \bar{p}_{j+n-1}$ . This is used for implementating cascade decays, like combining

$$e^+(p_1)e^-(p_2) \rightarrow W^-(p_3)\nu_e(p_4)e^+(p_5) \quad (5.6a)$$

$$W^-(p_3) \rightarrow d(p'_3)\bar{u}(p'_4) \quad (5.6b)$$

to

$$e^+(p_1)e^-(p_2) \rightarrow d(p_3)\bar{u}(p_4)\nu_e(p_5)e^+(p_6) \quad (5.7)$$

in narrow width approximation for the  $W^-$ .

$$\text{val } \text{split} : \text{int} \rightarrow \text{int} \rightarrow t \rightarrow t$$

### 5.1.1 Scattering Kinematics

From here on, we assume scattering kinematics  $\{1, 2\} \rightarrow \{3, 4, \dots\}$ , i. e.  $n_{\text{in}} = 2$ .



Since functions like *timelike* can be used for decays as well (in which case they must *always* return *true*, the representation—and consequently the constructors—should be extended by a flag discriminating between the two cases!

$$\text{module } \text{Scattering} : \\ \text{sig}$$

Test if the momentum is an incoming one:  $p = \bar{p}_1 \vee p = \bar{p}_2$

$$\text{val } \text{incoming} : t \rightarrow bool$$

$$p = \bar{p}_3 \vee p = \bar{p}_4 \vee \dots$$

$$\text{val } \text{outgoing} : t \rightarrow bool$$

$p^2 \geq 0$ . NB: *par abus de langage*, we report the incoming individual momenta as spacelike, instead as timelike. This will be useful for phasespace constructions below.

$$\text{val } \text{timelike} : t \rightarrow bool$$

$p^2 \leq 0$ . NB: the simple algebraic criterion can be violated for heavy initial state particles.

$$\text{val } \text{spacelike} : t \rightarrow bool$$

$$p = \bar{p}_1 + \bar{p}_2$$

$$\text{val } \text{s\_channel\_in} : t \rightarrow bool$$

$$p = \bar{p}_3 + \bar{p}_4 + \dots + \bar{p}_n$$

```

    val s_channel_out : t → bool

$p = \bar{p}_1 + \bar{p}_2 \vee p = \bar{p}_3 + \bar{p}_4 + \dots + \bar{p}_n$


    val s_channel : t → bool

$\bar{p}_1 + \bar{p}_2 \rightarrow \bar{p}_3 + \bar{p}_4 + \dots + \bar{p}_n$


    val flip_s_channel_in : t → t
end

```

### 5.1.2 Decay Kinematics

```

module Decay :
  sig
    Test if the momentum is an incoming one:  $p = \bar{p}_1$ 
    val incoming : t → bool

$p = \bar{p}_2 \vee p = \bar{p}_3 \vee \dots$


    val outgoing : t → bool

$p^2 \geq 0$ . NB: here, we report the incoming individual momenta as timelike.


    val timelike : t → bool

$p^2 \leq 0$ .


    val spacelike : t → bool
  end
  val rCS : RCS.t
end
module Lists : T
module Bits : T
module Default : T

```

Wolfgang's funny tree codes:

$$(2^n, 2^{n-1}) \rightarrow (1, 2, 4, \dots, 2^{n-2}) \quad (5.8)$$

```

module type Whizard =
  sig
    type t
    val of_momentum : t → int
    val to_momentum : int → int → t
  end
module ListsW : Whizard with type t = Lists.t
module BitsW : Whizard with type t = Bits.t
module DefaultW : Whizard with type t = Default.t

```



## 5.2 Implementation of *Momentum*

```

let rcs_file = RCS.parse "Momentum" ["Finite_disjoint_sums_of_momenta"]
{ RCS.revision = "$Revision: 6222$";
  RCS.date = "$Date: 2014-10-13 10:40:53 +0200 (Mon, 13 Oct 2014)$";
  RCS.author = "$Author: ohl$";
  RCS.source
    = "$URL: svn+ssh://jr-reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/s";

module type T =
sig
  type t
  val of_ints : int → int list → t
  exception Duplicate of int
  exception Range of int
  exception Mismatch of string × t × t
  exception Negative
  val to_ints : t → int list
  val dim : t → int
  val rank : t → int
  val singleton : int → int → t
  val zero : int → t
  val compare : t → t → int
  val neg : t → t
  val abs : t → t
  val add : t → t → t
  val sub : t → t → t
  val try_add : t → t → t option
  val try_sub : t → t → t option
  val less : t → t → bool
  val lesseq : t → t → bool
  val try_fusion : t → t → t → (bool × bool) option
  val to_string : t → string
  val split : int → int → t → t
  module Scattering :
    sig
      val incoming : t → bool
      val outgoing : t → bool
      val timelike : t → bool
      val spacelike : t → bool
      val s_channel_in : t → bool
      val s_channel_out : t → bool
      val s_channel : t → bool
      val flip_s_channel_in : t → t
    end
  module Decay :
    sig
      val incoming : t → bool
      val outgoing : t → bool
      val timelike : t → bool
    end
end

```

```

    val spacelike : t → bool
  end
  val rcs : RCS.t
end

```

### 5.2.1 Lists of Integers

The first implementation (as part of *Fusion*) was based on sorted lists, because I did not want to preclude the use of more general indices than integers. However, there's probably not much use for this generality (the indices are typically generated automatically and integer are the most natural choice) and it is no longer supported by the current signature. Thus one can also use the more efficient implementation based on bitvectors below.

```

module Lists =
  struct
    let rcs = RCS.rename rcs_file "Momentum.Lists()"
      (RCS.description rcs_file @
       ["using_lists_as_representation."])

    type t = { d : int; r : int; p : int list }

    exception Range of int
    exception Duplicate of int

    let rec check d = function
      | p1 :: p2 :: _ when p2 ≤ p1 → raise (Duplicate p1)
      | p1 :: (p2 :: _ as rest) → check d rest
      | [p] when p < 1 ∨ p > d → raise (Range p)
      | [p] → ()
      | [] → ()

    let of_ints d p =
      let p' = List.sort compare p in
      check d p';
      { d = d; r = List.length p; p = p' }

    let to_ints p = p.p
    let dim p = p.d
    let rank p = p.r
    let zero d = { d = d; r = 0; p = [] }
    let singleton d p = { d = d; r = 1; p = [p] }

    let to_string p =
      "[" ^ String.concat "," (List.map string_of_int p.p) ^
      "/" ^ string_of_int p.r ^ "/" ^ string_of_int p.d ^ "]"

    exception Mismatch of string × t × t
    let mismatch s p1 p2 = raise (Mismatch (s, p1, p2))

    let matching f s p1 p2 =
      if p1.d = p2.d then
        f p1 p2
      else

```

```

    mismatch s p1 p2
let compare p1 p2 =
  if p1.d = p2.d then begin
    let c = compare p1.r p2.r in
    if c ≠ 0 then
      c
    else
      compare p1.p p2.p
  end else
    mismatch "compare" p1 p2
let rec neg' d i = function
| [] →
  if i ≤ d then
    i :: neg' d (succ i) []
  else
    []
| i' :: rest as p →
  if i' > d then
    failwith "Integer_List.neg: internal error"
  else if i' = i then
    neg' d (succ i) rest
  else
    i :: neg' d (succ i) p
let neg p = { d = p.d; r = p.d - p.r; p = neg' p.d 1 p.p }
let abs p =
  if 2 × p.r > p.d then
    neg p
  else
    p
let rec add' p1 p2 =
  match p1, p2 with
  | [], p → p
  | p, [] → p
  | x1 :: p1', x2 :: p2' →
    if x1 < x2 then
      x1 :: add' p1' p2
    else if x2 < x1 then
      x2 :: add' p1 p2'
    else
      raise (Duplicate x1)
let add p1 p2 =
  if p1.d = p2.d then
    { d = p1.d; r = p1.r + p2.r; p = add' p1.p p2.p }
  else
    mismatch "add" p1 p2
let rec try_add' d r acc p1 p2 =
  match p1, p2 with

```

---

```

| [], p → Some ({ d = d; r = r; p = List.rev_append acc p })
| p, [] → Some ({ d = d; r = r; p = List.rev_append acc p })
| x1 :: p1', x2 :: p2' →
  if x1 < x2 then
    try_add' d r (x1 :: acc) p1' p2
  else if x2 < x1 then
    try_add' d r (x2 :: acc) p1 p2'
  else
    None

let try_add p1 p2 =
  if p1.d = p2.d then
    try_add' p1.d (p1.r + p2.r) [] p1.p p2.p
  else
    mismatch "try_add" p1 p2

exception Negative

let rec sub' p1 p2 =
  match p1, p2 with
  | p, [] → p
  | [], - → raise Negative
  | x1 :: p1', x2 :: p2' →
    if x1 < x2 then
      x1 :: sub' p1' p2
    else if x1 = x2 then
      sub' p1' p2'
    else
      raise Negative

let rec sub p1 p2 =
  if p1.d = p2.d then begin
    if p1.r ≥ p2.r then
      { d = p1.d; r = p1.r - p2.r; p = sub' p1.p p2.p }
    else
      neg (sub p2 p1)
  end else
    mismatch "sub" p1 p2

let rec try_sub' d r acc p1 p2 =
  match p1, p2 with
  | p, [] → Some ({ d = d; r = r; p = List.rev_append acc p })
  | [], - → None
  | x1 :: p1', x2 :: p2' →
    if x1 < x2 then
      try_sub' d r (x1 :: acc) p1' p2
    else if x1 = x2 then
      try_sub' d r acc p1' p2'
    else
      None

let try_sub p1 p2 =
  if p1.d = p2.d then begin

```

```

    if  $p1.r \geq p2.r$  then
      try_sub' p1.d (p1.r - p2.r) [] p1.p p2.p
    else
      match try_sub' p1.d (p2.r - p1.r) [] p2.p p1.p with
      | None → None
      | Some p → Some (neg p)
    end else
      mismatch "try_sub" p1 p2

let rec less' equal p1 p2 =
  match p1, p2 with
  | [], [] →  $\neg$  equal
  | [], _ → true
  | x1 :: _, [] → false
  | x1 :: p1', x2 :: p2' when x1 = x2 → less' equal p1' p2'
  | x1 :: p1', x2 :: p2' → less' false p1 p2'

let less p1 p2 =
  if p1.d = p2.d then
    less' true p1.p p2.p
  else
    mismatch "sub" p1 p2

let rec lesseq' p1 p2 =
  match p1, p2 with
  | [], _ → true
  | x1 :: _, [] → false
  | x1 :: p1', x2 :: p2' when x1 = x2 → lesseq' p1' p2'
  | x1 :: p1', x2 :: p2' → lesseq' p1 p2'

let lesseq p1 p2 =
  if p1.d = p2.d then
    lesseq' p1.p p2.p
  else
    mismatch "lesseq" p1 p2

module Scattering =
struct
  let incoming p =
    if p.r = 1 then
      match p.p with
      | [1] | [2] → true
      | _ → false
    else
      false

  let outgoing p =
    if p.r = 1 then
      match p.p with
      | [1] | [2] → false
      | _ → true
    else
      false

```

```

let s_channel_in p =
  match p.p with
  | [1; 2] → true
  | _ → false

let rec s_channel_out' d i = function
  | [] → i = succ d
  | i' :: p when i' = i → s_channel_out' d (succ i) p
  | _ → false

let s_channel_out p =
  match p.p with
  | 3 :: p' → s_channel_out' p.d 4 p'
  | _ → false

let s_channel p = s_channel_in p ∨ s_channel_out p

let timelike p =
  match p.p with
  | p1 :: p2 :: _ → p1 > 2 ∨ (p1 = 1 ∧ p2 = 2)
  | p1 :: _ → p1 > 2
  | [] → false

let spacelike p = ¬(timelike p)

let flip_s_channel_in p =
  if s_channel_in p then
    neg (of_ints p.d [1; 2])
  else
    p

end

module Decay =
struct
  let incoming p =
    if p.r = 1 then
      match p.p with
      | [1] → true
      | _ → false
    else
      false

  let outgoing p =
    if p.r = 1 then
      match p.p with
      | [1] → false
      | _ → true
    else
      false

  let timelike p =
    match p.p with
    | [1] → true
    | p1 :: _ → p1 > 1

```

---

```

    | [] → false
    let spacelike p = ¬ (timelike p)
  end
let test_sum p inv1 p1 inv2 p2 =
  if p.d = p1.d then begin
    if p.d = p2.d then begin
      match (if inv1 then try_add else try_sub) p p1 with
      | None → false
      | Some p' →
        begin match (if inv2 then try_add else try_sub) p' p2 with
        | None → false
        | Some p'' → p''.r = 0 ∨ p''.r = p.d
        end
      end else
        mismatch "test_sum" p p2
    end else
      mismatch "test_sum" p p1
  end
let try_fusion p p1 p2 =
  if test_sum p false p1 false p2 then
    Some (false, false)
  else if test_sum p true p1 false p2 then
    Some (true, false)
  else if test_sum p false p1 true p2 then
    Some (false, true)
  else if test_sum p true p1 true p2 then
    Some (true, true)
  else
    None
let split i n p =
  let n' = n - 1 in
  let rec split' head = function
    | [] → (p.r, List.rev head)
    | i1 :: ilist →
      if i1 < i then
        split' (i1 :: head) ilist
      else if i1 > i then
        (p.r, List.rev_append head (List.map ((+) n') (i1 :: ilist)))
      else
        (p.r + n',
         List.rev_append head
          ((ThoList.range i1 (i1 + n')) @ (List.map ((+) n') ilist)))
  in
  let r', p' = split' [] p.p in
  { d = p.d + n'; r = r'; p = p' }
end

```

### 5.2.2 Bit Fiddlings

Bit vectors are popular in Fortran based implementations [1, 2, 11] and can be more efficient. In particular, when all information is packed into a single integer, much of the memory overhead is reduced.

```
module Bits =
  struct
    let rcs = RCS.rename rcs_file "Momentum.Bits()"
      (RCS.description rcs_file @
       [ "using_bitfields_as_representation." ])
    type t = int
```

Bits 1...21 are used as a bitvector, indicating whether a particular momentum is included. Bits 22...26 represent the numbers of bits set in bits 1...21 and bits 27...31 denote the maximum number of momenta.

```
let mask n = (1 lsl n) - 1
let mask2 = mask 2
let mask5 = mask 5
let mask21 = mask 21

let maskd = mask5 lsl 26
let maskr = mask5 lsl 21
let maskb = mask21

let dim0 p = p land maskd
let rank0 p = p land maskr
let bits0 p = p land maskb

let dim p = (dim0 p) lsr 26
let rank p = (rank0 p) lsr 21
let bits p = bits0 p

let drb0 d r b = d lor r lor b
let drb d r b = d lsl 26 lor r lsl 21 lor b
```

For a 64-bit architecture, the corresponding sizes could be increased to 1...51, 52...57, and 58...63. However, the combinatorial complexity will have killed us long before we can reach these values.

```
exception Range of int
exception Duplicate of int

exception Mismatch of string × t × t
let mismatch s p1 p2 = raise (Mismatch (s, p1, p2))

let of_ints d p =
  let r = List.length p in
  if d ≤ 21 ∧ r ≤ 21 then begin
    List.fold_left (fun b p' →
      if p' ≤ d then
        b lor (1 lsl (pred p'))
      else
        raise (Range p')) (drb d r 0) p
```



```

end else
  raise (Range r)
let zero d = drb d 0 0
let singleton d p = drb d 1 (1 lsl (pred p))
let rec to_ints' acc p b =
  if b = 0 then
    List.rev acc
  else if (b land 1) = 1 then
    to_ints' (p :: acc) (succ p) (b lsr 1)
  else
    to_ints' acc (succ p) (b lsr 1)
let to_ints p = to_ints' [] 1 (bits p)
let to_string p =
  "[" ^ String.concat "," (List.map string_of_int (to_ints p)) ^
  "/" ^ string_of_int (rank p) ^ "/" ^ string_of_int (dim p) ^ "]"
let compare p1 p2 =
  if dim0 p1 = dim0 p2 then begin
    let c = compare (rank0 p1) (rank0 p2) in
    if c ≠ 0 then
      c
    else
      compare (bits p1) (bits p2)
  end else
    mismatch "compare" p1 p2
let neg p =
  let d = dim p and r = rank p in
  drb d (d - r) ((mask d) land (lnot p))
let abs p =
  if 2 × (rank p) > dim p then
    neg p
  else
    p
let add p1 p2 =
  let d1 = dim0 p1 and d2 = dim0 p2 in
  if d1 = d2 then begin
    let b1 = bits p1 and b2 = bits p2 in
    if b1 land b2 = 0 then
      drb0 d1 (rank0 p1 + rank0 p2) (b1 lor b2)
    else
      raise (Duplicate 0)
  end else
    mismatch "add" p1 p2
exception Negative
let rec sub p1 p2 =
  let d1 = dim0 p1 and d2 = dim0 p2 in

```

```

if d1 = d2 then begin
  let r1 = rank0 p1 and r2 = rank0 p2 in
  if r1 ≥ r2 then begin
    let b1 = bits p1 and b2 = bits p2 in
    if b1 lor b2 = b1 then
      drb0 d1 (r1 - r2) (b1 lxor b2)
    else
      raise Negative
  end else
    neg (sub p2 p1)
end else
  mismatch "sub" p1 p2

let try_add p1 p2 =
  let d1 = dim0 p1 and d2 = dim0 p2 in
  if d1 = d2 then begin
    let b1 = bits p1 and b2 = bits p2 in
    if b1 land b2 = 0 then
      Some (drb0 d1 (rank0 p1 + rank0 p2) (b1 lor b2))
    else
      None
  end else
    mismatch "try-add" p1 p2

let rec try_sub p1 p2 =
  let d1 = dim0 p1 and d2 = dim0 p2 in
  if d1 = d2 then begin
    let r1 = rank0 p1 and r2 = rank0 p2 in
    if r1 ≥ r2 then begin
      let b1 = bits p1 and b2 = bits p2 in
      if b1 lor b2 = b1 then
        Some (drb0 d1 (r1 - r2) (b1 lxor b2))
      else
        None
    end else
      begin match try_sub p2 p1 with
        | Some p → Some (neg p)
        | None → None
      end
  end else
    mismatch "sub" p1 p2

let lesseq p1 p2 =
  let d1 = dim0 p1 and d2 = dim0 p2 in
  if d1 = d2 then begin
    let r1 = rank0 p1 and r2 = rank0 p2 in
    if r1 ≤ r2 then begin
      let b1 = bits p1 and b2 = bits p2 in
      b1 lor b2 = b2
    end else
      false
  end else
    false
end else
  false

```

```

    mismatch "less" p1 p2
let less p1 p2 = p1 ≠ p2 ∧ lesseq p1 p2
let mask_in1 = 1
let mask_in2 = 2
let mask_in = mask_in1 lor mask_in2
module Scattering =
  struct
    let incoming p =
      rank p = 1 ∧ (mask_in land p ≠ 0)
    let outgoing p =
      rank p = 1 ∧ (mask_in land p = 0)
    let timelike p =
      (rank p > 0 ∧ (mask_in land p = 0)) ∨ (bits p = mask_in)
    let spacelike p =
      (rank p > 0) ∧ ¬ (timelike p)
    let s_channel_in p =
      bits p = mask_in
    let s_channel_out p =
      rank p > 0 ∧ (mask_in lxor p = 0)
    let s_channel p =
      s_channel_in p ∨ s_channel_out p
    let flip_s_channel_in p =
      if s_channel_in p then
        neg p
      else
        p
  end
module Decay =
  struct
    let incoming p =
      rank p = 1 ∧ (mask_in1 land p = mask_in1)
    let outgoing p =
      rank p = 1 ∧ (mask_in1 land p = 0)
    let timelike p =
      incoming p ∨ (rank p > 0 ∧ mask_in1 land p = 0)
    let spacelike p =
      ¬ (timelike p)
  end
let test_sum p inv1 p1 inv2 p2 =
  let d = dim p in
  if d = dim p1 then begin

```

```

    if  $d = \dim p2$  then begin
      match (if  $inv1$  then try_add else try_sub)  $p\ p1$  with
      | None  $\rightarrow$  false
      | Some  $p' \rightarrow$ 
        begin match (if  $inv2$  then try_add else try_sub)  $p'\ p2$  with
        | None  $\rightarrow$  false
        | Some  $p'' \rightarrow$ 
          let  $r = \text{rank } p''$  in
           $r = 0 \vee r = d$ 
        end
      end else
        mismatch "test_sum"  $p\ p2$ 
      end else
        mismatch "test_sum"  $p\ p1$ 
    let try_fusion  $p\ p1\ p2 =$ 
      if test_sum  $p\ \text{false}\ p1\ \text{false}\ p2$  then
        Some (false, false)
      else if test_sum  $p\ \text{true}\ p1\ \text{false}\ p2$  then
        Some (true, false)
      else if test_sum  $p\ \text{false}\ p1\ \text{true}\ p2$  then
        Some (false, true)
      else if test_sum  $p\ \text{true}\ p1\ \text{true}\ p2$  then
        Some (true, true)
      else
        None

```

First create a gap of size  $n - 1$  and subsequently fill it if and only if the bit  $i$  was set.

```

let split  $i\ n\ p =$ 
  let  $\text{delta\_d} = n - 1$ 
  and  $b = \text{bits } p$  in
  let  $\text{mask\_low} = \text{mask } (\text{pred } i)$ 
  and  $\text{mask\_i} = 1 \text{ lsl } (\text{pred } i)$ 
  and  $\text{mask\_high} = \text{lnot } (\text{mask } i)$  in
  let  $b\_low = \text{mask\_low} \text{ land } b$ 
  and  $b\_med, \text{delta\_r} =$ 
    if  $\text{mask\_i} \text{ land } b \neq 0$  then
       $((\text{mask } n) \text{ lsl } (\text{pred } i), \text{delta\_d})$ 
    else
       $(0, 0)$ 
  and  $b\_high =$ 
    if  $\text{delta\_d} > 0$  then
       $(\text{mask\_high} \text{ land } b) \text{ lsl } \text{delta\_d}$ 
    else if  $\text{delta\_d} = 0$  then
       $\text{mask\_high} \text{ land } b$ 
    else
       $(\text{mask\_high} \text{ land } b) \text{ lsr } (-\text{delta\_d})$  in
   $\text{drb } (\dim p + \text{delta\_d}) (\text{rank } p + \text{delta\_r}) (b\_low \text{ lor } b\_med \text{ lor } b\_high)$ 
end

```

5.2.3 *Whizard*

```

module type Whizard =
  sig
    type t
    val of_momentum : t → int
    val to_momentum : int → int → t
  end

module BitsW =
  struct
    type t = Bits.t
    open Bits (* NB: this includes the internal functions not in T! *)

    let of_momentum p =
      let d = dim p in
      let bit_in1 = 1 land p
      and bit_in2 = 1 land (p lsr 1)
      and bits_out = ((mask d) land p) lsr 2 in
      bits_out lor (bit_in1 lsl (d - 1)) lor (bit_in2 lsl (d - 2))

    let rec count_non_zero' acc i last b =
      if i > last then
        acc
      else if (1 lsl (pred i)) land b = 0 then
        count_non_zero' acc (succ i) last b
      else
        count_non_zero' (succ acc) (succ i) last b

    let count_non_zero first last b =
      count_non_zero' 0 first last b

    let to_momentum d w =
      let bit_in1 = 1 land (w lsr (d - 1))
      and bit_in2 = 1 land (w lsr (d - 2))
      and bits_out = (mask (d - 2)) land w in
      let b = (bits_out lsl 2) lor bit_in1 lor (bit_in2 lsl 1) in
      drb d (count_non_zero 1 d b) b

  end

```

The following would be a tad more efficient, if coded directly, but there's no point in wasting effort on this.

```

module ListsW =
  struct
    type t = Lists.t
    let of_momentum p =
      BitsW.of_momentum (Bits.of_ints p.Lists.d p.Lists.p)
    let to_momentum d w =
      Lists.of_ints d (Bits.to_ints (BitsW.to_momentum d w))
  end

```

#### 5.2.4 *Suggesting a Default Implementation*

*Lists* is better tested, but the more recent *Bits* appears to work as well and is *much* more efficient, resulting in a relative factor of better than 2. This performance ratio is larger than I had expected and we are not likely to reach its limit of 21 independent vectors anyway.

```
module Default = Bits  
module DefaultW = BitsW
```

---

## —6—

### CASCADES

#### 6.1 Interface of *Cascade\_syntax*

```
type ('flavor, 'p) t =
  | True
  | False
  | On_shell of 'flavor list × 'p
  | On_shell_not of 'flavor list × 'p
  | Off_shell of 'flavor list × 'p
  | Off_shell_not of 'flavor list × 'p
  | Gauss of 'flavor list × 'p
  | Gauss_not of 'flavor list × 'p
  | Any_flavor of 'p
  | Or of ('flavor, 'p) t list
  | And of ('flavor, 'p) t list

val mk_true : unit → ('flavor, 'p) t
val mk_false : unit → ('flavor, 'p) t
val mk_on_shell : 'flavor list → 'p → ('flavor, 'p) t
val mk_on_shell_not : 'flavor list → 'p → ('flavor, 'p) t
val mk_off_shell : 'flavor list → 'p → ('flavor, 'p) t
val mk_off_shell_not : 'flavor list → 'p → ('flavor, 'p) t
val mk_gauss : 'flavor list → 'p → ('flavor, 'p) t
val mk_gauss_not : 'flavor list → 'p → ('flavor, 'p) t
val mk_any_flavor : 'p → ('flavor, 'p) t
val mk_or : ('flavor, 'p) t → ('flavor, 'p) t → ('flavor, 'p) t
val mk_and : ('flavor, 'p) t → ('flavor, 'p) t → ('flavor, 'p) t

val to_string : ('flavor → string) → ('p → string) → ('flavor, 'p) t →
  string

exception Syntax_Error of string × int × int
```

#### 6.2 Implementation of *Cascade\_syntax*

Concerning the Gaussian propagators, we admit the following: In principle, they would allow for flavor sums like the off-shell lines, but for all practical purposes

they are used only for determining the significance of a specified intermediate state. So we select them in the same manner as on-shell states.

```

type ('flavor, 'p) t =
  | True
  | False
  | On_shell of 'flavor list × 'p
  | On_shell_not of 'flavor list × 'p
  | Off_shell of 'flavor list × 'p
  | Off_shell_not of 'flavor list × 'p
  | Gauss of 'flavor list × 'p
  | Gauss_not of 'flavor list × 'p
  | Any_flavor of 'p
  | Or of ('flavor, 'p) t list
  | And of ('flavor, 'p) t list

let mk_true () = True
let mk_false () = False
let mk_on_shell f p = On_shell (f, p)
let mk_on_shell_not f p = On_shell_not (f, p)
let mk_off_shell f p = Off_shell (f, p)
let mk_off_shell_not f p = Off_shell_not (f, p)
let mk_gauss f p = Gauss (f, p)
let mk_gauss_not f p = Gauss_not (f, p)
let mk_any_flavor p = Any_flavor p

let mk_or c1 c2 =
  match c1, c2 with
  | -, True | True, - → True
  | c, False | False, c → c
  | Or cs, Or cs' → Or (cs @ cs')
  | Or cs, c | c, Or cs → Or (c :: cs)
  | c, c' → Or [c; c']

let mk_and c1 c2 =
  match c1, c2 with
  | c, True | True, c → c
  | c, False | False, c → False
  | And cs, And cs' → And (cs @ cs')
  | And cs, c | c, And cs → And (c :: cs)
  | c, c' → And [c; c']

let to_string flavor_to_string momentum_to_string cascades =
  let rec to_string' = function
    | True → "true"
    | False → "false"
    | On_shell (fs, p) →
        momentum_to_string p ^ "□=□" ^ (String.concat ":" (List.map flavor_to_string fs))
    | On_shell_not (fs, p) →
        momentum_to_string p ^ "□=□!" ^ (String.concat ":" (List.map flavor_to_string fs))
    | Off_shell (fs, p) →
        momentum_to_string p ^ "□~□" ^
        (String.concat ":" (List.map flavor_to_string fs))

```



```

| Off_shell_not (fs, p) →
  momentum_to_string p ^ "□~□!" ^
  (String.concat ":" (List.map flavor_to_string fs))
| Gauss (fs, p) →
  momentum_to_string p ^ "□#□" ^ (String.concat ":" (List.map flavor_to_string fs))
| Gauss_not (fs, p) →
  momentum_to_string p ^ "□#□!" ^ (String.concat ":" (List.map flavor_to_string fs))
| Any_flavor p →
  momentum_to_string p ^ "□~□?"
| Or cs →
  String.concat "□||□" (List.map (fun c → "(" ^ to_string' c ^ ")") cs)
| And cs →
  String.concat "□&□" (List.map (fun c → "(" ^ to_string' c ^ ")") cs) in
to_string' cascades

let int_list_to_string p =
  String.concat "+" (List.map string_of_int (Sort.list (<) p))

exception Syntax_Error of string × int × int

```

### 6.3 Lexer

```

{
open Cascade_parser
let unquote s =
  String.sub s 1 (String.length s - 2)
}

let digit = ['0'-'9']
let upper = ['A'-'Z']
let lower = ['a'-'z']
let char = upper | lower
let white = [' ' '\t' '\n']

```

We use a very liberal definition of strings for flavor names.

```

rule token = parse
  white { token lexbuf } (* skip blanks *)
| '%' [^'\n']* '\n'
  { token lexbuf } (* skip comments *)
| digit+ { INT (int_of_string (Lexing.lexeme lexbuf)) }
| '+' { PLUS }
| ':' { COLON }
| '~' { OFFSHELL }
| '=' { ONSHELL }
| '#' { GAUSS }
| '!' { NOT }
| '&' '&'? { AND }
| '|' '|'? { OR }
| '(' { LPAREN }
| ')' { RPAREN }

```

```

| char [ ^ ' , ' , \t ' , \n ' , | ' , & ' , ( ' , ) ' , : ' , ] *
      { FLAVOR (Lexing.lexeme lexbuf) }
| ' ' ' [ ^ ' ' ' ] * ' ' '
      { FLAVOR (unquote (Lexing.lexeme lexbuf)) }
| eof { END }

```

## 6.4 Parser

### Header

```

open Cascade_syntax
let parse_error msg =
  raise (Syntax_Error (msg, symbol_start (), symbol_end ()))

```

### Token declarations

```

%token < string > FLAVOR
%token < int > INT
%token LPAREN RPAREN
%token AND OR PLUS COLON NOT
%token ONSHELL OFFSHELL GAUSS
%token END
%left OR
%left AND
%left PLUS COLON
%left NOT

%start main
%type < (string, int list) Cascade_syntax.t > main

```

### Grammar rules

```

main ::=
  END { mk_true () }
| cascades END { $1 }

cascades ::=
  cascade { $1 }
| LPAREN cascades RPAREN { $2 }
| cascades AND cascades { mk_and $1 $3 }
| cascades OR cascades { mk_or $1 $3 }

```

```

cascade ::=
  | momentum_list { mk_any_flavor $1 }
  | momentum_list ONSHELL flavor_list
    { mk_on_shell $3 $1 }
  | momentum_list ONSHELL NOT flavor_list
    { mk_on_shell_not $4 $1 }
  | momentum_list OFFSHELL flavor_list
    { mk_off_shell $3 $1 }
  | momentum_list OFFSHELL NOT flavor_list
    { mk_off_shell_not $4 $1 }
  | momentum_list GAUSS flavor_list { mk_gauss $3 $1 }
  | momentum_list GAUSS NOT flavor_list
    { mk_gauss_not $4 $1 }

momentum_list ::=
  | momentum { [$1] }
  | momentum_list PLUS momentum { $3 :: $1 }

momentum ::=
  INT { $1 }

flavor_list ::=
  | FLAVOR { [$1] }
  | flavor_list COLON FLAVOR { $3 :: $1 }

```

## 6.5 Interface of *Cascade*

```

module type T =
  sig
    type flavor
    type p
    type t
    val of_string_list : int → string list → t
    val to_string : t → string

```

An opaque type that describes the set of all constraints on an amplitude and how to construct it from a cascade description.

```

  type selectors
  val to_selectors : t → selectors

```

Don't throw anything away:

```

  val no_cascades : selectors

```

*select\_wf* *s* *is\_timelike* *f* *p* *ps* returns true iff either

- the flavor *f* and momentum *p* match the selection *s* or

- *all* combinations of the momenta in *ps* are compatible, i. e.  $\pm \sum p_i \leq q$ .

The latter test is only required in theories with quartic or higher vertices, where *ps* will be the list of all incoming momenta in a fusion. *is\_timelike* is required to determine, whether particles and anti-particles should be distinct.

*val select\_wf : selectors → (p → bool) → flavor → p → p list → bool*  
*select\_p s p ps* same as *select\_wf s f p ps*, but ignores the flavor *f*

*val select\_p : selectors → p → p list → bool*

*on\_shell s p*

*val on\_shell : selectors → flavor → p → bool*

*is\_gauss s p*

*val is\_gauss : selectors → flavor → p → bool*

*partition s* returns a partition of the external particles that can not be reordered without violating the cascade constraints.

*val partition : selectors → int list list*

Diagnostics:

*val description : selectors → string option*

end

module *Make* (*M* : *Model.T*) (*P* : *Momentum.T*) :  
*T* with type *flavor* = *M.flavor* and type *p* = *P.t*

## 6.6 Implementation of *Cascade*

module type *T* =

sig

type *flavor*

type *p*

type *t*

*val of\_string\_list : int → string list → t*

*val to\_string : t → string*

type *selectors*

*val to\_selectors : t → selectors*

*val no\_cascades : selectors*

*val select\_wf : selectors → (p → bool) → flavor → p → p list → bool*

*val select\_p : selectors → p → p list → bool*

*val on\_shell : selectors → flavor → p → bool*

*val is\_gauss : selectors → flavor → p → bool*

*val partition : selectors → int list list*

*val description : selectors → string option*

end

```

module Make (M : Model.T) (P : Momentum.T) :
  (T with type flavor = M.flavor and type p = P.t) =
  struct
    module CS = Cascade_syntax
    type flavor = M.flavor
    type p = P.t
  end

```

Since we have

$$p \leq q \iff (-q) \leq (-p) \quad (6.1)$$

also for  $\leq$  as set inclusion *lesseq*, only four of the eight combinations are independent

$$\begin{aligned}
 p \leq q &\iff (-q) \leq (-p) \\
 q \leq p &\iff (-p) \leq (-q) \\
 p \leq (-q) &\iff q \leq (-p) \\
 (-q) \leq p &\iff (-p) \leq q
 \end{aligned} \quad (6.2)$$

```

let one_compatible p q =
  let neg_q = P.neg q in
  P.lesseq p q ∨
  P.lesseq q p ∨
  P.lesseq p neg_q ∨
  P.lesseq neg_q p

```

'tis wasteful ... (at least by a factor of two, because every momentum combination is generated, including the negative ones.

```

let all_compatible p p_list q =
  let l = List.length p_list in
  if l ≤ 2 then
    one_compatible p q
  else
    let tuple_lengths = ThoList.range 2 (succ l / 2) in
    let tuples = ThoList.flatmap (fun n → Combinatorics.choose n p_list) tuple_lengths in
    let momenta = List.map (List.fold_left P.add (P.zero (P.dim q))) tuples in
    List.for_all (one_compatible q) momenta

```

The following assumes that the *flavor list* is always very short. Otherwise one should use an efficient set implementation.

```

type t =
| True
| False
| On_shell of flavor list × P.t
| On_shell_not of flavor list × P.t
| Off_shell of flavor list × P.t
| Off_shell_not of flavor list × P.t
| Gauss of flavor list × P.t
| Gauss_not of flavor list × P.t
| Any_flavor of P.t
| And of t list

```

```
let of_string s =
  Cascade_parser.main Cascade_lexer.token (Lexing.from_string s)
```



If we knew that we're dealing with a scattering, we could apply *P.flip\_s\_channel\_in* to all momenta, so that 1 + 2 accepts the particle and not the antiparticle. Right now, we don't have this information.

```
let import dim cascades =
  let rec import' = function
    | CS.True →
      True
    | CS.False →
      False
    | CS.On_shell (f, p) →
      On_shell (List.map M.flavor_of_string f, P.of_ints dim p)
    | CS.On_shell_not (f, p) →
      On_shell_not (List.map M.flavor_of_string f, P.of_ints dim p)
    | CS.Off_shell (fs, p) →
      Off_shell (List.map M.flavor_of_string fs, P.of_ints dim p)
    | CS.Off_shell_not (fs, p) →
      Off_shell_not (List.map M.flavor_of_string fs, P.of_ints dim p)
    | CS.Gauss (f, p) →
      Gauss (List.map M.flavor_of_string f, P.of_ints dim p)
    | CS.Gauss_not (f, p) →
      Gauss (List.map M.flavor_of_string f, P.of_ints dim p)
    | CS.Any_flavor p →
      Any_flavor (P.of_ints dim p)
    | CS.Or cs →
      invalid_arg "Cascade: OR patterns (||) not supported in this version!"
    | CS.And cs → And (List.map import' cs) in
  import' cascades

let of_string_list dim strings =
  match List.map of_string strings with
  | [] → True
  | first :: next →
    import dim (List.fold_right CS.mk_and next first)

let flavors_to_string fs =
  (String.concat ":" (List.map M.flavor_to_string fs))

let momentum_to_string p =
  String.concat "+" (List.map string_of_int (P.to_ints p))

let rec to_string = function
  | True →
    "true"
  | False →
    "false"
  | On_shell (fs, p) →
    momentum_to_string p ^ "=" ^ flavors_to_string fs
  | On_shell_not (fs, p) →
```

```

      momentum_to_string p ^ "□=□!" ^ flavors_to_string fs
| Off_shell (fs, p) →
      momentum_to_string p ^ "□~□" ^ flavors_to_string fs
| Off_shell_not (fs, p) →
      momentum_to_string p ^ "□~□!" ^ flavors_to_string fs
| Gauss (fs, p) →
      momentum_to_string p ^ "□#□" ^ flavors_to_string fs
| Gauss_not (fs, p) →
      momentum_to_string p ^ "□#□!" ^ flavors_to_string fs
| Any_flavor p →
      momentum_to_string p ^ "□~□?"
| And cs →
      String.concat "□&&□" (List.map (fun c → "(" ^ to_string c ^ ")") cs)

type selectors =
{ select_p : p → p list → bool;
  select_wf : (p → bool) → flavor → p → p list → bool;
  on_shell : flavor → p → bool;
  is_gauss : flavor → p → bool;
  partition : int list list;
  description : string option }

let no_cascades =
{ select_p = (fun _ _ → true);
  select_wf = (fun _ _ _ _ → true);
  on_shell = (fun _ _ → false);
  is_gauss = (fun _ _ → false);
  partition = [];
  description = None }

let select_p s = s.select_p
let select_wf s = s.select_wf
let on_shell s = s.on_shell
let is_gauss s = s.is_gauss
let partition s = s.partition
let description s = s.description

let to_select_p cascades p p_in =
let rec to_select_p' = function
| True → true
| False → false
| On_shell (_, momentum) | On_shell_not (_, momentum)
| Off_shell (_, momentum) | Off_shell_not (_, momentum)
| Gauss (_, momentum) | Gauss_not (_, momentum)
| Any_flavor momentum → all_compatible p p_in momentum
| And [] → false
| And cs → List.for_all to_select_p' cs in
to_select_p' cascades

let to_select_wf cascades is_timelike f p p_in =
let f' = M.conjugate f in
let rec to_select_wf' = function
| True → true

```

```

| False → false
| Off_shell (flavors, momentum) →
  if p = momentum then
    List.mem f' flavors ∨ (if is_timelike p then false else List.mem f flavors)
  else if p = P.neg momentum then
    List.mem f flavors ∨ (if is_timelike p then false else List.mem f' flavors)
  else
    one_compatible p momentum ∧ all_compatible p p_in momentum
| On_shell (flavors, momentum) | Gauss (flavors, momentum) →
  if is_timelike p then begin
    if p = momentum then
      List.mem f' flavors
    else if p = P.neg momentum then
      List.mem f flavors
    else
      one_compatible p momentum ∧ all_compatible p p_in momentum
  end else
    false
| Off_shell_not (flavors, momentum) →
  if p = momentum then
    ¬ (List.mem f' flavors ∨ (if is_timelike p then false else List.mem f flavors))
  else if p = P.neg momentum then
    ¬ (List.mem f flavors ∨ (if is_timelike p then false else List.mem f' flavors))
  else
    one_compatible p momentum ∧ all_compatible p p_in momentum
| On_shell_not (flavors, momentum) | Gauss_not (flavors, momentum) →

  if is_timelike p then begin
    if p = momentum then
      ¬ (List.mem f' flavors)
    else if p = P.neg momentum then
      ¬ (List.mem f flavors)
    else
      one_compatible p momentum ∧ all_compatible p p_in momentum
  end else
    false
| Any_flavor momentum →
  one_compatible p momentum ∧ all_compatible p p_in momentum
| And [] → false
| And cs → List.for_all to_select_wf' cs in
  to_select_wf' cascades

```

In case you're wondering: *to\_on\_shell* *f* *p* and *is\_gauss* *f* *p* only search for on shell conditions and are to be used in a target, not in *Fusion*!

```

let to_on_shell cascades f p =
  let f' = M.conjugate f in
  let rec to_on_shell' = function
    | True | False | Any_flavor _
    | Off_shell (_, _) | Off_shell_not (_, _)
    | Gauss (_, _) | Gauss_not (_, _) → false

```



```

      | On_shell (flavors, momentum) →
        (p = momentum ∨ p = P.neg momentum) ∧ (List.mem f flavors ∨
List.mem f' flavors)
      | On_shell_not (flavors, momentum) →
        (p = momentum ∨ p = P.neg momentum) ∧ ¬ (List.mem f flavors ∨
List.mem f' flavors)
      | And [] → false
      | And cs → List.for_all to_on_shell' cs in
to_on_shell' cascades

let to_gauss cascades f p =
  let f' = M.conjugate f in
  let rec to_gauss' = function
    | True | False | Any_flavor _
    | Off_shell (_, _) | Off_shell_not (_, _)
    | On_shell (_, _) | On_shell_not (_, _) → false
    | Gauss (flavors, momentum) →
      (p = momentum ∨ p = P.neg momentum) ∧ (List.mem f flavors ∨
List.mem f' flavors)
    | Gauss_not (flavors, momentum) →
      (p = momentum ∨ p = P.neg momentum) ∧ ¬ (List.mem f flavors ∨
List.mem f' flavors)
    | And [] → false
    | And cs → List.for_all to_gauss' cs in
to_gauss' cascades

```



Not a working implementation yet, but it isn't used either ...

```

module IPowSet =
  PowSet.Make (struct type t = int let compare = compare let to_string = string_of_int end)

let rec coarsest_partition' = function
  | True | False → IPowSet.empty
  | On_shell (_, momentum) | On_shell_not (_, momentum)
  | Off_shell (_, momentum) | Off_shell_not (_, momentum)
  | Gauss (_, momentum) | Gauss_not (_, momentum)
  | Any_flavor momentum → IPowSet.of_lists [P.to_ints momentum]
  | And [] → IPowSet.empty
  | And cs → IPowSet.basis (IPowSet.union (List.map coarsest_partition' cs))

let coarsest_partition cascades =
  let p = coarsest_partition' cascades in
  if IPowSet.is_empty p then
    []
  else
    IPowSet.to_lists p

let part_to_string part =
  "{" ^ String.concat "," (List.map string_of_int part) ^ "}"

let partition_to_string = function
  | [] → ""

```

```
| parts →  
  "␣␣grouping␣{" ^ String.concat "␣," (List.map part_to_string parts) ^ "}"  
let to_selectors = function  
| True → no_cascades  
| c →  
  let partition = coarsest_partition c in  
  { select_p = to_select_p c;  
    select_wf = to_select_wf c;  
    on_shell = to_on_shell c;  
    is_gauss = to_gauss c;  
    partition = partition;  
    description = Some (to_string c ^ partition_to_string partition) }  
end
```

---

# —7—

## COLOR

### 7.1 Interface of Color

#### 7.1.1 Quantum Numbers

Color is not necessarily the  $SU(3)$  of QCD. Conceptually, it can be any *unbroken* symmetry (*broken* symmetries correspond to *Model.flavor*). In order to keep the group theory simple, we confine ourselves to the fundamental and adjoint representation of a single  $SU(N_C)$  for the moment. Therefore, particles are either color singlets or live in the defining representation of  $SU(N_C)$ :  $SUN(|N_C|)$ , its conjugate  $SUN(-|N_C|)$  or in the adjoint representation of  $SU(N_C)$ :  $AdjSUN(N_C)$ .

`type t = Singlet | SUN of int | AdjSUN of int`

`val conjugate : t → t`

`val compare : t → t → int`

#### 7.1.2 Color Flows

`module type Flow =`

`sig`

`type color`

`type t = color list × color list`

`val rank : t → int`

`val of_list : int list → color`

`val ghost : unit → color`

`val to_lists : t → int list list`

`val in_to_lists : t → int list list`

`val out_to_lists : t → int list list`

`val ghost_flags : t → bool list`

`val in_ghost_flags : t → bool list`

`val out_ghost_flags : t → bool list`

A factor is a list of powers

$$\sum_i \left( \frac{num_i}{den_i} \right)^{power_i} \quad (7.1)$$

```

type power = { num : int; den : int; power : int }
type factor = power list

val factor : t → t → factor
val zero : factor

end

module Flow : Flow

```

## 7.2 Implementation of *Color*

### 7.2.1 Quantum Numbers

```

type t =
| Singlet
| SUN of int
| AdjSUN of int

let conjugate = function
| Singlet → Singlet
| SUN n → SUN (-n)
| AdjSUN n → AdjSUN n

let compare c1 c2 =
match c1, c2 with
| Singlet, Singlet → 0
| Singlet, _ → -1
| _, Singlet → 1
| SUN n, SUN n' → compare n n'
| SUN _, AdjSUN _ → -1
| AdjSUN _, SUN _ → 1
| AdjSUN n, AdjSUN n' → compare n n'

module type Line =
sig
type t
val conj : t → t
val equal : t → t → bool
val to_string : t → string
end

module type Cycles =
sig
type line
type t = (line × line) list

```

Contract the graph by connecting lines and return the number of cycles together with the contracted graph.



The semantics of the contracted graph is not yet 100%ly fixed.

```

val contract : t → int × t

```

The same as *contract*, but returns only the number of cycles and raises *Open\_line* when not all lines are closed.

```
val count : t → int
exception Open_line
```

Mainly for debugging ...

```
val to_string : t → string
```

```
end
```

```
module Cycles (L : Line) : Cycles with type line = L.t =
struct
```

```
  type line = L.t
  type t = (line × line) list
  exception Open_line
```

NB: The following algorithm for counting the cycles is quadratic since it performs nested scans of the lists. If this was a serious problem one could replace the lists of pairs by a *Map* and replace one power by a logarithm.

```
let rec find_fst c_final c1 disc seen = function
| [] → ((L.conj c_final, c1) :: disc, List.rev seen)
| (c1', c2') as c12' :: rest →
  if L.equal c1 c1' then
    find_snd c_final (L.conj c2') disc [] (List.rev_append seen rest)
  else
    find_fst c_final c1 disc (c12' :: seen) rest

and find_snd c_final c2 disc seen = function
| [] → ((L.conj c_final, L.conj c2) :: disc, List.rev seen)
| (c1', c2') as c12' :: rest →
  if L.equal c2' c2 then begin
    if L.equal c1' c_final then
      (disc, List.rev_append seen rest)
    else
      find_fst c_final (L.conj c1') disc [] (List.rev_append seen rest)
  end else
    find_snd c_final c2 disc (c12' :: seen) rest

let consume = function
| [] → ([], [])
| (c1, c2) :: rest → find_snd (L.conj c1) (L.conj c2) [] [] rest

let contract lines =
  let rec contract' acc disc = function
  | [] → (acc, List.rev disc)
  | rest →
    begin match consume rest with
    | [], rest' → contract' (succ acc) disc rest'
    | disc', rest' → contract' acc (List.rev_append disc' disc) rest'
    end in
  contract' 0 [] lines
```

```

let count lines =
  match contract lines with
  | n, [] → n
  | n, _ → raise Open_line
let to_string lines =
  String.concat ""
  (List.map
   (fun (c1, c2) → "[" ^ L.to_string c1 ^ ", " ^ L.to_string c2 ^ "]")
   lines)
end

```

### 7.2.2 Color Flows

```

module type Flow =
sig
  type color
  type t = color list × color list
  val rank : t → int
  val of_list : int list → color
  val ghost : unit → color
  val to_lists : t → int list list
  val in_to_lists : t → int list list
  val out_to_lists : t → int list list
  val ghost_flags : t → bool list
  val in_ghost_flags : t → bool list
  val out_ghost_flags : t → bool list
  type power = { num : int; den : int; power : int }
  type factor = power list
  val factor : t → t → factor
  val zero : factor
end

module Flow (* : Flow *) =
struct
  type color =
    | Lines of int × int
    | Ghost
  type t = color list × color list
  let rank cflow =
    2

```

#### Constructors

```

let ghost () =
  Ghost
let of_list = function

```

```

| [c1; c2] → Lines (c1, c2)
| - → invalid_arg "Color.Flow.of_list:_num_lines_!=_2"

let to_list = function
| Lines (c1, c2) → [c1; c2]
| Ghost → [0; 0]

let to_lists (cfin, cfout) =
(List.map to_list cfin) @ (List.map to_list cfout)

let in_to_lists (cfin, _) =
List.map to_list cfin

let out_to_lists (_, cfout) =
List.map to_list cfout

let ghost_flag = function
| Lines _ → false
| Ghost → true

let ghost_flags (cfin, cfout) =
(List.map ghost_flag cfin) @ (List.map ghost_flag cfout)

let in_ghost_flags (cfin, _) =
List.map ghost_flag cfin

let out_ghost_flags (_, cfout) =
List.map ghost_flag cfout

```

### Evaluation

```

type power = { num : int; den : int; power : int }
type factor = power list
let zero = []

let count_ghosts1 colors =
List.fold_left
(fun acc → function Ghost → succ acc | - → acc)
0 colors

let count_ghosts (fin, fout) =
count_ghosts1 fin + count_ghosts1 fout

type α square =
| Square of α
| Mismatch

let conjugate = function
| Lines (c1, c2) → Lines (-c2, -c1)
| Ghost → Ghost

let cross_in (cin, cout) =
cin @ (List.map conjugate cout)

let cross_out (cin, cout) =
(List.map conjugate cin) @ cout

```

```

module C = Cycles (struct
  type t = int
  let conj = (-)
  let equal = (=)
  let to_string = string_of_int
end)

let square f1 f2 =
  let rec square' acc f1' f2' =
    match f1', f2' with
    | [], [] → Square (List.rev acc)
    | -, [] | [], - → Mismatch
    | Ghost :: rest1, Ghost :: rest2 →
        square' acc rest1 rest2
    | Lines (0, 0) :: rest1, Lines (0, 0) :: rest2 →
        square' acc rest1 rest2
    | Lines (0, c1') :: rest1, Lines (0, c2') :: rest2 →
        square' ((c1', c2') :: acc) rest1 rest2
    | Lines (c1, 0) :: rest1, Lines (c2, 0) :: rest2 →
        square' ((c1, c2) :: acc) rest1 rest2
    | Lines (0, -) :: -, - | -, Lines (0, -) :: -
    | Lines (-, 0) :: -, - | -, Lines (-, 0) :: - → Mismatch
    | Lines (-, -) :: -, Ghost :: - | Ghost :: -, Lines (-, -) :: - →
Mismatch
    | Lines (c1, c1') :: rest1, Lines (c2, c2') :: rest2 →
        square' ((c1', c2') :: (c1, c2) :: acc) rest1 rest2 in
  square' [] (cross_out f1) (cross_out f2)

```

In addition to counting closed color loops, we also need to count closed gluon loops. Fortunately, we can use the same algorithm on a different data type, provided it doesn't require all lines to be closed.

```

module C2 = Cycles (struct
  type t = int × int
  let conj (c1, c2) = (- c2, - c1)
  let equal (c1, c2) (c1', c2') = c1 = c1' ∧ c2 = c2'
  let to_string (c1, c2) = "(" ^ string_of_int c1 ^ ", " ^ string_of_int c2 ^ ")"
end)

let square2 f1 f2 =
  let rec square2' acc f1' f2' =
    match f1', f2' with
    | [], [] → Square (List.rev acc)
    | -, [] | [], - → Mismatch
    | Ghost :: rest1, Ghost :: rest2 →
        square2' acc rest1 rest2
    | Lines (0, 0) :: rest1, Lines (0, 0) :: rest2 →
        square2' acc rest1 rest2
    | Lines (0, -) :: rest1, Lines (0, -) :: rest2
    | Lines (-, 0) :: rest1, Lines (-, 0) :: rest2 →
        square2' acc rest1 rest2
    | Lines (0, -) :: -, - | -, Lines (0, -) :: -

```



```

      | Lines (_, 0) :: -, - | -, Lines (_, 0) :: - → Mismatch
      | Lines (_, -) :: -, Ghost :: - | Ghost :: -, Lines (_, -) :: - →
Mismatch
      | Lines (c1, c1') :: rest1, Lines (c2, c2') :: rest2 →
        square2' (((c1, c1'), (c2, c2'))) :: acc) rest1 rest2 in
square2' [] (cross_out f1) (cross_out f2)

```

*int\_power* :  $n\ p \rightarrow n^p$  for integers is missing from *Pervasives*!

```

let int_power n p =
  let rec int_power' acc i =
    if i < 0 then
      invalid_arg "int_power"
    else if i = 0 then
      acc
    else
      int_power' (n × acc) (pred i) in
  int_power' 1 p

```

Instead of implementing a full fledged algebraic evaluator, let's simply expand the binomial by hand:

$$\left(\frac{N_C^2 - 2}{N_C^2}\right)^n = \sum_{i=0}^n \binom{n}{i} (-2)^i N_C^{-2i} \quad (7.2)$$

NB: Any result of *square* other than *Mismatch* guarantees *count\_ghosts f1* = *count\_ghosts f2*.

```

let factor f1 f2 =
  match square f1 f2, square2 f1 f2 with
  | Mismatch, _ | -, Mismatch → []
  | Square f12, Square f12' →
    let num_cycles = C.count f12
    and num_cycles2, disc = C2.contract f12'
    and num_ghosts = count_ghosts f1 in
    List.map
      (fun i →
        let parity = if num_ghosts mod 2 = 0 then 1 else -1
        and power = num_cycles - num_ghosts in
        let coeff = int_power (-2) i × Combinatorics.binomial num_cycles2 i
        and power2 = - 2 × i in
        { num = parity × coeff;
          den = 1;
          power = power + power2 })
      (ThoList.range 0 num_cycles2)

```

end

later:

```

module General_Flow =
  struct
    type color =
      | Lines of int list

```

---

```
| Ghost of int
type t = color list × color list
let rank_default = 2 (* Standard model *)
let rank cflow =
  try
    begin match List.hd cflow with
    | Lines lines → List.length lines
    | Ghost n_lines → n_lines
    end
  with
  | _ → rank_default
end
```

---

# —8—

## FUSIONS

### 8.1 *Interface of Fusion*

```
module type T =
  sig
```

```
    val options : Options.t
```

Wavefunctions are an abstract data type, containing a momentum  $p$  and additional quantum numbers, collected in *flavor*.

```
    type wf
    val conjugate : wf → wf
```

Obviously, *flavor* is not restricted to the physical notion of flavor, but can carry spin, color, etc.

```
    type flavor
    val flavor : wf → flavor
    type flavor_sans_color
    val flavor_sans_color : wf → flavor_sans_color
```

Momenta are represented by an abstract datatype (defined in *Momentum*) that is optimized for performance. They can be accessed either abstractly or as lists of indices of the external momenta. These indices are assigned sequentially by *amplitude* below.

```
    type p
    val momentum : wf → p
    val momentum_list : wf → int list
```

At tree level, the wave functions are uniquely specified by *flavor* and momentum. If loops are included, we need to distinguish among orders. Also, if we build a result from an incomplete sum of diagrams, we need to add a distinguishing mark. At the moment, we assume that a *string* that can be attached to the symbol suffices.

```
    val wf_tag : wf → string option
```

Coupling constants

```
    type constant
```

and right hand sides of assignments. The latter are formed from a sign from Fermi statistics, a coupling (constant and Lorentz structure) and wave functions.

```

type coupling
type rhs
type  $\alpha$  children
val sign : rhs  $\rightarrow$  int
val coupling : rhs  $\rightarrow$  constant Coupling.t
val coupling_tag : rhs  $\rightarrow$  string option

```

In renormalized perturbation theory, couplings come in different orders of the loop expansion. Be prepared: `val order : rhs  $\rightarrow$  int`



This is here only for the benefit of *Target* and shall become `val children : rhs  $\rightarrow$  wf children` later ...

```

val children : rhs  $\rightarrow$  wf list

```

Fusions come in two types: fusions of wave functions to off-shell wave functions:

$$\phi(p+q) = \phi(p)\phi(q)$$

```

type fusion
val lhs : fusion  $\rightarrow$  wf
val rhs : fusion  $\rightarrow$  rhs list

```

and products at the keystones:

$$\phi(-p-q) \cdot \phi(p)\phi(q)$$

```

type braket
val bra : braket  $\rightarrow$  wf
val ket : braket  $\rightarrow$  rhs list

```

*amplitude goldstones incoming outgoing* calculates the amplitude for scattering of *incoming* to *outgoing*. If *goldstones* is true, also non-propagating off-shell Goldstone amplitudes are included to allow the checking of Slavnov-Taylor identities.

```

type amplitude
type selectors
val amplitudes : bool  $\rightarrow$  selectors  $\rightarrow$ 
  flavor_sans_color list  $\rightarrow$  flavor_sans_color list  $\rightarrow$  amplitude list
val dependencies : amplitude  $\rightarrow$  wf  $\rightarrow$  (wf, coupling) Tree2.t

```

We should be precise regarding the semantics of the following functions, since modules implementating *Target* must not make any mistakes interpreting the return values. Instead of calculating the amplitude

$$\langle f_3, p_3, f_4, p_4, \dots | T | f_1, p_1, f_2, p_2 \rangle \quad (8.1a)$$

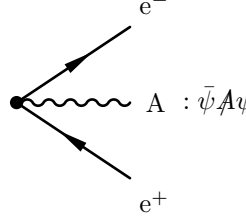
directly, O'Mega calculates the—equivalent, but more symmetrical—crossed amplitude

$$\langle \bar{f}_1, -p_1, \bar{f}_2, -p_2, f_3, p_3, f_4, p_4, \dots | T | 0 \rangle \quad (8.1b)$$

Internally, all flavors are represented by their charge conjugates

$$A(f_1, -p_1, f_2, -p_2, \bar{f}_3, p_3, \bar{f}_4, p_4, \dots) \quad (8.1c)$$

The correspondence of vertex and term in the lagrangian



$$(8.2)$$

suggests to denote the *outgoing* particle by the flavor of the *antiparticle* and the *outgoing antiparticle* by the flavor of the *particle*, since this choice allows to represent the vertex by a triple

$$\bar{\psi} A \psi : (e^+, A, e^-) \quad (8.3)$$

which is more intuitive than the alternative  $(e^-, A, e^+)$ . Also, when thinking in terms of building wavefunctions from the outside in, the outgoing *antiparticle* is represented by a *particle* propagator and vice versa<sup>1</sup>. *incoming* and *outgoing* are the physical flavors as in (8.1a)

`val incoming : amplitude → flavor list`

`val outgoing : amplitude → flavor list`

*externals* are flavors and momenta as in (8.1c)

`val externals : amplitude → wf list`

`val variables : amplitude → wf list`

`val fusions : amplitude → fusion list`

`val brackets : amplitude → bracket list`

`val on_shell : amplitude → (wf → bool)`

`val is_gauss : amplitude → (wf → bool)`

`val constraints : amplitude → string option`

`val symmetry : amplitude → int`

`val allowed : amplitude → bool`

### Performance Hacks

`val initialize_cache : string → unit`

`val set_cache_name : string → unit`

### Diagnostics

`val check_charges : unit → flavor_sans_color list list`

`val count_fusions : amplitude → int`

<sup>1</sup>Even if this choice will appear slightly counter-intuitive on the *Target* side, one must keep in mind that much more people are expected to prepare *Models*.

```

val count_propagators : amplitude → int
val count_diagrams : amplitude → int

val forest : wf → amplitude → ((wf × coupling option, wf) Tree.t) list
val poles : amplitude → wf list list
val s_channel : amplitude → wf list

val tower_to_dot : out_channel → amplitude → unit
val amplitude_to_dot : out_channel → amplitude → unit

val rcs_list : RCS.t list
end

```

There is more than one way to make fusions.

```

module type Maker =
  functor (P : Momentum.T) → functor (M : Model.T) →
    T with type p = P.t
    and type flavor = Colorize.It(M).flavor
    and type flavor_sans_color = M.flavor
    and type constant = M.constant
    and type selectors = Cascade.Make(M)(P).selectors

```

Straightforward Dirac fermions vs. slightly more complicated Majorana fermions:

```

module Binary : Maker
module Binary_Majorana : Maker

module Mixed23 : Maker
module Mixed23_Majorana : Maker

module Nary : functor (B : Tuple.Bound) → Maker
module Nary_Majorana : functor (B : Tuple.Bound) → Maker

```

We can also proceed á la [2]. Empirically, this will use slightly ( $O(10\%)$ ) fewer fusions than the symmetric factorization. Our implementation uses significantly ( $O(50\%)$ ) fewer fusions than reported by [2]. Our pruning of the DAG might be responsible for this.

```

module Helac : functor (B : Tuple.Bound) → Maker
module Helac_Majorana : functor (B : Tuple.Bound) → Maker

```

### 8.1.1 Multiple Amplitudes

```

module type Multi =
  sig
    exception Mismatch
    val options : Options.t

    type flavor
    type process = flavor list × flavor list
    type amplitude
    type fusion
    type wf
    type selectors

```

`type amplitudes`

Construct all possible color flow amplitudes for a given process.

```
val amplitudes : bool → int option → selectors → process list →
amplitudes
val empty : amplitudes
```

Precompute the vertex table cache.

```
val initialize_cache : string → unit
val set_cache_name : string → unit
```

The list of all combinations of incoming and outgoing particles with a nonvanishing scattering amplitude.

```
val flavors : amplitudes → process list
```

The list of all combinations of incoming and outgoing particles that don't lead to any color flow with non vanishing scattering amplitude.

```
val vanishing_flavors : amplitudes → process list
```

The list of all color flows with a nonvanishing scattering amplitude.

```
val color_flows : amplitudes → Color.Flow.t list
```

The list of all valid helicity combinations.

```
val helicities : amplitudes → (int list × int list) list
```

The list of all amplitudes.

```
val processes : amplitudes → amplitude list
```

$(process\_table\ a).(f).(c)$  returns the amplitude for the  $f$ th allowed flavor combination and the  $c$ th allowed color flow as an *amplitude option*.

```
val process_table : amplitudes → amplitude option array array
```

The list of all non redundant fusions together with the amplitudes they came from.

```
val fusions : amplitudes → (fusion × amplitude) list
```

If there's more than external flavor state, the wavefunctions are *not* uniquely specified by *flavor* and *Momentum.t*. This function can be used to determine how many variables must be allocated.

```
val multiplicity : amplitudes → wf → int
```

This function can be used to disambiguate wavefunctions with the same combination of *flavor* and *Momentum.t*.

```
val dictionary : amplitudes → amplitude → wf → int
```

$(color\_factors\ a).(c1).(c2)$  power of  $N_C$  for the given product of color flows.

```
val color_factors : amplitudes → Color.Flow.factor array array
```

A description of optional diagram selectors.

```
val constraints : amplitudes → string option
```

```

end

module type Multi_Maker = functor (Fusion_Maker : Maker) →
  functor (P : Momentum.T) →
    functor (M : Model.T) →
      Multi with type flavor = M.flavor
      and type amplitude = Fusion_Maker(P)(M).amplitude
      and type fusion = Fusion_Maker(P)(M).fusion
      and type wf = Fusion_Maker(P)(M).wf
      and type selectors = Fusion_Maker(P)(M).selectors

module Multi : Multi_Maker

```

### 8.1.2 Tags

It appears that there are useful applications for tagging couplings and wave functions, e.g. skeleton expansion and diagram selections. We can abstract this in a *Tags* signature:

```

module type Tags =
  sig
    type wf
    type coupling
    type  $\alpha$  children
    val null_wf : wf
    val null_coupling : coupling
    val fuse : coupling → wf children → wf
    val wf_to_string : wf → string option
    val coupling_to_string : coupling → string option
  end

module type Tagger =
  functor (PT : Tuple.Poly) → Tags with type  $\alpha$  children =  $\alpha$  PT.t

module type Tagged_Maker =
  functor (Tagger : Tagger) →
    functor (P : Momentum.T) → functor (M : Model.T) →
      T with type p = P.t
      and type flavor = Colorize.It(M).flavor
      and type flavor_sans_color = M.flavor
      and type constant = M.constant

module Tagged_Binary : Tagged_Maker

```

## 8.2 Implementation of *Fusion*

```

let rcs_file = RCS.parse "Fusion" ["General_Fusions"]
{ RCS.revision = "$Revision: 5023$";
  RCS.date = "$Date: 2013-12-20 13:03:39 +0100 (Fri, 20 Dec 2013)$";
  RCS.author = "$Author: ohl$";
  RCS.source

```



```

      = "$URL:␣svn+ssh://jr_reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/s
module type T =
  sig
    val options : Options.t
    type wf
    val conjugate : wf → wf
    type flavor
    type flavor_sans_color
    val flavor : wf → flavor
    val flavor_sans_color : wf → flavor_sans_color
    type p
    val momentum : wf → p
    val momentum_list : wf → int list
    val wf_tag : wf → string option
    type constant
    type coupling
    type rhs
    type  $\alpha$  children
    val sign : rhs → int
    val coupling : rhs → constant Coupling.t
    val coupling_tag : rhs → string option
    val children : rhs → wf list
    type fusion
    val lhs : fusion → wf
    val rhs : fusion → rhs list
    type braket
    val bra : braket → wf
    val ket : braket → rhs list
    type amplitude
    type selectors
    val amplitudes : bool → selectors →
      flavor_sans_color list → flavor_sans_color list → amplitude list
    val dependencies : amplitude → wf → (wf, coupling) Tree2.t
    val incoming : amplitude → flavor list
    val outgoing : amplitude → flavor list
    val externals : amplitude → wf list
    val variables : amplitude → wf list
    val fusions : amplitude → fusion list
    val brackets : amplitude → braket list
    val on_shell : amplitude → (wf → bool)
    val is_gauss : amplitude → (wf → bool)
    val constraints : amplitude → string option
    val symmetry : amplitude → int
    val allowed : amplitude → bool
    val initialize_cache : string → unit
    val set_cache_name : string → unit
    val check_charges : unit → flavor_sans_color list list
    val count_fusions : amplitude → int
    val count_propagators : amplitude → int

```

```

val count_diagrams : amplitude → int
val forest : wf → amplitude → ((wf × coupling option, wf) Tree.t) list
val poles : amplitude → wf list list
val s_channel : amplitude → wf list
val tower_to_dot : out_channel → amplitude → unit
val amplitude_to_dot : out_channel → amplitude → unit
val rcs_list : RCS.t list
end

module type Maker =
  functor (P : Momentum.T) → functor (M : Model.T) →
    T with type p = P.t
    and type flavor = Colorize.It(M).flavor
    and type flavor_sans_color = M.flavor
    and type constant = M.constant
    and type selectors = Cascade.Make(M)(P).selectors

```

### 8.2.1 Fermi Statistics

```

module type Stat =
  sig
    type flavor
    type stat
    exception Impossible
    val stat : flavor → int → stat
    val stat_fuse : stat → stat → flavor → stat
    val stat_sign : stat → int
    val rcs : RCS.t
  end

module type Stat_Maker = functor (M : Model.T) →
  Stat with type flavor = M.flavor

```

### 8.2.2 Dirac Fermions

```

module Stat_Dirac (M : Model.T) : (Stat with type flavor = M.flavor) =
  struct
    let rcs = RCS.rename rcs_file "Fusion.Stat_Dirac()"
      [ "Fermi_statistics_for_Dirac_fermions" ]
    type flavor = M.flavor
  end

```

$$\gamma_\mu \psi(1) G^{\mu\nu} \bar{\psi}(2) \gamma_\nu \psi(3) - \gamma_\mu \psi(3) G^{\mu\nu} \bar{\psi}(2) \gamma_\nu \psi(1) \quad (8.4)$$

```

type stat =
  | Fermion of int × (int option × int option) list
  | AntiFermion of int × (int option × int option) list
  | Boson of (int option × int option) list

let stat f p =

```

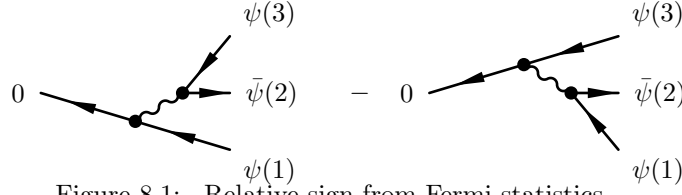


Figure 8.1: Relative sign from Fermi statistics.

```

let s = M.fermion f in
if s = 0 then
  Boson []
else if s < 0 then
  AntiFermion (p, [])
else (* if s > 0 then *)
  Fermion (p, [])
exception Impossible
let stat_fuse s1 s2 f =
  match s1, s2 with
  | Boson l1, Boson l2 → Boson (l1 @ l2)
  | Boson l1, Fermion (p, l2) → Fermion (p, l1 @ l2)
  | Boson l1, AntiFermion (p, l2) → AntiFermion (p, l1 @ l2)
  | Fermion (p, l1), Boson l2 → Fermion (p, l1 @ l2)
  | AntiFermion (p, l1), Boson l2 → AntiFermion (p, l1 @ l2)
  | AntiFermion (pbar, l1), Fermion (p, l2) →
    Boson ((Some pbar, Some p) :: l1 @ l2)
  | Fermion (p, l1), AntiFermion (pbar, l2) →
    Boson ((Some pbar, Some p) :: l1 @ l2)
  | Fermion _, Fermion _ | AntiFermion _, AntiFermion _ →
    raise Impossible

```

$$\epsilon(\{(0,1),(2,3)\}) = -\epsilon(\{(0,3),(2,1)\}) \quad (8.5)$$

```

let permutation lines =
  let fout, fin = List.split lines in
  let eps_in, _ = Combinatorics.sort_signed compare fin
  and eps_out, _ = Combinatorics.sort_signed compare fout in
  (eps_in × eps_out)

```



This comparing of permutations of fermion lines is a bit tedious and takes a macroscopic fraction of time. However, it's less than 20 %, so we don't focus on improving on it yet.

```

let stat_sign = function
| Boson lines → permutation lines
| Fermion (p, lines) → permutation ((None, Some p) :: lines)
| AntiFermion (pbar, lines) → permutation ((Some pbar, None) :: lines)
end

```

## 8.2.3 Tags

```

module type Tags =
sig
  type wf
  type coupling
  type  $\alpha$  children
  val null_wf : wf
  val null_coupling : coupling
  val fuse : coupling → wf children → wf
  val wf_to_string : wf → string option
  val coupling_to_string : coupling → string option
end

module type Tagger =
  functor (PT : Tuple.Poly) → Tags with type  $\alpha$  children =  $\alpha$  PT.t

module type Tagged_Maker =
  functor (Tagger : Tagger) →
    functor (P : Momentum.T) → functor (M : Model.T) →
      T with type p = P.t
      and type flavor = Colorize.It(M).flavor
      and type flavor_sans_color = M.flavor
      and type constant = M.constant

No tags is one option for good tags ...

module No_Tags (PT : Tuple.Poly) =
  struct
    type wf = unit
    type coupling = unit
    type  $\alpha$  children =  $\alpha$  PT.t
    let null_wf = ()
    let null_coupling = ()
    let fuse () - = ()
    let wf_to_string () = None
    let coupling_to_string () = None
  end

```



Here's a simple additive tag that can grow into something useful for loop calculations.

```

module Loop_Tags (PT : Tuple.Poly) =
  struct
    type wf = int
    type coupling = int
    type  $\alpha$  children =  $\alpha$  PT.t
    let null_wf = 0
    let null_coupling = 0
    let fuse c wfs = PT.fold_left (+) c wfs
    let wf_to_string n = Some (string_of_int n)
    let coupling_to_string n = Some (string_of_int n)
  end

```

```

end
module Order_Tags (PT : Tuple.Poly) =
struct
  type wf = int
  type coupling = int
  type  $\alpha$  children =  $\alpha$  PT.t
  let null_wf = 0
  let null_coupling = 0
  let fuse c wfs = PT.fold_left (+) c wfs
  let wf_to_string n = Some (string_of_int n)
  let coupling_to_string n = Some (string_of_int n)
end

```

#### 8.2.4 Tagged, the *Fusion.Make* Functor

```

module Tagged (Tagger : Tagger) (PT : Tuple.Poly)
  (Stat : Stat_Maker) (T : Topology.T with type  $\alpha$  children =  $\alpha$  PT.t)
  (P : Momentum.T) (M : Model.T) =
struct
  let rcs = RCS.rename rcs_file "Fusion.Make()"
    [ "Fusions_for_arbitrary_topologies" ]

  type cache_mode = Cache_Use | Cache_Ignore | Cache_Overwrite
  let cache_option = ref Cache_Use
  type qcd_order =
    | QCD_order of int
  type ew_order =
    | EW_order of int
  let qcd_order = ref (QCD_order 99)
  let ew_order = ref (EW_order 99)

  let options = Options.create
    [ "ignore-cache", Arg.Unit (fun () → cache_option := Cache_Ignore),
      "ignore_cached_model_tables";
      "overwrite-cache", Arg.Unit (fun () → cache_option := Cache_Overwrite),
      "overwrite_cached_model_tables";
      "qcd", Arg.Int (fun n → qcd_order := QCD_order n),
      "set_QCD_order_n [>=0, default=99]";
      "ew", Arg.Int (fun n → ew_order := EW_order n),
      "set_QCD_order_n [>=0, default=99]" ]

  exception Negative_QCD_order
  exception Negative_EW_order
  exception Vanishing_couplings
  exception Negative_QCD_EW_orders

  let int_orders =
    match !qcd_order, !ew_order with
    | QCD_order n, EW_order n' when n < 0  $\wedge$  n'  $\geq$  0 →
      raise Negative_QCD_order
    | QCD_order n, EW_order n' when n  $\geq$  0  $\wedge$  n' < 0 →

```

```

      raise Negative_EW_order
    | QCD_order n, EW_order n' when n < 0 ∧ n' < 0 →
      raise Negative_QCD_EW_orders
    | QCD_order n, EW_order n' → (n, n')

open Coupling

module S = Stat(M)

type stat = S.stat
let stat = S.stat
let stat_sign = S.stat_sign

```



This will do *something* for 4-, 6-, ... fermion vertices, but not necessarily the right thing ...

```

let stat_fuse s f =
  PT.fold_right_internal (fun s' acc → S.stat_fuse s' acc f) s
type constant = M.constant

```

### Wave Functions



The code below is not yet functional. Too often, we assign to *Tags.null\_wf* instead of calling *Tags.fuse*.

We will need two types of amplitudes: with color and without color. Since we can build them using the same types with only *flavor* replaced, it pays to use a functor to set up the scaffolding.

```

module Tags = Tagger(PT)

```

In the future, we might want to have *Coupling* among the functor arguments. However, for the moment, *Coupling* is assumed to be comprehensive.

```

module type Tagged_Coupling =
sig
  type sign = int
  type t =
    { sign : sign;
      coupling : constant Coupling.t;
      coupling_tag : Tags.coupling }
  val sign : t → sign
  val coupling : t → constant Coupling.t
  val coupling_tag : t → string option
end

module Tagged_Coupling : Tagged_Coupling =
struct
  type sign = int
  type t =
    { sign : sign;
      coupling : constant Coupling.t;

```

```

      coupling_tag : Tags.coupling }
let sign c = c.sign
let coupling c = c.coupling
let coupling_tag_raw c = c.coupling_tag
let coupling_tag rhs = Tags.coupling_to_string (coupling_tag_raw rhs)
end

```

### Amplitudes: Monochrome and Colored

```

module type Amplitude =
sig
  module Tags : Tags

  type flavor
  type p

  type wf =
    { flavor : flavor;
      momentum : p;
      wf_tag : Tags.wf }

  val flavor : wf → flavor
  val conjugate : wf → wf
  val momentum : wf → p
  val momentum_list : wf → int list
  val wf_tag : wf → string option
  val wf_tag_raw : wf → Tags.wf
  val order_wf : wf → wf → int
  val external_wfs : int → (flavor × int) list → wf list

  type α children
  type coupling = Tagged_Coupling.t
  type rhs = coupling × wf children
  val sign : rhs → int
  val coupling : rhs → constant Coupling.t
  val coupling_tag : rhs → string option
  val children : rhs → wf list

  type fusion = wf × rhs list
  val lhs : fusion → wf
  val rhs : fusion → rhs list

  type braket = wf × rhs list
  val bra : braket → wf
  val ket : braket → rhs list

  module D :
    DAG.T with type node = wf and type edge = coupling and type children = wf children

  val wavefunctions : braket list → wf list

  type amplitude =
    { fusions : fusion list;

```

```

    brackets : braket list;
    on_shell : (wf → bool);
    is_gauss : (wf → bool);
    constraints : string option;
    incoming : flavor list;
    outgoing : flavor list;
    externals : wf list;
    symmetry : int;
    dependencies : (wf → (wf, coupling) Tree2.t);
    fusion_tower : D.t;
    fusion_dag : D.t }

val incoming : amplitude → flavor list
val outgoing : amplitude → flavor list
val externals : amplitude → wf list
val variables : amplitude → wf list
val fusions : amplitude → fusion list
val brackets : amplitude → braket list
val on_shell : amplitude → (wf → bool)
val is_gauss : amplitude → (wf → bool)
val constraints : amplitude → string option
val symmetry : amplitude → int
val dependencies : amplitude → wf → (wf, coupling) Tree2.t
val fusion_dag : amplitude → D.t

end

module Amplitude (PT : Tuple.Poly) (P : Momentum.T) (M : Model.T) :
  Amplitude
  with type p = P.t
  and type flavor = M.flavor
  and type  $\alpha$  children =  $\alpha$  PT.t
  and module Tags = Tags =
  struct

    type flavor = M.flavor
    type p = P.t

    module Tags = Tags

    type wf =
      { flavor : flavor;
        momentum : p;
        wf_tag : Tags.wf }

    let flavor wf = wf.flavor
    let conjugate wf = { wf with flavor = M.conjugate wf.flavor }
    let momentum wf = wf.momentum
    let momentum_list wf = P.to_ints wf.momentum
    let wf_tag wf = Tags.wf_to_string wf.wf_tag
    let wf_tag_raw wf = wf.wf_tag

    let external_wfs rank particles =
      List.map

```



```

(fun (f, p) →
  { flavor = f;
    momentum = P.singleton rank p;
    wf_tag = Tags.null_wf })
particles

```

Order wavefunctions so that the external come first, then the pairs, etc. Also put possible Goldstone bosons *before* their gauge bosons.

```

let lorentz_ordering f =
  match M.lorentz f with
  | Coupling.Scalar → 0
  | Coupling.Spinor → 1
  | Coupling.ConjSpinor → 2
  | Coupling.Majorana → 3
  | Coupling.Vector → 4
  | Coupling.Massive_Vector → 5
  | Coupling.Tensor_2 → 6
  | Coupling.Tensor_1 → 7
  | Coupling.Vectorspinor → 8
  | Coupling.BRS Coupling.Scalar → 9
  | Coupling.BRS Coupling.Spinor → 10
  | Coupling.BRS Coupling.ConjSpinor → 11
  | Coupling.BRS Coupling.Majorana → 12
  | Coupling.BRS Coupling.Vector → 13
  | Coupling.BRS Coupling.Massive_Vector → 14
  | Coupling.BRS Coupling.Tensor_2 → 15
  | Coupling.BRS Coupling.Tensor_1 → 16
  | Coupling.BRS Coupling.Vectorspinor → 17
  | Coupling.BRS _ → invalid_arg "Fusion.lorentz_ordering: not needed"
  | Coupling.Maj_Ghost → 18

let order_flavor f1 f2 =
  let c = compare (lorentz_ordering f1) (lorentz_ordering f2) in
  if c ≠ 0 then
    c
  else
    compare f1 f2

```

Note that *Momentum().compare* guarantees that wavefunctions will be ordered according to *increasing Momentum().rank* of their momenta.

```

let order_wf wf1 wf2 =
  let c = P.compare wf1.momentum wf2.momentum in
  if c ≠ 0 then
    c
  else
    let c = order_flavor wf1.flavor wf2.flavor in
    if c ≠ 0 then
      c
    else
      compare wf1.wf_tag wf2.wf_tag

```

This *must* be a pair matching the *edge*  $\times$  *node children* pairs of *DAG.Forest*!

```

type coupling = Tagged_Coupling.t
type  $\alpha$  children =  $\alpha$  PT.t
type rhs = coupling  $\times$  wf children
let sign (c, _) = Tagged_Coupling.sign c
let coupling (c, _) = Tagged_Coupling.coupling c
let coupling_tag (c, _) = Tagged_Coupling.coupling_tag c
let children (_, wfs) = PT.to_list wfs

type fusion = wf  $\times$  rhs list
let lhs (l, _) = l
let rhs (_, r) = r

type braket = wf  $\times$  rhs list
let bra (b, _) = b
let ket (_, k) = k

module D = DAG.Make
  (DAG.Forest(PT)
    (struct type t = wf let compare = order_wf end)
    (struct type t = coupling let compare = compare end))

module WFSet =
  Set.Make (struct type t = wf let compare = order_wf end)

let wavefunctions brackets =
  WFSet.elements (List.fold_left (fun set (wf1, wf23)  $\rightarrow$ 
    WFSet.add wf1 (List.fold_left (fun set' (_, wfs)  $\rightarrow$ 
      PT.fold_right WFSet.add wfs set') set wf23)) WFSet.empty brackets)

type amplitude =
  { fusions : fusion list;
    brackets : braket list;
    on_shell : (wf  $\rightarrow$  bool);
    is_gauss : (wf  $\rightarrow$  bool);
    constraints : string option;
    incoming : flavor list;
    outgoing : flavor list;
    externals : wf list;
    symmetry : int;
    dependencies : (wf  $\rightarrow$  (wf, coupling) Tree2.t);
    fusion_tower : D.t;
    fusion_dag : D.t }

let incoming a = a.incoming
let outgoing a = a.outgoing
let externals a = a.externals
let fusions a = a.fusions
let brackets a = a.brackets
let symmetry a = a.symmetry
let on_shell a = a.on_shell
let is_gauss a = a.is_gauss
let constraints a = a.constraints

```

```

    let variables a = List.map lhs a.fusions
    let dependencies a = a.dependencies
    let fusion_dag a = a.fusion_dag
  end

  module A = Amplitude(PT)(P)(M)

```

Operator insertions can be fused only if they are external.

```

let is_source wf =
  match M.propagator wf.A.flavor with
  | Only_Insertion → P.rank wf.A.momentum = 1
  | _ → true

```

*is\_goldstone\_of g v* is *true* if and only if *g* is the Goldstone boson corresponding to the gauge particle *v*.

```

let is_goldstone_of g v =
  match M.goldstone v with
  | None → false
  | Some (g', _) → g = g'

```



In the end, *PT.to\_list* should become redundant!

```

let fuse_rhs rhs = M.fuse (PT.to_list rhs)

```

### Vertices

Compute the set of all vertices in the model from the allowed fusions and the set of all flavors:



One could think of using *M.vertices* instead of *M.fuse2*, *M.fuse3* and *M.fuse* ...

```

module VSet = Map.Make(struct type t = A.flavor let compare = compare end)

let add_vertices f rhs m =
  VSet.add f (try rhs :: VSet.find f m with Not_found → [rhs]) m

let collect_vertices rhs =
  List.fold_right (fun (f1, c) → add_vertices (M.conjugate f1) (c, rhs))
    (fuse_rhs rhs)

```

The set of all vertices with common left fields factored.

I used to think that constant initializers are a good idea to allow compile time optimizations. The down side turned out to be that the constant initializers will be evaluated *every time* the functor is applied. *Relying on the fact that the functor will be called only once is not a good idea!*

```

type vertices = (A.flavor × (constant Coupling.t × A.flavor PT.t) list) list

let vertices_nocache max_degree flavors : vertices =
  VSet.fold (fun f rhs v → (f, rhs) :: v)
    (PT.power_fold collect_vertices flavors VSet.empty) []

```

Performance hack:

```

type vertex_table =
  ((A.flavor × A.flavor × A.flavor) × constant Coupling.vertex3 ×
  constant) list
  × ((A.flavor × A.flavor × A.flavor × A.flavor)
  × constant Coupling.vertex4 × constant) list
  × (A.flavor list × constant Coupling.vertexn × constant) list

module VCache =
  Cache.Make (struct type t = vertex_table end) (struct type t = RCS.t ×
  vertices end)

  let vertices_cache = ref None
  let hash = VCache.hash (M.vertices ())

```



Can we do better than the executable name provided by *Config.cache\_prefix*???  
 We need a better way to avoid collisions among the caches for different models in the same program.

```

let cache_name =
  ref (Config.cache_prefix ^ "." ^ Config.cache_suffix)

let set_cache_name name =
  cache_name := name

let initialize_cache dir =
  Printf.eprintf
    "____>>>Initializing vertex table for model %s. ____This may take some time ____"
    (RCS.name M.rcs);
  flush stderr;
  VCache.write_dir hash dir !cache_name
    (M.rcs, vertices_nocache (M.max_degree ()) (M.flavors()));
  Printf.eprintf "done.____<<<\n"

let vertices max_degree flavors : vertices =
  match !vertices_cache with
  | None →
    begin match !cache_option with
    | Cache_Use →
      begin match VCache.maybe_read hash !cache_name with
      | VCache.Hit (rcs, result) →
        result
      | VCache.Miss →
        Printf.eprintf
          "____>>>Initializing vertex table for model %s. ____This may take some time ____"
          (RCS.name M.rcs);
        flush stderr;
        let result = vertices_nocache max_degree flavors in
          VCache.write hash !cache_name (M.rcs, result);
          vertices_cache := Some result;
          Printf.eprintf "done.____<<<\n";
          flush stderr;

```

```

      result
    | VCache.Stale file →
      Printf.eprintf
        "␣>>>␣Re-initializing␣stale␣vertex␣table␣for␣model␣%s␣in␣file␣%s␣␣"
        (RCS.name M.rcs) file;
      Printf.eprintf "This␣may␣take␣some␣time␣...␣";
      flush stderr;
      let result = vertices_nocache max_degree flavors in
        VCache.write hash !cache_name (M.rcs, result);
        vertices_cache := Some result;
        Printf.eprintf "done.␣<<<␣\n";
        flush stderr;
        result
      end
    | Cache_Overwrite →
      Printf.eprintf
        "␣>>>␣Overwriting␣vertex␣table␣for␣model␣%s␣␣This␣may␣take␣some␣time␣...␣"
        (RCS.name M.rcs);
      flush stderr;
      let result = vertices_nocache max_degree flavors in
        VCache.write hash !cache_name (M.rcs, result);
        vertices_cache := Some result;
        Printf.eprintf "done.␣<<<␣\n";
        flush stderr;
        result
      end
    | Cache_Ignore →
      Printf.eprintf
        "␣>>>␣Ignoring␣vertex␣table␣for␣model␣%s␣␣This␣may␣take␣some␣time␣...␣"
        (RCS.name M.rcs);
      flush stderr;
      let result = vertices_nocache max_degree flavors in
        vertices_cache := Some result;
        Printf.eprintf "done.␣<<<␣\n";
        flush stderr;
        result
      end
  end
| Some result → result

```

### Partitions

Vertices that are not crossing invariant need special treatment so that they're only generated for the correct combinations of momenta.

NB: the *crossing* checks here are a bit redundant, because *CM.fuse* below will bring the killed vertices back to life and will have to filter once more. Nevertheless, we keep them here, for the unlikely case that anybody ever wants to use uncolored amplitudes directly.

NB: the analogous problem does not occur for *select\_wf*, because this applies to momenta instead of vertices.



This approach worked before the colorize, but has become *futile*, because *CM.fuse* will bring the killed vertices back to life. We need to implement the same checks there again!!!



Using *PT.Mismatched\_arity* is not really good style ...

Tho's approach doesn't work since he does not catch charge conjugated processes or crossed processes. Another very strange thing is that O'Mega seems always to run in the q2 q3 timelike case, but not in the other two. (Property of how the DAG is built?). For the *ZZZZ* vertex I add the same vertex again, but interchange 1 and 3 in the *crossing* vertex

```

let kmatrix_cuts c momenta =
  match c with
  | V4 (Vector4_K_Matrix_tho (disc, _), fusion, _)
  | V4 (Vector4_K_Matrix_jr (disc, _), fusion, _) →
    let s12, s23, s13 =
      begin match PT.to_list momenta with
      | [q1; q2; q3] → (P.Scattering.timelike (P.add q1 q2),
                        P.Scattering.timelike (P.add q2 q3),
                        P.Scattering.timelike (P.add q1 q3))
      | _ → raise PT.Mismatched_arity
      end in
    begin match disc, s12, s23, s13, fusion with
    | 0, true, false, false, (F341 | F431 | F342 | F432 | F123 | F213 |
      F124 | F214)
    | 0, false, true, false, (F134 | F143 | F234 | F243 | F312 | F321 |
      F412 | F421)
    | 0, false, false, true, (F314 | F413 | F324 | F423 | F132 | F231 |
      F142 | F241) →
      true
    | 1, true, false, false, (F341 | F431 | F342 | F432)
    | 1, false, true, false, (F134 | F143 | F234 | F243)
    | 1, false, false, true, (F314 | F413 | F324 | F423) →
      true
    | 2, true, false, false, (F123 | F213 | F124 | F214)
    | 2, false, true, false, (F312 | F321 | F412 | F421)
    | 2, false, false, true, (F132 | F231 | F142 | F241) →
      true
    | 3, true, false, false, (F143 | F413 | F142 | F412 | F321 | F231 |
      F324 | F234)
    | 3, false, true, false, (F314 | F341 | F214 | F241 | F132 | F123 |
      F432 | F423)
    | 3, false, false, true, (F134 | F431 | F124 | F421 | F312 | F213 |
      F342 | F243) →
      true
    | _ → false
    end
  | _ → true

```

Counting QCD and EW orders.

```

let qcd_ew_check orders =
  if fst (orders) ≤ fst (int_orders) ∧
     snd (orders) ≤ snd (int_orders) then
    true
  else
    false

```

Match a set of flavors to a set of momenta. Form the direct product for the lists of momenta two and three with the list of couplings and flavors two and three.

```

let flavor_keystone select_p dim (f1, f23) (p1, p23) =
  ({ A.flavor = f1;
    A.momentum = P.of_ints dim p1;
    A.wf_tag = A.Tags.null_wf },
   Product.fold2 (fun (c, f) p acc →
     try
       let p' = PT.map (P.of_ints dim) p in
       if select_p (P.of_ints dim p1) (PT.to_list p') ∧ kmatrix_cuts c p' then
         (c, PT.map2 (fun f'' p'' → { A.flavor = f'';
                                         A.momentum = p'';
                                         A.wf_tag = A.Tags.null_wf }) f p') :: acc
       else
         acc
     with
     | PT.Mismatched_arity → acc) f23 p23 [])

```

Produce all possible combinations of vertices (flavor keystones) and momenta by forming the direct product. The semantically equivalent *Product.list2 (flavor\_keystone select\_wf n) vertices k* with *subsequent* filtering would be a *very bad* idea, because a potentially huge intermediate list is built for large models. E.g. for the MSSM this would lead to non-termination by thrashing for  $2 \rightarrow 4$  processes on most PCs.

```

let flavor_keystones filter select_p dim vertices keystones =
  Product.fold2 (fun v k acc →
    filter (flavor_keystone select_p dim v k) acc) vertices keystones []

```

Flatten the nested lists of vertices into a list of attached lines.

```

let flatten_keystones t =
  ThoList.flatmap (fun (p1, p23) →
    p1 :: (ThoList.flatmap (fun (_, rhs) → PT.to_list rhs) p23)) t

```

### Subtrees

Fuse a tuple of wavefunctions, keeping track of Fermi statistics. Record only the the sign *relative* to the children. (The type annotation is only for documentation.)

```

let fuse select_wf wfss : (A.wf × stat × A.rhs) list =
  if PT.for_all (fun (wf, _) → is_source wf) wfss then
    try
      let wfs, ss = PT.split wfss in
      let flavors = PT.map A.flavor wfs

```

```

and momenta = PT.map A.momentum wfs
and wf_tags = PT.map A.wf_tag_raw wfs in
let p = PT.fold_left_internal P.add momenta in
List.fold_left
  (fun acc (f, c) →
    if select_wf f p (PT.to_list momenta) ∧ kmatrix_cuts c momenta then
      let s = stat_fuse ss f in
      let flip =
        PT.fold_left (fun acc s' → acc × stat_sign s') (stat_sign s) ss in
      ({ A.flavor = f;
        A.momentum = p;
        A.wf_tag = A.Tags.null_wf }, s,
      ({ Tagged_Coupling.sign = flip;
        Tagged_Coupling.coupling = c;
        Tagged_Coupling.coupling_tag = A.Tags.null_coupling }, wfs)) :: acc
    else
      acc)
  [] (fuse_rhs flavors)
with
| P.Duplicate _ | S.Impossible → []
else
[]

```



Eventually, the pairs of *tower* and *dag* in *fusion\_tower'* below could and should be replaced by a graded *DAG*. This will look like, but currently *tower* contains statistics information that is missing from *dag*:

Type `node = flavor * p` is not compatible with type `wf * stat`

This should be easy to fix. However, replacing type `t = wf` with type `t = wf × stat` is *not* a good idea because the variable *stat* makes it impossible to test for the existence of a particular *wf* in a *DAG*.



In summary, it seems that  $(wf \times stat) \text{ list array} \times A.D.t$  should be replaced by  $(wf \rightarrow stat) \times A.D.t$ .

```

module GF =
struct
  module Nodes =
    struct
      type t = A.wf
      module G = struct type t = int let compare = compare end
      let compare = A.order_wf
      let rank wf = P.rank wf.A.momentum
    end
  module Edges = struct type t = A.coupling let compare = compare end
  module F = DAG.Forest(PT)(Nodes)(Edges)
  type node = Nodes.t
  type edge = F.edge
  type children = F.children

```



```

type t = F.t
let compare = F.compare
let for_all = F.for_all
let fold = F.fold
end

module D' = DAG.Graded(GF)

let tower_of_dag dag =
  let _, max_rank = D'.min_max_rank dag in
  Array.init max_rank (fun n → D'.ranked n dag)

```

The function *fusion\_tower'* recursively builds the tower of all fusions from bottom up to a chosen level. The argument *tower* is an array of lists, where the *i*-th sublist (counting from 0) represents all off shell wave functions depending on *i* + 1 momenta and their Fermistatistics.

$$\begin{aligned}
 & \left[ \{ \phi_1(p_1), \phi_2(p_2), \phi_3(p_3), \dots \}, \right. \\
 & \quad \{ \phi_{12}(p_1 + p_2), \phi'_{12}(p_1 + p_2), \dots, \phi_{13}(p_1 + p_3), \dots, \phi_{23}(p_2 + p_3), \dots \}, \\
 & \quad \dots \\
 & \quad \left. \{ \phi_{1\dots n}(p_1 + \dots + p_n), \phi'_{1\dots n}(p_1 + \dots + p_n), \dots \} \right] \quad (8.6)
 \end{aligned}$$

The argument *dag* is a DAG representing all the fusions calculated so far. NB: The outer array in *tower* is always very short, so we could also have accessed a list with *List.nth*. Appending of new members at the end brings no loss of performance. NB: the array is supposed to be immutable. The towers must be sorted so that the combinatorical functions can make consistent selections.



Intuitively, this seems to be correct. However, one could have expected that no element appears twice and that this ordering is not necessary ...

```

let grow_select_wf tower =
  let rank = succ (Array.length tower) in
  List.sort Pervasives.compare
    (PT.graded_sym_power_fold rank
     (fun wfs acc → fuse select_wf wfs @ acc) tower [])
let add_offspring dag (wf, _, rhs) =
  A.D.add_offspring wf rhs dag
let filter_offspring fusions =
  List.map (fun (wf, s, _) → (wf, s)) fusions
let rec fusion_tower' n_max select_wf tower dag : (A.wf × stat) list array × A.D.t =
  if Array.length tower ≥ n_max then
    (tower, dag)
  else
    let tower' = grow_select_wf tower in
    fusion_tower' n_max select_wf
      (Array.append tower [filter_offspring tower'])

```

*(List.fold\_left add\_offspring dag tower')*

Discard the tower and return a map from wave functions to Fermistatistics together with the DAG.

```

let make_external_dag wfs =
  List.fold_left (fun m (wf, _) → A.D.add_node wf m) A.D.empty wfs
let mixed_fold_left f acc lists =
  Array.fold_left (List.fold_left f) acc lists
module Stat_Map =
  Map.Make (struct type t = A.wf let compare = A.order_wf end)
let fusion_tower height select_wf wfs : (A.wf → stat) × A.D.t =
  let tower, dag =
    fusion_tower' height select_wf [|wfs|] (make_external_dag wfs) in
  let stats = mixed_fold_left
    (fun m (wf, s) → Stat_Map.add wf s m) Stat_Map.empty tower in
  ((fun wf → Stat_Map.find wf stats), dag)

```

Calculate the minimal tower of fusions that suffices for calculating the amplitude.

```

let minimal_fusion_tower n select_wf wfs : (A.wf → stat) × A.D.t =
  fusion_tower (T.max_subtree n) select_wf wfs

```

Calculate the complete tower of fusions. It is much larger than required, but it allows a complete set of gauge checks.

```

let complete_fusion_tower select_wf wfs : (A.wf → stat) × A.D.t =
  fusion_tower (List.length wfs - 1) select_wf wfs

```



There is a natural product of two DAGs using *fuse*. Can this be used in a replacement for *fusion\_tower*? The hard part is to avoid double counting, of course. A straight forward solution could do a diagonal sum (in order to reject flipped offspring representing the same fusion) and rely on the uniqueness in *DAG* otherwise. However, this will (probably) slow down the procedure significantly, because most fusions (including Fermi signs!) will be calculated before being rejected by *DAG().add\_offspring*.

Add to *dag* all Goldstone bosons defined in *tower* that correspond to gauge bosons in *dag*. This is only required for checking Slavnov-Taylor identities in unitarity gauge. Currently, it is not used, because we use the complete tower for gauge checking.

```

let harvest_goldstones tower dag =
  A.D.fold_nodes (fun wf dag' →
    match M.goldstone wf.A.flavor with
    | Some (g, _) →
      let wf' = { wf with A.flavor = g } in
      if A.D.is_node wf' tower then begin
        A.D.harvest tower wf' dag'
      end else begin
        dag'

```

```

    end
    | None → dag') dag dag

```

Calculate the sign from Fermi statistics that is not already included in the children.



The use of *PT.of2\_kludge* is the largest skeleton on the cupboard of unified fusions. Currently, it is just another name for *PT.of2*, but the existence of the latter requires binary fusions. Of course, this is just a symptom for not fully supporting four fermion vertices ...

```

let stat_keystone stats wf1 wfs =
  let wf1' = stats wf1
  and wfs' = PT.map stats wfs in
  stat_sign
    (stat_fuse
      (PT.of2_kludge wf1' (stat_fuse wfs' (M.conjugate (A.flavor wf1))))
      (A.flavor wf1))
    × PT.fold_left (fun acc wf → acc × stat_sign wf) (stat_sign wf1') wfs'

```

Test all members of a list of wave functions are defined by the DAG simultaneously:

```

let test_rhs dag (_, wfs) =
  PT.for_all (fun wf → is_source wf ∧ A.D.is_node wf dag) wfs

```

Add the keystone (*wf1*, *pairs*) to *acc* only if it is present in *dag* and calculate the statistical factor depending on *stats en passant*:

```

let filter_keystone stats dag (wf1, pairs) acc =
  if is_source wf1 ∧ A.D.is_node wf1 dag then
    match List.filter (test_rhs dag) pairs with
    | [] → acc
    | pairs' → (wf1, List.map (fun (c, wfs) →
      ({ Tagged_Coupling.sign = stat_keystone stats wf1 wfs;
        Tagged_Coupling.coupling = c;
        Tagged_Coupling.coupling_tag = A.Tags.null_coupling },
        wfs)) pairs') :: acc
  else
    acc

```

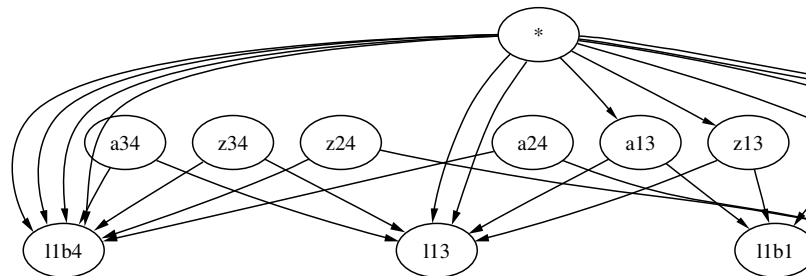
### Amplitudes

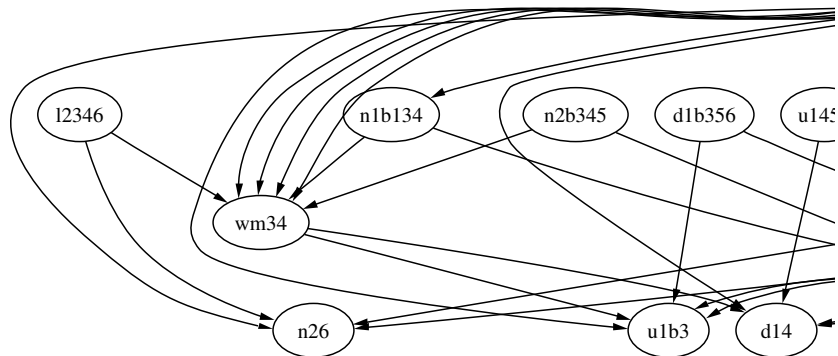
```

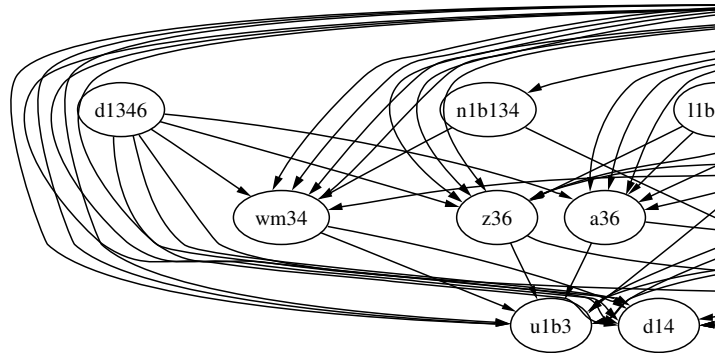
module C = Cascade.Make(M)(P)
type selectors = C.selectors

let external_wfs n particles =
  List.map (fun (f, p) →
    ({ A.flavor = f;
      A.momentum = P.singleton n p;
      A.wf_tag = A.Tags.null_wf },
      stat f p)) particles

```







*Main Function*

module *WFFMap* = *Map.Make* (struct type *t* = *A.wf* let *compare* = *compare* end)

*map\_amplitude\_wfs* *f a* applies the function  $f : wf \rightarrow wf$  to all wavefunctions appearing in the amplitude *a*.

```

let map_amplitude_wfs f a =
  let map_rhs (c, wfs) = (c, PT.map f wfs) in
  let map_braket (wf, rhs) = (f wf, List.map map_rhs rhs) in
  and map_fusion (lhs, rhs) = (f lhs, List.map map_rhs rhs) in
  let map_dag = A.D.map f (fun node rhs → map_rhs rhs) in
  let tower = map_dag a.A.fusion_tower
  and dag = map_dag a.A.fusion_dag in
  let dependencies_map =
    A.D.fold (fun wf _ → WFFMap.add wf (A.D.dependencies dag wf)) dag WFFMap.empty in
  { A.fusions = List.map map_fusion a.A.fusions;
    A.brakets = List.map map_braket a.A.brakets;
    A.on_shell = a.A.on_shell;
    A.is_gauss = a.A.is_gauss;
    A.constraints = a.A.constraints;
    A.incoming = a.A.incoming;
    A.outgoing = a.A.outgoing;
    A.externals = List.map f a.A.externals;
    A.symmetry = a.A.symmetry;
    A.dependencies = (fun wf → WFFMap.find wf dependencies_map);
    A.fusion_tower = tower;
    A.fusion_dag = dag }

```

This is the main function that constructs the amplitude for sets of incoming and outgoing particles and returns the results in conveniently packaged pieces.

let *amplitude* *goldstones selectors fin fout* =

Set up external lines and match flavors with numbered momenta.

```

let f = fin @ List.map M.conjugate fout in
let nin, nout = List.length fin, List.length fout in
let n = nin + nout in
let externals = List.combine f (ThoList.range 1 n) in
let wfs = external_wfs n externals in
let select_p = C.select_p selectors in
let select_wf =
  match fin with
  | [-] → C.select_wf selectors P.Decay.timelike
  | _ → C.select_wf selectors P.Scattering.timelike in

```

Build the full fusion tower (including nodes that are never needed in the amplitude).

```

let stats, tower =
  if goldstones then
    complete_fusion_tower select_wf wfs

```

```

else
  minimal_fusion_tower n select_wf wfs in

```

Find all vertices for which *all* off shell wavefunctions are defined by the tower.

```

let brackets =
  flavor_keystones (filter_keystone stats tower) select_p n
  (vertices (M.max_degree ()) (M.flavors ()))
  (T.keystones (ThoList.range 1 n)) in

```

Remove the part of the DAG that is never needed in the amplitude.

```

let dag =
  if goldstones then
    tower
  else
    A.D.harvest_list tower (A.wavefunctions brackets) in

```

Remove the leaf nodes of the DAG, corresponding to external lines.

```

let fusions =
  List.filter (function (_, []) → false | _ → true) (A.D.lists dag) in

```

Calculate the symmetry factor for identical particles in the final state.

```

let symmetry =
  Combinatorics.symmetry fout in

let dependencies_map =
  A.D.fold (fun wf _ → WFMap.add wf (A.D.dependencies dag wf)) dag WFMap.empty in

```

Finally: package the results:

```

{ A.fusions = fusions;
  A.brackets = brackets;
  A.on_shell = (fun wf → C.on_shell selectors (A.flavor wf) wf.A.momentum);
  A.is_gauss = (fun wf → C.is_gauss selectors (A.flavor wf) wf.A.momentum);
  A.constraints = C.description selectors;
  A.incoming = fin;
  A.outgoing = fout;
  A.externals = List.map fst wfs;
  A.symmetry = symmetry;
  A.dependencies = (fun wf → WFMap.find wf dependencies_map);
  A.fusion_tower = tower;
  A.fusion_dag = dag }

```

### Color

```

module CM = Colorize.It(M)
module CA = Amplitude(PT)(P)(CM)

let colorize_wf flavor wf =
  { CA.flavor = flavor;
    CA.momentum = wf.A.momentum;
    CA.wf_tag = wf.A.wf_tag }

```



```

let uncolorize_wf wf =
  { A.flavor = CM.flavor_sans_color wf.CA.flavor;
    A.momentum = wf.CA.momentum;
    A.wf_tag = wf.CA.wf_tag }

```



At the end of the day, I shall want to have some sort of *fibred DAG* as abstract data type, with a projection of colored nodes to their uncolored counterparts.

```

module CWFBundle = Bundle.Make
  (struct
    type elt = CA.wf
    let compare_elt = compare
    type base = A.wf
    let compare_base = compare
    let pi wf =
      { A.flavor = CM.flavor_sans_color wf.CA.flavor;
        A.momentum = wf.CA.momentum;
        A.wf_tag = wf.CA.wf_tag }
  end)

```



For now, we can live with simple aggregation:

```

type fibred_dag = { dag : CA.D.t; bundle : CWFBundle.t }

```

Not yet(?) needed: `module CS = Stat (CM)`

```

let colorize_sterile_nodes dag f wf fibred_dag =
  if A.D.is_sterile wf dag then
    let wf', wf_bundle' = f wf fibred_dag in
    { dag = CA.D.add_node wf' fibred_dag.dag;
      bundle = wf_bundle' }
  else
    fibred_dag

let colorize_nodes f wf rhs fibred_dag =
  let wf_rhs_list', wf_bundle' = f wf rhs fibred_dag in
  let dag' =
    List.fold_right
      (fun (wf', rhs') → CA.D.add_offspring wf' rhs')
      wf_rhs_list' fibred_dag.dag in
  { dag = dag';
    bundle = wf_bundle' }

```

O'Caml (correctly) infers the type `val colorize_dag : (D.node → D.edge × D.children → fibred_dag → (CA.D.node × (CA.D.edge × CA.D.children)) list × CWFBundle.t) → (D.node → fibred_dag → CA.D.node × CWFBundle.t) → D.t → CWFBundle.t → fibred_dag`.

```

let colorize_dag f_node f_ext dag wf_bundle =
  A.D.fold (colorize_nodes f_node) dag
  (A.D.fold_nodes (colorize_sterile_nodes dag f_ext) dag)

```

```

    { dag = CA.D.empty; bundle = wf_bundle })
let colorize_external wf fibered_dag =
  match CWFBundle.inv_pi wf fibered_dag.bundle with
  | [c_wf] → (c_wf, fibered_dag.bundle)
  | [] → failwith "colorize_external: not found"
  | _ → failwith "colorize_external: not unique"
let fuse_c_wf rhs =
  let momenta = PT.map (fun wf → wf.CA.momentum) rhs in
  List.filter
    (fun (_, c) → kmatrix_cuts c momenta)
    (CM.fuse (List.map (fun wf → wf.CA.flavor) (PT.to_list rhs)))
let colorize_coupling c coupling =
  { coupling with Tagged_Coupling.coupling = c }
let colorize_fusion wf (coupling, children) fibered_dag =
  let match_flavor (f, _) = (CM.flavor_sans_color f = A.flavor wf)
  and find_colored wf' = CWFBundle.inv_pi wf' fibered_dag.bundle in
  let fusions =
    ThoList.flatmap
      (fun c_children →
        List.map
          (fun (f, c) →
            (colorize_wf f wf, (colorize_coupling c coupling, c_children)))
          (List.filter match_flavor (fuse_c_wf c_children)))
      (PT.product (PT.map find_colored children)) in
  let bundle =
    List.fold_right
      (fun (c_wf, _) → CWFBundle.add c_wf)
      fusions fibered_dag.bundle in
    (fusions, bundle)
let colorize_braket1 (wf, (coupling, children)) fibered_dag =
  let find_colored wf' = CWFBundle.inv_pi wf' fibered_dag.bundle in
  Product.fold2
    (fun bra ket acc →
      List.fold_left
        (fun brackets (f, c) →
          if CM.conjugate bra.CA.flavor = f then
            (bra, (colorize_coupling c coupling, ket)) :: brackets
          else
            brackets)
        acc (fuse_c_wf ket))
    (find_colored wf) (PT.product (PT.map find_colored children)) []
module CWFMap =
  Map.Make (struct type t = CA.wf let compare = CA.order_wf end)
module CKetSet =
  Set.Make (struct type t = CA.rhs let compare = compare end)

```

Find a set of kets in *map* that belong to *bra*. Return the empty set, if nothing is found.

```
let lookup_ketset bra map =
  try CWFMap.find bra map with Not_found → CKetSet.empty
```

Return the set of kets belonging to *bra* in *map*, augmented by *ket*.

```
let addto_ketset bra ket map =
  CKetSet.add ket (lookup_ketset bra map)
```

Augment or update *map* with a new (*bra*, *ket*) relation.

```
let addto_ketset_map map (bra, ket) =
  CWFMap.add bra (addto_ketset bra ket map) map
```

Take a list of (*bra*, *ket*) pairs and group the *kets* according to *bra*. This is very similar to *ThoList.factorize* on page 741, but the latter keeps duplicate copies, while we keep only one, with equality determined by *CA.order\_wf*.



Isn't *Bundle M.1* the correct framework for this?

```
let factorize_brackets brackets =
  CWFMap.fold
    (fun bra ket acc → (bra, CKetSet.elements ket) :: acc)
    (List.fold_left addto_ketset_map CWFMap.empty brackets)
    []
```

```
let colorize_braket (wf, rhs_list) fibered_dag =
  factorize_brackets
    (ThoList.flatmap
      (fun rhs → (colorize_braket1 (wf, rhs) fibered_dag))
      rhs_list)
```

```
let colorize_amplitude a fin fout =
  let f = fin @ List.map CM.conjugate fout in
  let nin, nout = List.length fin, List.length fout in
  let n = nin + nout in
  let externals = List.combine f (ThoList.range 1 n) in
  let external_wfs = CA.external_wfs n externals in
  let wf_bundle = CWFBundle.of_list external_wfs in

  let fibered_dag =
    colorize_dag
      colorize_fusion colorize_external a.A.fusion_dag wf_bundle in

  let brackets =
    ThoList.flatmap
      (fun braket → colorize_braket braket fibered_dag)
      a.A.brackets in

  let dag = CA.D.harvest_list fibered_dag.dag (CA.wavefunctions brackets) in

  let fusions =
    List.filter (function (_, []) → false | _ → true) (CA.D.lists dag) in

  let dependencies_map =
    CA.D.fold
      (fun wf _ → CWFMap.add wf (CA.D.dependencies dag wf))
```

```

    dag CWFMap.empty in
  { CA.fusions = fusions;
    CA.brakets = brakets;
    CA.constraints = a.A.constraints;
    CA.incoming = fin;
    CA.outgoing = fout;
    CA.externals = external_wfs;
    CA.fusion_dag = dag;
    CA.fusion_tower = dag;
    CA.symmetry = a.A.symmetry;
    CA.on_shell = (fun wf → a.A.on_shell (uncolorize_wf wf));
    CA.is_gauss = (fun wf → a.A.is_gauss (uncolorize_wf wf));
    CA.dependencies = (fun wf → CWFMap.find wf dependencies_map) }

let allowed_amplitude =
  match amplitude.CA.brakets with
  | [] → false
  | _ → true

let colorize_amplitudes a =
  List.fold_left
    (fun amps (fin, fout) →
      let amp = colorize_amplitude a fin fout in
      if allowed amp then
        amp :: amps
      else
        amps)
    [] (CM.amplitude a.A.incoming a.A.outgoing)

let amplitudes_goldstones_selectors fin fout =
  colorize_amplitudes (amplitude goldstones selectors fin fout)

type flavor = CA.flavor
type flavor_sans_color = A.flavor
type p = A.p
type wf = CA.wf
let conjugate = CA.conjugate
let flavor = CA.flavor
let flavor_sans_color wf = CM.flavor_sans_color (CA.flavor wf)
let momentum = CA.momentum
let momentum_list = CA.momentum_list
let wf_tag = CA.wf_tag

type coupling = CA.coupling

let sign = CA.sign
let coupling = CA.coupling
let coupling_tag = CA.coupling_tag

type  $\alpha$  children =  $\alpha$  CA.children
type rhs = CA.rhs
let children = CA.children

type fusion = CA.fusion

```

```

let lhs = CA.lhs
let rhs = CA.rhs

type bracket = CA.braket
let bra = CA.bra
let ket = CA.ket

type amplitude = CA.amplitude
let incoming = CA.incoming
let outgoing = CA.outgoing
let externals = CA.externals
let fusions = CA.fusions
let brackets = CA.brackets
let symmetry = CA.symmetry
let on_shell = CA.on_shell
let is_gauss = CA.is_gauss
let constraints = CA.constraints
let variables a = List.map lhs (fusions a)
let dependencies = CA.dependencies

```

### Checking Conservation Laws

```

let check_charges () =
  let vlist3, vlist4, vlistn = M.vertices () in
  List.filter
    (fun flist → ¬ (M.Ch.is_null (M.Ch.sum (List.map M.charges flist))))
    (List.map (fun ((f1, f2, f3), -, -) → [f1; f2; f3]) vlist3
      @ List.map (fun ((f1, f2, f3, f4), -, -) → [f1; f2; f3; f4]) vlist4
      @ List.map (fun (flist, -, -) → flist) vlistn)

```

### Diagnostics

```

let count_propagators a =
  List.length a.CA.fusions

let count_fusions a =
  List.fold_left (fun n (_, a) → n + List.length a) 0 a.CA.fusions
  + List.fold_left (fun n (_, t) → n + List.length t) 0 a.CA.brackets
  + List.length a.CA.brackets

```



This brute force approach blows up for more than ten particles. Find a smarter algorithm.

```

let count_diagrams a =
  List.fold_left (fun n (wf1, wf23) →
    n + CA.D.count_trees wf1 a.CA.fusion_dag ×
    (List.fold_left (fun n' (_, wfs) →
      n' + PT.fold_left (fun n'' wf →
        n'' × CA.D.count_trees wf a.CA.fusion_dag) 1 wfs) 0 wf23))
    0 a.CA.brackets

```

```

exception Impossible

let forest' a =
  let below wf = CA.D.forest_memoized wf a.CA.fusion_dag in
  ThoList.flatmap
    (fun (bra, ket) →
      (Product.list2 (fun bra' ket' → bra' :: ket')
        (below bra)
        (ThoList.flatmap
          (fun (_, wfs) →
            Product.list (fun w → w) (PT.to_list (PT.map below wfs)))
          ket)))
    a.CA.brackets

let cross wf =
  { CA.flavor = CM.conjugate wf.CA.flavor;
    CA.momentum = P.neg wf.CA.momentum;
    CA.wf_tag = wf.CA.wf_tag }

let fuse_trees wf ts =
  Tree.fuse (fun (wf', e) → (cross wf', e))
    wf (fun t → List.mem wf (Tree.leafs t)) ts

let forest wf a =
  List.map (fuse_trees wf) (forest' a)

let poles_beneath wf dag =
  CA.D.eval_memoized (fun wf' → [[]])
    (fun wf' p → List.map (fun p' → wf' :: p') p)
    (fun wf1 wf2 →
      Product.fold2 (fun wf' wfs' wfs'' → (wf' @ wfs') :: wfs'') wf1 wf2 [])
    (@) [[]] [[]] wf dag

let poles a =
  ThoList.flatmap (fun (wf1, wf23) →
    let poles_wf1 = poles_beneath wf1 a.CA.fusion_dag in
    (ThoList.flatmap (fun (_, wfs) →
      Product.list List.flatten
        (PT.to_list (PT.map (fun wf →
          poles_wf1 @ poles_beneath wf a.CA.fusion_dag) wfs)))
      wf23))
    a.CA.brackets

module WFSets =
  Set.Make (struct type t = CA.wf let compare = CA.order_wf end)

let s_channel a =
  WFSets.elements
    (ThoList.fold_right2
      (fun wf wfs →
        if P.Scattering.timelike wf.CA.momentum then
          WFSets.add wf wfs
        else
          wfs) (poles a) WFSets.empty)

```



This should be much faster! Is it correct? Is it faster indeed?

```
let poles' a =
  List.map CA.lhs a.CA.fusions

let s_channel a =
  WFSets.elements
    (List.fold_right
      (fun wf wfs →
        if P.Scattering.timelike wf.CA.momentum then
          WFSets.add wf wfs
        else
          wfs) (poles' a) WFSets.empty)
```

### Pictures

Export the DAG in the `dot(1)` file format so that we can draw pretty pictures to impress audiences ...

```
let p2s p =
  if p ≥ 0 ∧ p ≤ 9 then
    string_of_int p
  else if p ≤ 36 then
    String.make 1 (Char.chr (Char.code 'A' + p - 10))
  else
    "_"

let variable wf =
  CM.flavor_symbol wf.CA.flavor ^
  String.concat "" (List.map p2s (P.to_ints wf.CA.momentum))

module Int = Map.Make (struct type t = int let compare = compare end)

let add_to_list i n m =
  Int.add i (n :: try Int.find i m with Not_found → []) m

let classify_nodes dag =
  Int.fold (fun i n acc → (i, n) :: acc)
    (CA.D.fold_nodes (fun wf → add_to_list (P.rank wf.CA.momentum) wf)
      dag Int.empty) []

let dag_to_dot ch brackets dag =
  Printf.fprintf ch "digraph_Ω_{\n";
  CA.D.iter_nodes (fun wf →
    Printf.fprintf ch "%%s\" [label=%%s\" ];\n"
      (variable wf) (variable wf)) dag;
  List.iter (fun (_, wfs) →
    Printf.fprintf ch "%%{rank=same;";
    List.iter (fun n →
      Printf.fprintf ch "%%s\";" (variable n)) wfs;
    Printf.fprintf ch "};\n") (classify_nodes dag);
  List.iter (fun n →
    Printf.fprintf ch "%%*\n->%%s\";\n" (variable n))
```

```

      (flatten_keystones brackets);
    CA.D.iter (fun n (_, ns) →
      let p = variable n in
      PT.iter (fun n' →
        Printf.fprintf ch "%s\%->%s\";\n" p (variable n') ns) dag;
      Printf.fprintf ch "}\n"
    )
  let tower_to_dot ch a =
    dag_to_dot ch a.CA.brackets a.CA.fusion_tower
  let amplitude_to_dot ch a =
    dag_to_dot ch a.CA.brackets a.CA.fusion_dag
  let rcs_list = [CA.D.rcs; T.rcs; P.rcs; CM.rcs; rcs]
end

module Make = Tagged(Order_Tags)
module Binary = Make(Tuple.Binary)(Stat_Dirac)(Topology.Binary)
module Tagged_Binary (T : Tagger) =
  Tagged(T)(Tuple.Binary)(Stat_Dirac)(Topology.Binary)

```

### 8.2.5 Fusions with Majorana Fermions

```

module Stat_Majorana (M : Model.T) : (Stat with type flavor = M.flavor) =
struct
  let rcs = RCS.rename rcs_file "Fusion.Stat_Majorana()"
    [ "Fermi_statistics_with_fermion_number_violation" ]
  type flavor = M.flavor
  type stat =
    | Fermion of int × int list
    | AntiFermion of int × int list
    | Boson of int list
    | Majorana of int × int list
  let stat f p =
    let s = M.fermion f in
    if s = 0 then
      Boson []
    else if s < 0 then
      AntiFermion (p, [])
    else if s = 1 then (* if s = 1 then *)
      Fermion (p, [])
    else (* if s > 1 then *)
      Majorana (p, [])

```



*JR sez'* (regarding the Majorana Feynman rules): In the formalism of [7], it does not matter to distinguish spinors and conjugate spinors, it is only important to know in which direction a fermion line is calculated. So the sign is made by the calculation together with an additional one due to the permutation of the pairs of endpoints of fermion lines in the direction they



are calculated. We propose a “canonical” direction from the right to the left child at a fusion point so we only have to keep in mind which external particle hangs at each side. Therefore we need not to have a list of pairs of conjugate spinors and spinors but just a list in which the pairs are right-left-right-left and so on. Unfortunately it is unavoidable to have couplings with clashing arrows in supersymmetric theories so we need transmutations from fermions in antifermions and vice versa as well. (*JR’s probably right, but I need to check myself . . .*)

exception *Impossible*

```

let stat_fuse s1 s2 f =
  match s1, s2, M.lorentz f with
  | Boson l1, Fermion (p, l2), Coupling.Majorana
  | Boson l1, AntiFermion (p, l2), Coupling.Majorana
  | Fermion (p, l1), Boson l2, Coupling.Majorana
  | AntiFermion (p, l1), Boson l2, Coupling.Majorana
  | Majorana (p, l1), Boson l2, Coupling.Majorana
  | Boson l1, Majorana (p, l2), Coupling.Majorana →
    Majorana (p, l1 @ l2)
  | Boson l1, Fermion (p, l2), Coupling.Spinor
  | Boson l1, AntiFermion (p, l2), Coupling.Spinor
  | Fermion (p, l1), Boson l2, Coupling.Spinor
  | AntiFermion (p, l1), Boson l2, Coupling.Spinor
  | Majorana (p, l1), Boson l2, Coupling.Spinor
  | Boson l1, Majorana (p, l2), Coupling.Spinor →
    Fermion (p, l1 @ l2)
  | Boson l1, Fermion (p, l2), Coupling.ConjSpinor
  | Boson l1, AntiFermion (p, l2), Coupling.ConjSpinor
  | Fermion (p, l1), Boson l2, Coupling.ConjSpinor
  | AntiFermion (p, l1), Boson l2, Coupling.ConjSpinor
  | Majorana (p, l1), Boson l2, Coupling.ConjSpinor
  | Boson l1, Majorana (p, l2), Coupling.ConjSpinor →
    AntiFermion (p, l1 @ l2)
  | Boson l1, Fermion (p, l2), Coupling.Vectorspinor
  | Boson l1, AntiFermion (p, l2), Coupling.Vectorspinor
  | Fermion (p, l1), Boson l2, Coupling.Vectorspinor
  | AntiFermion (p, l1), Boson l2, Coupling.Vectorspinor
  | Majorana (p, l1), Boson l2, Coupling.Vectorspinor
  | Boson l1, Majorana (p, l2), Coupling.Vectorspinor →
    Majorana (p, l1 @ l2)
  | Boson l1, Boson l2, - → Boson (l1 @ l2)
  | AntiFermion (p1, l1), Fermion (p2, l2), -
  | Fermion (p1, l1), AntiFermion (p2, l2), -
  | Fermion (p1, l1), Fermion (p2, l2), -
  | AntiFermion (p1, l1), AntiFermion (p2, l2), -
  | Fermion (p1, l1), Majorana (p2, l2), -
  | Majorana (p1, l1), Fermion (p2, l2), -
  | AntiFermion (p1, l1), Majorana (p2, l2), -
  | Majorana (p1, l1), AntiFermion (p2, l2), -

```

```

| Majorana (p1, l1), Majorana (p2, l2), - →
|   Boson ([p2; p1] @ l1 @ l2)
| Boson l1, Majorana (p, l2), - → Majorana (p, l1 @ l2)
| Boson l1, Fermion (p, l2), - → Fermion (p, l1 @ l2)
| Boson l1, AntiFermion (p, l2), - → AntiFermion (p, l1 @ l2)
| Fermion (p, l1), Boson l2, - → Fermion (p, l1 @ l2)
| AntiFermion (p, l1), Boson l2, - → AntiFermion (p, l1 @ l2)
| Majorana (p, l1), Boson l2, - → Majorana (p, l1 @ l2)

let permutation lines = fst(Combinatorics.sort_signed compare lines)

let stat_sign = function
| Boson lines → permutation lines
| Fermion (p, lines) → permutation (p :: lines)
| AntiFermion (pbar, lines) → permutation (pbar :: lines)
| Majorana (pm, lines) → permutation (pm :: lines)

end

module Binary_Majorana =
  Make(Tuple.Binary)(Stat_Majorana)(Topology.Binary)

module Nary (B : Tuple.Bound) =
  Make(Tuple.Nary(B))(Stat_Dirac)(Topology.Nary(B))

module Nary_Majorana (B : Tuple.Bound) =
  Make(Tuple.Nary(B))(Stat_Majorana)(Topology.Nary(B))

module Mixed23 =
  Make(Tuple.Mixed23)(Stat_Dirac)(Topology.Mixed23)

module Mixed23_Majorana =
  Make(Tuple.Mixed23)(Stat_Majorana)(Topology.Mixed23)

module Helac (B : Tuple.Bound) =
  Make(Tuple.Nary(B))(Stat_Dirac)(Topology.Helac(B))

module Helac_Majorana (B : Tuple.Bound) =
  Make(Tuple.Nary(B))(Stat_Majorana)(Topology.Helac(B))

```

### 8.2.6 Multiple Amplitudes

```

module type Multi =
sig
  exception Mismatch
  val options : Options.t
  type flavor
  type process = flavor list × flavor list
  type amplitude
  type fusion
  type wf
  type selectors
  type amplitudes
  val amplitudes : bool → int option → selectors → process list →
amplitudes
  val empty : amplitudes

```

```

val initialize_cache : string → unit
val set_cache_name : string → unit
val flavors : amplitudes → process list
val vanishing_flavors : amplitudes → process list
val color_flows : amplitudes → Color.Flow.t list
val helicities : amplitudes → (int list × int list) list
val processes : amplitudes → amplitude list
val process_table : amplitudes → amplitude option array array
val fusions : amplitudes → (fusion × amplitude) list
val multiplicity : amplitudes → wf → int
val dictionary : amplitudes → amplitude → wf → int
val color_factors : amplitudes → Color.Flow.factor array array
val constraints : amplitudes → string option
end

module type Multi_Maker = functor (Fusion_Maker : Maker) →
  functor (P : Momentum.T) →
    functor (M : Model.T) →
      Multi with type flavor = M.flavor
      and type amplitude = Fusion_Maker(P)(M).amplitude
      and type fusion = Fusion_Maker(P)(M).fusion
      and type wf = Fusion_Maker(P)(M).wf
      and type selectors = Fusion_Maker(P)(M).selectors

module Multi (Fusion_Maker : Maker) (P : Momentum.T) (M : Model.T) =
  struct
    exception Mismatch

    type progress_mode =
      | Quiet
      | Channel of out_channel
      | File of string

    let progress_option = ref Quiet

    module CM = Colorize.It(M)
    module F = Fusion_Maker(P)(M)
    module C = Cascade.Make(M)(P)
  end

```



A kludge, at best ...

```

let options = Options.extend F.options
  [ "progress", Arg.Unit (fun () → progress_option := Channel stderr),
    "report_progress_to_the_standard_error_stream";
    "progress_file", Arg.String (fun s → progress_option := File s),
    "report_progress_to_a_file" ]

type flavor = M.flavor
type p = F.p
type process = flavor list × flavor list
type amplitude = F.amplitude
type fusion = F.fusion

```

```

type wf = F.wf
type selectors = F.selectors

type flavors = flavor list array
type helicities = int list array
type colors = Color.Flow.t array

type amplitudes' = amplitude array array array
type amplitudes =
  { flavors : process list;
    vanishing_flavors : process list;
    color_flows : Color.Flow.t list;
    helicities : (int list × int list) list;
    processes : amplitude list;
    process_table : amplitude option array array;
    fusions : (fusion × amplitude) list;
    multiplicity : (wf → int);
    dictionary : (amplitude → wf → int);
    color_factors : Color.Flow.factor array array;
    constraints : string option }

let flavors a = a.flavors
let vanishing_flavors a = a.vanishing_flavors
let color_flows a = a.color_flows
let helicities a = a.helicities
let processes a = a.processes
let process_table a = a.process_table
let fusions a = a.fusions
let multiplicity a = a.multiplicity
let dictionary a = a.dictionary
let color_factors a = a.color_factors
let constraints a = a.constraints

let sans_colors f =
  List.map CM.flavor_sans_color f

let colors (fin, fout) =
  List.map M.color (fin @ fout)

let process_sans_color a =
  (sans_colors (F.incoming a), sans_colors (F.outgoing a))

let color_flow a =
  CM.flow (F.incoming a) (F.outgoing a)

let process_to_string fin fout =
  String.concat "␣" (List.map M.flavor_to_string fin)
  ^ "␣->␣" ^ String.concat "␣" (List.map M.flavor_to_string fout)

let count_processes colored_processes =
  List.length colored_processes

module FMap =
  Map.Make (struct type t = process let compare = compare end)

```

```

module CMap =
  Map.Make (struct type t = Color.Flow.t let compare = compare end)

```

Recently *Product.list* began to guarantee lexicographic order for sorted arguments. Anyway, we still force a lexicographic order.

```

let rec order_spin_table1 s1 s2 =
  match s1, s2 with
  | h1 :: t1, h2 :: t2 →
    let c = compare h1 h2 in
    if c ≠ 0 then
      c
    else
      order_spin_table1 t1 t2
  | [], [] → 0
  | - → invalid_arg "order_spin_table: inconsistent lengths"

let order_spin_table (s1_in, s1_out) (s2_in, s2_out) =
  let c = compare s1_in s2_in in
  if c ≠ 0 then
    c
  else
    order_spin_table1 s1_out s2_out

let sort_spin_table table =
  List.sort order_spin_table table

let id x = x

let pair x y = (x, y)

```



Improve support for on shell Ward identities: *Coupling.Vector* → [4] for one and only one external vector.

```

let rec hs_of_lorentz = function
  | Coupling.Scalar → [0]
  | Coupling.Spinor | Coupling.ConjSpinor
  | Coupling.Majorana | Coupling.Maj_Ghost → [-1; 1]
  | Coupling.Vector → [-1; 1]
  | Coupling.Massive_Vector → [-1; 0; 1]
  | Coupling.Tensor_1 → [-1; 0; 1]
  | Coupling.Vectorspinor → [-2; -1; 1; 2]
  | Coupling.Tensor_2 → [-2; -1; 0; 1; 2]
  | Coupling.BRS f → hs_of_lorentz f

let hs_of_flavor f =
  hs_of_lorentz (M.lorentz f)

let hs_of_flavors (fin, fout) =
  (List.map hs_of_flavor fin, List.map hs_of_flavor fout)

let rec unphysical_of_lorentz = function
  | Coupling.Vector → [4]
  | Coupling.Massive_Vector → [4]

```

```

| - → invalid_arg "unphysical_of_lorentz: not a vector particle"

let unphysical_of_flavor f =
  unphysical_of_lorentz (M.lorentz f)

let unphysical_of_flavors1 n f_list =
  ThoList.map1
    (fun i f → if i = n then unphysical_of_flavor f else hs_of_flavor f)
    1 f_list

let unphysical_of_flavors n (fin, fout) =
  (unphysical_of_flavors1 n fin, unphysical_of_flavors1 (n - List.length fin) fout)

let helicity_table unphysical flavors =
  let hs =
    begin match unphysical with
    | None → List.map hs_of_flavors flavors
    | Some n → List.map (unphysical_of_flavors n) flavors
    end in
  if ¬ (ThoList.homogeneous hs) then
    invalid_arg "Fusion.helicity_table: not all flavors have the same helicity states!"
  else
    match hs with
    | [] → []
    | (hs_in, hs_out) :: _ →
      sort_spin_table (Product.list2 pair (Product.list id hs_in) (Product.list id hs_out))

module Proc = Process.Make(M)

module WFFMap = Map.Make (struct type t = F.wf let compare = compare end)
module WFSet2 =
  Set.Make (struct type t = F.wf × (F.wf, F.coupling) Tree2.t let compare = compare end)
module WFFMap2 =
  Map.Make (struct type t = F.wf × (F.wf, F.coupling) Tree2.t let compare = compare end)
module WFTSet =
  Set.Make (struct type t = (F.wf, F.coupling) Tree2.t let compare = compare end)

```

All wavefunctions are unique per amplitude. So we can use per-amplitude dependency trees without additional *internal* tags to identify identical wave functions.

**NB:** we miss potential optimizations, because we assume all coupling to be different, while in fact we have horizontal/family symmetries and non abelian gauge couplings are universal anyway.

```

let disambiguate_fusions amplitudes =
  let fusions =
    ThoList.flatmap (fun amplitude →
      List.map
        (fun fusion → (fusion, F.dependencies amplitude (F.lhs fusion)))
        (F.fusions amplitude))
    amplitudes in
  let duplicates =
    List.fold_left
      (fun map (fusion, dependencies) →

```

```

    let wf = F.lhs fusion in
    let set = try WFMap.find wf map with Not_found → WFTSet.empty in
    WFTSet.add wf (WFTSet.add dependencies set) map)
  WFTSet.empty fusions in
let multiplicity_map =
  WFTSet.fold (fun wf dependencies acc →
    let cardinal = WFTSet.cardinal dependencies in
    if cardinal ≤ 1 then
      acc
    else
      WFTSet.add wf cardinal acc)
  duplicates WFTSet.empty
and dictionary_map =
  WFTSet.fold (fun wf dependencies acc →
    let cardinal = WFTSet.cardinal dependencies in
    if cardinal ≤ 1 then
      acc
    else
      snd (WFTSet.fold
        (fun dependency (i', acc') →
          (succ i', WFTSet.add (wf, dependency) i' acc'))
        dependencies (1, acc)))
  duplicates WFTSet.empty in
let multiplicity wf =
  WFTSet.find wf multiplicity_map
and dictionary_amplitude wf =
  WFTSet2.find (wf, F.dependencies amplitude wf) dictionary_map in
(multiplicity, dictionary)

let eliminate_common_fusions1 seen_wfs amplitude =
  List.fold_left
    (fun (seen, acc) f →
      let wf = F.lhs f in
      let dependencies = F.dependencies amplitude wf in
      if WFTSet2.mem (wf, dependencies) seen then
        (seen, acc)
      else
        (WFTSet2.add (wf, dependencies) seen, (f, amplitude) :: acc))
    seen_wfs (F.fusions amplitude)

let eliminate_common_fusions processes =
  let _, rev_fusions =
    List.fold_left
      eliminate_common_fusions1
      (WFTSet2.empty, []) processes in
  List.rev rev_fusions

```

### Calculate All The Amplitudes

```

let amplitudes_goldstones_unphysical_select_wf processes =

```



Eventually, we might want to support inhomogeneous helicities. However, this makes little physics sense for external particles on the mass shell, unless we have a model with degenerate massive fermions and bosons.

```

if ¬ (ThoList.homogeneous (List.map hs_of_flavors processes)) then
  invalid_arg "Fusion.Multi.amplitudes: incompatible helicities";

let unique_uncolored_processes =
  Proc.remove_duplicate_final_states (C.partition select_wf) processes in

let progress =
  match !progress_option with
  | Quiet → Progress.dummy
  | Channel oc → Progress.channel oc (count_processes unique_uncolored_processes)
  | File name → Progress.file name (count_processes unique_uncolored_processes) in

let allowed =
  ThoList.flatmap
    (fun (fi, fo) →
      Progress.begin_step progress (process_to_string fi fo);
      let amps = F.amplitudes goldstones select_wf fi fo in
      begin match amps with
      | [] → Progress.end_step progress "forbidden"
      | _ → Progress.end_step progress "allowed"
      end;
      amps) unique_uncolored_processes in

Progress.summary progress "all processes done";

let color_flows =
  ThoList.uniq (List.sort compare (List.map color_flow allowed))
and flavors =
  ThoList.uniq (List.sort compare (List.map process_sans_color allowed)) in

let vanishing_flavors =
  Proc.diff processes flavors in

let helicities =
  helicity_table unphysical flavors in

let f_index =
  fst (List.fold_left
    (fun (m, i) f → (FMap.add f i m, succ i))
    (FMap.empty, 0) flavors)
and c_index =
  fst (List.fold_left
    (fun (m, i) c → (CMap.add c i m, succ i))
    (CMap.empty, 0) color_flows) in

let table =
  Array.make_matrix (List.length flavors) (List.length color_flows) None in
List.iter
  (fun a →
    let f = FMap.find (process_sans_color a) f_index

```



---

```

        and c = CMap.find (color_flow a) c_index in
        table.(f).(c) ← Some (a))
    allowed;

let cf_array = Array.of_list color_flows in
let ncf = Array.length cf_array in
let color_factor_table = Array.make_matrix ncf ncf Color.Flow.zero in
for i = 0 to pred ncf do
  for j = 0 to i do
    color_factor_table.(i).(j) ←
      Color.Flow.factor cf_array.(i) cf_array.(j);
    color_factor_table.(j).(i) ←
      color_factor_table.(i).(j)
  done
done;

let fusions = eliminate_common_fusions allowed
and multiplicity, dictionary = disambiguate_fusions allowed in
{ flavors = flavors;
  vanishing_flavors = vanishing_flavors;
  color_flows = color_flows;
  helicities = helicities;
  processes = allowed;
  process_table = table;
  fusions = fusions;
  multiplicity = multiplicity;
  dictionary = dictionary;
  color_factors = color_factor_table;
  constraints = C.description select_wf }

let initialize_cache = F.initialize_cache
let set_cache_name = F.set_cache_name

let empty =
{ flavors = [];
  vanishing_flavors = [];
  color_flows = [];
  helicities = [];
  processes = [];
  process_table = Array.make_matrix 0 0 None;
  fusions = [];
  multiplicity = (fun _ → 1);
  dictionary = (fun _ _ → 1);
  color_factors = Array.make_matrix 0 0 Color.Flow.zero;
  constraints = None }

end

```

---

## —9—

# LORENTZ REPRESENTATIONS, COUPLINGS, MODELS AND TARGETS

## 9.1 Interface of Coupling

The enumeration types used for communication from *Models* to *Targets*. On the physics side, the modules in *Models* must implement the Feynman rules according to the conventions set up here. On the numerics side, the modules in *Targets* must handle all cases according to the same conventions.

### 9.1.1 Propagators

The Lorentz representation of the particle. NB: O’Mega treats all lines as *outgoing* and particles are therefore transforming as *ConjSpinor* and antiparticles as *Spinor*.

```
type lorentz =
  | Scalar
  | Spinor (*  $\psi$  *)
  | ConjSpinor (*  $\bar{\psi}$  *)
  | Majorana (*  $\chi$  *)
  | Maj_Ghost (* SUSY ghosts *)
  | Vector
  | Massive_Vector
  | Vectorspinor (* supersymmetric currents and gravitinos *)
  | Tensor_1
  | Tensor_2 (* massive gravitons (large extra dimensions) *)
  | BRS of lorentz
```

If there were no vectors or auxiliary fields, we could deduce the propagator from the Lorentz representation. While we’re at it, we can introduce “propagators” for the contact interactions of auxiliary fields as well. *Prop\_Gauge* and *Prop\_Feynman* are redundant as special cases of *Prop\_Rxi*.

The special case *Only\_Insertion* corresponds to operator insertions that do not correspond to a propagating field all. These are used for checking Slavnov-Taylor identities

$$\partial_\mu \langle \text{out} | W^\mu(x) | \text{in} \rangle = m_W \langle \text{out} | \phi(x) | \text{in} \rangle \quad (9.1)$$

	only Dirac fermions	incl. Majorana fermions
<i>Prop_Scalar</i>	$\phi(p) \leftarrow \frac{i}{p^2 - m^2 + im\Gamma} \phi(p)$	
<i>Prop_Spinor</i>	$\psi(p) \leftarrow \frac{i(-\not{p} + m)}{p^2 - m^2 + im\Gamma} \psi(p)$	$\psi(p) \leftarrow \frac{i(-\not{p} + m)}{p^2 - m^2 + im\Gamma} \psi(p)$
<i>Prop_ConjSpinor</i>	$\bar{\psi}(p) \leftarrow \bar{\psi}(p) \frac{i(\not{p} + m)}{p^2 - m^2 + im\Gamma}$	$\psi(p) \leftarrow \frac{i(-\not{p} + m)}{p^2 - m^2 + im\Gamma} \psi(p)$
<i>Prop_Majorana</i>	N/A	$\chi(p) \leftarrow \frac{i(-\not{p} + m)}{p^2 - m^2 + im\Gamma} \chi(p)$
<i>Prop_Unitarity</i>	$\epsilon_\mu(p) \leftarrow \frac{i}{p^2 - m^2 + im\Gamma} \left( -g_{\mu\nu} + \frac{p_\mu p_\nu}{m^2} \right) \epsilon^\nu(p)$	
<i>Prop_Feynman</i>	$\epsilon^\nu(p) \leftarrow \frac{-i}{p^2 - m^2 + im\Gamma} \epsilon^\nu(p)$	
<i>Prop_Gauge</i>	$\epsilon_\mu(p) \leftarrow \frac{i}{p^2} \left( -g_{\mu\nu} + (1 - \xi) \frac{p_\mu p_\nu}{p^2} \right) \epsilon^\nu(p)$	
<i>Prop_Rxi</i>	$\epsilon_\mu(p) \leftarrow \frac{i}{p^2 - m^2 + im\Gamma} \left( -g_{\mu\nu} + (1 - \xi) \frac{p_\mu p_\nu}{p^2 - \xi m^2} \right) \epsilon^\nu(p)$	

Table 9.1: Propagators. NB: The sign of the momenta in the spinor propagators comes about because O'Mega treats all momenta as *outgoing* and the charge flow for *Spinor* is therefore opposite to the momentum, while the charge flow for *ConjSpinor* is parallel to the momentum.

<i>Aux_Scalar</i>	$\phi(p) \leftarrow i\phi(p)$
<i>Aux_Spinor</i>	$\psi(p) \leftarrow i\psi(p)$
<i>Aux_ConjSpinor</i>	$\bar{\psi}(p) \leftarrow i\bar{\psi}(p)$
<i>Aux_Vector</i>	$\epsilon^\mu(p) \leftarrow i\epsilon^\mu(p)$
<i>Aux_Tensor_1</i>	$T^{\mu\nu}(p) \leftarrow iT^{\mu\nu}(p)$
<i>Only_Insertion</i>	N/A

Table 9.2: Auxiliary and non propagating fields

of gauge theories in unitarity gauge where the Goldstone bosons are not propagating. Numerically, it would suffice to use a vanishing propagator, but then superfluous fusions would be calculated in production code in which the Slavnov-Taylor identities are not tested.

```

type  $\alpha$  propagator =
  | Prop_Scalar | Prop_Ghost
  | Prop_Spinor | Prop_ConjSpinor | Prop_Majorana
  | Prop_Unitarity | Prop_Feynman | Prop_Gauge of  $\alpha$  | Prop_Rxi of  $\alpha$ 
  | Prop_Tensor_2 | Prop_Vectorspinor
  | Prop_Col_Scalar | Prop_Col_Feynman | Prop_Col_Majorana
  | Prop_Col_Unitarity
  | Aux_Scalar | Aux_Vector | Aux_Tensor_1
  | Aux_Col_Scalar | Aux_Col_Vector | Aux_Col_Tensor_1
  | Aux_Spinor | Aux_ConjSpinor | Aux_Majorana
  | Only_Insertion

```



*JR sez'* (regarding the Majorana Feynman rules): We don't need different fermionic propagators as supposed by the variable names *Prop\_Spinor*, *Prop\_ConjSpinor* or *Prop\_Majorana*. The propagator in all cases has to be multiplied on the left hand side of the spinor out of which a new one should be built. All momenta are treated as *outgoing*, so for the propagation of the different fermions the following table arises, in which the momentum direction is always downwards and the arrows show whether the momentum and the fermion line, respectively are parallel or antiparallel to the direction of calculation:

Fermion type	fermion arrow	mom.	calc.	sign
Dirac fermion	↑	↑ ↓	↑ ↑	negative
Dirac antifermion	↓	↓ ↓	↑ ↓	negative
Majorana fermion	-	↑ ↓	-	negative

So the sign of the momentum is always negative and no further distinction is needed. (*JR's probably right, but I need to check myself ...*)

```

type width =
  | Vanishing
  | Constant
  | Timelike
  | Running
  | Fudged
  | Custom of string

```

### 9.1.2 Vertices

The combined  $S - P$  and  $V - A$  couplings (see tables 9.5, 9.6, 9.8 and 9.12) are redundant, of course, but they allow some targets to create more efficient numerical code.<sup>1</sup> Choosing VA2 over VA will cause the FORTRAN backend to pass the coupling as a whole array

<sup>1</sup>An additional benefit is that the counting of Feynman diagrams is not upset by a splitting of the vectorial and axial pieces of gauge bosons.

```

type fermion = Psi | Chi | Grav
type fermionbar = Psibar | Chibar | Gravbar
type boson =
  | SP | SPM | S | P | SL | SR | SLR | VA | V | A | VL | VR |
  | VLR | VLRM | VAM
  | TVA | TLR | TRL | TVAM | TLRM | TRLM
  | POT | MOM | MOM5 | MOML | MOMR | LMOM | RMOM |
  | VMOM | VA2 | VA3 | VA3M
type boson2 = S2 | P2 | S2P | S2L | S2R | S2LR
  | SV | PV | SLV | SRV | SLRV | V2 | V2LR

```

The integer is an additional coefficient that multiplies the respective coupling constant. This allows to reduce the number of required coupling constants in manifestly symmetric cases. Most of times it will be equal unity, though.

The two vertex types *PBP* and *BBB* for the couplings of two fermions or two antifermions ("clashing arrows") is unavoidable in supersymmetric theories.



... tho doesn't like the names and has promised to find a better mnemonics!

```

type α vertex3 =
  | FBF of int × fermionbar × boson × fermion
  | PBP of int × fermion × boson × fermion
  | BBB of int × fermionbar × boson × fermionbar
  | GBG of int × fermionbar × boson × fermion (* gravitino-boson-fermion
*)
  | Gauge_Gauge_Gauge of int | Aux_Gauge_Gauge of int
  | Scalar_Vector_Vector of int
  | Aux_Vector_Vector of int | Aux_Scalar_Vector of int
  | Scalar_Scalar_Scalar of int | Aux_Scalar_Scalar of int
  | Vector_Scalar_Scalar of int
  | Graviton_Scalar_Scalar of int
  | Graviton_Vector_Vector of int
  | Graviton_Spinor_Spinor of int
  | Dim4_Vector_Vector_Vector_T of int
  | Dim4_Vector_Vector_Vector_L of int
  | Dim4_Vector_Vector_Vector_T5 of int
  | Dim4_Vector_Vector_Vector_L5 of int
  | Dim6_Gauge_Gauge_Gauge of int
  | Dim6_Gauge_Gauge_Gauge_5 of int
  | Aux_DScalar_DScalar of int | Aux_Vector_DScalar of int
  | Dim5_Scalar_Gauge2 of int (*  $\frac{1}{2}\phi F_{1,\mu\nu}F_2^{\mu\nu} = -\frac{1}{2}\phi(i\partial_{[\mu}V_{1,\nu]})(i\partial^{[\mu}V_2^{\nu]})$  *)
  | Dim5_Scalar_Gauge2_Skew of int
    (*  $\frac{1}{2}\phi F_{1,\mu\nu}\tilde{F}_2^{\mu\nu} = -\phi(i\partial_\mu V_{1,\nu})(i\partial_\rho V_{2,\sigma})\epsilon^{\mu\nu\rho\sigma}$  *)
  | Dim5_Scalar_Vector_Vector_T of int (*  $\phi(i\partial_\mu V_1^\nu)(i\partial_\nu V_2^\mu)$  *)
  | Dim5_Scalar_Vector_Vector_TU of int (*  $(i\partial_\nu\phi)(i\partial_\mu V_1^\nu)V_2^\mu$  *)
  | Dim5_Scalar_Vector_Vector_U of int (*  $(i\partial_\nu\phi)(i\partial_\mu V^\nu)V^\mu$  *)
  | Scalar_Vector_Vector_t of int (*  $(\partial_\mu V_\nu - \partial_\nu V_\mu)^2$  *)
  | Dim6_Vector_Vector_Vector_T of int (*  $V_1^\mu((i\partial_\nu V_2^\rho)\overleftrightarrow{i\partial}_\mu(i\partial_\rho V_3^\nu))$  *)
  | Tensor_2_Vector_Vector of int (*  $T^{\mu\nu}(V_{1,\mu}V_{2,\nu} + V_{1,\nu}V_{2,\mu})$  *)
  | Tensor_2_Vector_Vector_1 of int (*  $T^{\mu\nu}(V_{1,\mu}V_{2,\nu} + V_{1,\nu}V_{2,\mu} - g_{\mu,\nu}V_1^\rho V_{2,\rho})$  *)
*)

```

```

| Tensor_2_Vector_Vector_t of int (* Tμν(V1,μV2,ν + V1,νV2,μ - gμ,νV1ρV2,ρ)
*)
| Dim5_Tensor_2_Vector_Vector_1 of int (* Tαβ(V1μi↔α↔βV2,μ *)
| Dim5_Tensor_2_Vector_Vector_2 of int
  (* Tαβ(V1μi↔β(i∂μV2,α) + V1μi↔α(i∂μV2,β)) *)
| Dim7_Tensor_2_Vector_Vector_T of int (* Tαβ((i∂μV1ν)i↔α↔β(i∂νV2,μ))
*)

```

As long as we stick to renormalizable couplings, there are only three types of quartic couplings: *Scalar4*, *Scalar2\_Vector2* and *Vector4*. However, there are three inequivalent contractions for the latter and the general vertex will be a linear combination with integer coefficients:

$$\text{Scalar4 } 1 : \quad \phi_1 \phi_2 \phi_3 \phi_4 \quad (9.2a)$$

$$\text{Scalar2\_Vector2 } 1 : \quad \phi_1 \phi_2 V_3^\mu V_{4,\mu} \quad (9.2b)$$

$$\text{Vector4 } [1, C\_12\_34] : \quad V_1^\mu V_{2,\mu} V_3^\nu V_{4,\nu} \quad (9.2c)$$

$$\text{Vector4 } [1, C\_13\_42] : \quad V_1^\mu V_2^\nu V_{3,\mu} V_{4,\nu} \quad (9.2d)$$

$$\text{Vector4 } [1, C\_14\_23] : \quad V_1^\mu V_2^\nu V_{3,\nu} V_{4,\mu} \quad (9.2e)$$

```

type contract4 = C_12_34 | C_13_42 | C_14_23

```

```

type α vertex4 =
| Scalar4 of int
| Scalar2_Vector2 of int
| Vector4 of (int × contract4) list
| DScalar4 of (int × contract4) list
| DScalar2_Vector2 of (int × contract4) list
| GBBG of int × fermionbar × boson2 × fermion

```

In some applications, we have to allow for contributions outside of perturbation theory. The most prominent example is heavy gauge boson scattering at very high energies, where the perturbative expression violates unitarity.

One solution is the ‘*K*-matrix’ ansatz. Such unitarizations typically introduce effective propagators and/or vertices that violate crossing symmetry and vanish in the *t*-channel. This can be taken care of in *Fusion* by filtering out vertices that have the wrong momenta.

In this case the ordering of the fields in a vertex of the Feynman rules becomes significant. In particular, we assume that  $(V_1, V_2, V_3, V_4)$  implies

$$(9.3)$$

The list of pairs of parameters denotes the location and strengths of the poles in the *K*-matrix ansatz:

$$(c_1, a_1, c_2, a_2, \dots, c_n, a_n) \implies f(s) = \sum_{i=1}^n \frac{c_i}{s - a_i} \quad (9.4)$$

```
| Vector4_K_Matrix_tho of int × (α × α) list
| Vector4_K_Matrix_jr of int × (int × contract4) list
```

type  $\alpha$  vertexn = unit

An obvious candidate for addition to *boson* is *T*, of course.



This list is sufficient for the minimal standard model, but not comprehensive enough for most of its extensions, supersymmetric or otherwise. In particular, we need a *general* parameterization for all trilinear vertices. One straightforward possibility are polynomials in the momenta for each combination of fields.



*JR sez' (regarding the Majorana Feynman rules):* Here we use the rules which can be found in [7] and are more properly described in *Targets* where the performing of the fusion rules in analytical expressions is encoded. (*JR's probably right, but I need to check myself ...*)

Signify which two of three fields are fused:

```
type fuse2 = F23 | F32 | F31 | F13 | F12 | F21
```

Signify which three of four fields are fused:

```
type fuse3 =
```

```
| F123 | F231 | F312 | F132 | F321 | F213
| F124 | F241 | F412 | F142 | F421 | F214
| F134 | F341 | F413 | F143 | F431 | F314
| F234 | F342 | F423 | F243 | F432 | F324
```

Explicit enumeration types make no sense for higher degrees.

```
type fusen = int list
```

The third member of the triplet will contain the coupling constant:

```
type α t =
```

```
| V3 of α vertex3 × fuse2 × α
| V4 of α vertex4 × fuse3 × α
| Vn of α vertexn × fusen × α
```

### 9.1.3 Gauge Couplings

Dimension-4 trilinear vector boson couplings

$$\begin{aligned} f_{abc} \partial^\mu A_\mu^{a,\nu} A_\nu^b A_\nu^c &\rightarrow i f_{abc} k_1^\mu A_\mu^{a,\nu}(k_1) A_\nu^b(k_2) A_\nu^c(k_3) \\ &= -\frac{i}{3!} f_{a_1 a_2 a_3} C^{\mu_1 \mu_2 \mu_3}(k_1, k_2, k_3) A_{\mu_1}^{a_1}(k_1) A_{\mu_2}^{a_2}(k_2) A_{\mu_3}^{a_3}(k_3) \end{aligned} \quad (9.5a)$$

with the totally antisymmetric tensor (under simultaneous permutations of all quantum numbers  $\mu_i$  and  $k_i$ ) and all momenta *outgoing*

$$C^{\mu_1 \mu_2 \mu_3}(k_1, k_2, k_3) = (g^{\mu_1 \mu_2}(k_1^{\mu_3} - k_2^{\mu_3}) + g^{\mu_2 \mu_3}(k_2^{\mu_1} - k_3^{\mu_1}) + g^{\mu_3 \mu_1}(k_3^{\mu_2} - k_1^{\mu_2})) \quad (9.5b)$$

	only Dirac fermions	incl. Majorana fermions
<i>FBF</i> ( <i>Psibar</i> , <i>S</i> , <i>Psi</i> ): $\mathcal{L}_I = g_S \bar{\psi}_1 S \psi_2$		
<i>F12</i>	$\bar{\psi}_2 \leftarrow i \cdot g_S \bar{\psi}_1 S$	$\psi_2 \leftarrow i \cdot g_S \psi_1 S$
<i>F21</i>	$\bar{\psi}_2 \leftarrow i \cdot g_S S \bar{\psi}_1$	$\psi_2 \leftarrow i \cdot g_S S \psi_1$
<i>F13</i>	$S \leftarrow i \cdot g_S \bar{\psi}_1 \psi_2$	$S \leftarrow i \cdot g_S \psi_1^T C \psi_2$
<i>F31</i>	$S \leftarrow i \cdot g_S \psi_{2,\alpha} \bar{\psi}_{1,\alpha}$	$S \leftarrow i \cdot g_S \psi_2^T C \psi_1$
<i>F23</i>	$\psi_1 \leftarrow i \cdot g_S S \psi_2$	$\psi_1 \leftarrow i \cdot g_S S \psi_2$
<i>F32</i>	$\psi_1 \leftarrow i \cdot g_S \psi_2 S$	$\psi_1 \leftarrow i \cdot g_S \psi_2 S$
<i>FBF</i> ( <i>Psibar</i> , <i>P</i> , <i>Psi</i> ): $\mathcal{L}_I = g_P \bar{\psi}_1 P \gamma_5 \psi_2$		
<i>F12</i>	$\bar{\psi}_2 \leftarrow i \cdot g_P \bar{\psi}_1 \gamma_5 P$	$\psi_2 \leftarrow i \cdot g_P \gamma_5 \psi_1 P$
<i>F21</i>	$\bar{\psi}_2 \leftarrow i \cdot g_P P \bar{\psi}_1 \gamma_5$	$\psi_2 \leftarrow i \cdot g_P P \gamma_5 \psi_1$
<i>F13</i>	$P \leftarrow i \cdot g_P \bar{\psi}_1 \gamma_5 \psi_2$	$P \leftarrow i \cdot g_P \psi_1^T C \gamma_5 \psi_2$
<i>F31</i>	$P \leftarrow i \cdot g_P [\gamma_5 \psi_2]_\alpha \bar{\psi}_{1,\alpha}$	$P \leftarrow i \cdot g_P \psi_2^T C \gamma_5 \psi_1$
<i>F23</i>	$\psi_1 \leftarrow i \cdot g_P P \gamma_5 \psi_2$	$\psi_1 \leftarrow i \cdot g_P P \gamma_5 \psi_2$
<i>F32</i>	$\psi_1 \leftarrow i \cdot g_P \gamma_5 \psi_2 P$	$\psi_1 \leftarrow i \cdot g_P \gamma_5 \psi_2 P$
<i>FBF</i> ( <i>Psibar</i> , <i>V</i> , <i>Psi</i> ): $\mathcal{L}_I = g_V \bar{\psi}_1 \not{V} \psi_2$		
<i>F12</i>	$\bar{\psi}_2 \leftarrow i \cdot g_V \bar{\psi}_1 \not{V}$	$\psi_{2,\alpha} \leftarrow i \cdot (-g_V) \psi_{1,\beta} \not{V}_{\alpha\beta}$
<i>F21</i>	$\bar{\psi}_{2,\beta} \leftarrow i \cdot g_V \not{V}_{\alpha\beta} \bar{\psi}_{1,\alpha}$	$\psi_2 \leftarrow i \cdot (-g_V) \not{V} \psi_1$
<i>F13</i>	$V_\mu \leftarrow i \cdot g_V \bar{\psi}_1 \gamma_\mu \psi_2$	$V_\mu \leftarrow i \cdot g_V (\psi_1)^T C \gamma_\mu \psi_2$
<i>F31</i>	$V_\mu \leftarrow i \cdot g_V [\gamma_\mu \psi_2]_\alpha \bar{\psi}_{1,\alpha}$	$V_\mu \leftarrow i \cdot (-g_V) (\psi_2)^T C \gamma_\mu \psi_1$
<i>F23</i>	$\psi_1 \leftarrow i \cdot g_V \not{V} \psi_2$	$\psi_1 \leftarrow i \cdot g_V \not{V} \psi_2$
<i>F32</i>	$\psi_{1,\alpha} \leftarrow i \cdot g_V \psi_{2,\beta} \not{V}_{\alpha\beta}$	$\psi_{1,\alpha} \leftarrow i \cdot g_V \psi_{2,\beta} \not{V}_{\alpha\beta}$
<i>FBF</i> ( <i>Psibar</i> , <i>A</i> , <i>Psi</i> ): $\mathcal{L}_I = g_A \bar{\psi}_1 \gamma_5 \not{A} \psi_2$		
<i>F12</i>	$\bar{\psi}_2 \leftarrow i \cdot g_A \bar{\psi}_1 \gamma_5 \not{A}$	$\psi_{2,\alpha} \leftarrow i \cdot g_A \psi_\beta [\gamma_5 \not{A}]_{\alpha\beta}$
<i>F21</i>	$\bar{\psi}_{2,\beta} \leftarrow i \cdot g_A [\gamma_5 \not{A}]_{\alpha\beta} \bar{\psi}_{1,\alpha}$	$\psi_2 \leftarrow i \cdot g_A \gamma_5 \not{A} \psi_1$
<i>F13</i>	$A_\mu \leftarrow i \cdot g_A \bar{\psi}_1 \gamma_5 \gamma_\mu \psi_2$	$A_\mu \leftarrow i \cdot g_A \psi_1^T C \gamma_5 \gamma_\mu \psi_2$
<i>F31</i>	$A_\mu \leftarrow i \cdot g_A [\gamma_5 \gamma_\mu \psi_2]_\alpha \bar{\psi}_{1,\alpha}$	$A_\mu \leftarrow i \cdot g_A \psi_2^T C \gamma_5 \gamma_\mu \psi_1$
<i>F23</i>	$\psi_1 \leftarrow i \cdot g_A \gamma_5 \not{A} \psi_2$	$\psi_1 \leftarrow i \cdot g_A \gamma_5 \not{A} \psi_2$
<i>F32</i>	$\psi_{1,\alpha} \leftarrow i \cdot g_A \psi_{2,\beta} [\gamma_5 \not{A}]_{\alpha\beta}$	$\psi_{1,\alpha} \leftarrow i \cdot g_A \psi_{2,\beta} [\gamma_5 \not{A}]_{\alpha\beta}$

Table 9.3: Dimension-4 trilinear fermionic couplings. The momenta are unambiguous, because there are no derivative couplings and all participating fields are different.



	only Dirac fermions	incl. Majorana fermions
<i>FBF</i> ( <i>Psibar</i> , <i>T</i> , <i>Psi</i> ): $\mathcal{L}_I = g_T T_{\mu\nu} \bar{\psi}_1 [\gamma^\mu, \gamma^\nu] - \psi_2$		
<i>F12</i>	$\bar{\psi}_2 \leftarrow i \cdot g_T \bar{\psi}_1 [\gamma^\mu, \gamma^\nu] - T_{\mu\nu}$	$\bar{\psi}_2 \leftarrow i \cdot g_T \dots$
<i>F21</i>	$\bar{\psi}_2 \leftarrow i \cdot g_T T_{\mu\nu} \bar{\psi}_1 [\gamma^\mu, \gamma^\nu] -$	$\bar{\psi}_2 \leftarrow i \cdot g_T \dots$
<i>F13</i>	$T_{\mu\nu} \leftarrow i \cdot g_T \bar{\psi}_1 [\gamma_\mu, \gamma_\nu] - \psi_2$	$T_{\mu\nu} \leftarrow i \cdot g_T \dots$
<i>F31</i>	$T_{\mu\nu} \leftarrow i \cdot g_T [[\gamma_\mu, \gamma_\nu] - \psi_2]_\alpha \bar{\psi}_{1,\alpha}$	$T_{\mu\nu} \leftarrow i \cdot g_T \dots$
<i>F23</i>	$\psi_1 \leftarrow i \cdot g_T T_{\mu\nu} [\gamma^\mu, \gamma^\nu] - \psi_2$	$\psi_1 \leftarrow i \cdot g_T \dots$
<i>F32</i>	$\psi_1 \leftarrow i \cdot g_T [\gamma^\mu, \gamma^\nu] - \psi_2 T_{\mu\nu}$	$\psi_1 \leftarrow i \cdot g_T \dots$

Table 9.4: Dimension-5 trilinear fermionic couplings (NB: the coefficients and signs are not fixed yet). The momenta are unambiguous, because there are no derivative couplings and all participating fields are different.

Since  $f_{a_1 a_2 a_3} C^{\mu_1 \mu_2 \mu_3}(k_1, k_2, k_3)$  is totally symmetric (under simultaneous permutations of all quantum numbers  $a_i$ ,  $\mu_i$  and  $k_i$ ), it is easy to take the partial derivative

$$A^{a,\mu}(k_2 + k_3) = -\frac{i}{2!} f_{abc} C^{\mu\rho\sigma}(-k_2 - k_3, k_2, k_3) A_\rho^b(k_2) A_\sigma^c(k_3) \quad (9.6a)$$

with

$$C^{\mu\rho\sigma}(-k_2 - k_3, k_2, k_3) = (g^{\rho\sigma}(k_2^\mu - k_3^\mu) + g^{\mu\sigma}(2k_3^\rho + k_2^\rho) - g^{\mu\rho}(2k_2^\sigma + k_3^\sigma)) \quad (9.6b)$$

i. e.

$$\begin{aligned} A^{a,\mu}(k_2 + k_3) = & -\frac{i}{2!} f_{abc} ((k_2^\mu - k_3^\mu) A^b(k_2) \cdot A^c(k_3) \\ & + (2k_3 + k_2) \cdot A^b(k_2) A^{c,\mu}(k_3) - A^{b,\mu}(k_2) A^c(k_3) \cdot (2k_2 + k_3)) \end{aligned} \quad (9.6c)$$



Investigate the rearrangements proposed in [5] for improved numerical stability.

### Non-Gauge Vector Couplings

As a basis for the dimension-4 couplings of three vector bosons, we choose “transversal” and “longitudinal” (with respect to the first vector field) tensors that are odd and even under permutation of the second and third argument

$$\mathcal{L}_T(V_1, V_2, V_3) = V_1^\mu (V_{2,\nu} i \overleftrightarrow{\partial}_\mu V_3^\nu) = -\mathcal{L}_T(V_1, V_3, V_2) \quad (9.7a)$$

$$\mathcal{L}_L(V_1, V_2, V_3) = (i \partial_\mu V_1^\mu) V_{2,\nu} V_3^\nu = \mathcal{L}_L(V_1, V_3, V_2) \quad (9.7b)$$

Using partial integration in  $\mathcal{L}_L$ , we find the convenient combinations

$$\mathcal{L}_T(V_1, V_2, V_3) + \mathcal{L}_L(V_1, V_2, V_3) = -2V_1^\mu i \partial_\mu V_{2,\nu} V_3^\nu \quad (9.8a)$$

$$\mathcal{L}_T(V_1, V_2, V_3) - \mathcal{L}_L(V_1, V_2, V_3) = 2V_1^\mu V_{2,\nu} i \partial_\mu V_3^\nu \quad (9.8b)$$

	only Dirac fermions	incl. Majorana fermions
<i>FBF</i> ( <i>Psibar</i> , <i>SP</i> , <i>Psi</i> ): $\mathcal{L}_I = \bar{\psi}_1 \phi (g_S + g_P \gamma_5) \psi_2$		
<i>F12</i>	$\bar{\psi}_2 \leftarrow i \cdot \bar{\psi}_1 (g_S + g_P \gamma_5) \phi$	$\psi_2 \leftarrow i \dots$
<i>F21</i>	$\bar{\psi}_2 \leftarrow i \cdot \phi \bar{\psi}_1 (g_S + g_P \gamma_5)$	$\psi_2 \leftarrow i \dots$
<i>F13</i>	$\phi \leftarrow i \cdot \bar{\psi}_1 (g_S + g_P \gamma_5) \psi_2$	$\phi \leftarrow i \dots$
<i>F31</i>	$\phi \leftarrow i \cdot [(g_S + g_P \gamma_5) \psi_2]_\alpha \bar{\psi}_{1,\alpha}$	$\phi \leftarrow i \dots$
<i>F23</i>	$\psi_1 \leftarrow i \cdot \phi (g_S + g_P \gamma_5) \psi_2$	$\psi_1 \leftarrow i \dots$
<i>F32</i>	$\psi_1 \leftarrow i \cdot (g_S + g_P \gamma_5) \psi_2 \phi$	$\psi_1 \leftarrow i \dots$
<i>FBF</i> ( <i>Psibar</i> , <i>SL</i> , <i>Psi</i> ): $\mathcal{L}_I = g_L \bar{\psi}_1 \phi (1 - \gamma_5) \psi_2$		
<i>F12</i>	$\bar{\psi}_2 \leftarrow i \cdot g_L \bar{\psi}_1 (1 - \gamma_5) \phi$	$\psi_2 \leftarrow i \dots$
<i>F21</i>	$\bar{\psi}_2 \leftarrow i \cdot g_L \phi \bar{\psi}_1 (1 - \gamma_5)$	$\psi_2 \leftarrow i \dots$
<i>F13</i>	$\phi \leftarrow i \cdot g_L \bar{\psi}_1 (1 - \gamma_5) \psi_2$	$\phi \leftarrow i \dots$
<i>F31</i>	$\phi \leftarrow i \cdot g_L [(1 - \gamma_5) \psi_2]_\alpha \bar{\psi}_{1,\alpha}$	$\phi \leftarrow i \dots$
<i>F23</i>	$\psi_1 \leftarrow i \cdot g_L \phi (1 - \gamma_5) \psi_2$	$\psi_1 \leftarrow i \dots$
<i>F32</i>	$\psi_1 \leftarrow i \cdot g_L (1 - \gamma_5) \psi_2 \phi$	$\psi_1 \leftarrow i \dots$
<i>FBF</i> ( <i>Psibar</i> , <i>SR</i> , <i>Psi</i> ): $\mathcal{L}_I = g_R \bar{\psi}_1 \phi (1 + \gamma_5) \psi_2$		
<i>F12</i>	$\bar{\psi}_2 \leftarrow i \cdot g_R \bar{\psi}_1 (1 + \gamma_5) \phi$	$\psi_2 \leftarrow i \dots$
<i>F21</i>	$\bar{\psi}_2 \leftarrow i \cdot g_R \phi \bar{\psi}_1 (1 + \gamma_5)$	$\psi_2 \leftarrow i \dots$
<i>F13</i>	$\phi \leftarrow i \cdot g_R \bar{\psi}_1 (1 + \gamma_5) \psi_2$	$\phi \leftarrow i \dots$
<i>F31</i>	$\phi \leftarrow i \cdot g_R [(1 + \gamma_5) \psi_2]_\alpha \bar{\psi}_{1,\alpha}$	$\phi \leftarrow i \dots$
<i>F23</i>	$\psi_1 \leftarrow i \cdot g_R \phi (1 + \gamma_5) \psi_2$	$\psi_1 \leftarrow i \dots$
<i>F32</i>	$\psi_1 \leftarrow i \cdot g_R (1 + \gamma_5) \psi_2 \phi$	$\psi_1 \leftarrow i \dots$
<i>FBF</i> ( <i>Psibar</i> , <i>SLR</i> , <i>Psi</i> ): $\mathcal{L}_I = g_L \bar{\psi}_1 \phi (1 - \gamma_5) \psi_2 + g_R \bar{\psi}_1 \phi (1 + \gamma_5) \psi_2$		

Table 9.5: Combined dimension-4 trilinear fermionic couplings.

	only Dirac fermions	incl. Majorana fermions
<i>FBF</i> ( <i>Psibar</i> , <i>VA</i> , <i>Psi</i> ): $\mathcal{L}_I = \bar{\psi}_1 \not{Z} (g_V - g_A \gamma_5) \psi_2$		
<i>F12</i>	$\bar{\psi}_2 \leftarrow i \cdot \bar{\psi}_1 \not{Z} (g_V - g_A \gamma_5)$	$\psi_2 \leftarrow i \dots$
<i>F21</i>	$\bar{\psi}_{2,\beta} \leftarrow i \cdot [\not{Z} (g_V - g_A \gamma_5)]_{\alpha\beta} \bar{\psi}_{1,\alpha}$	$\psi_2 \leftarrow i \dots$
<i>F13</i>	$Z_\mu \leftarrow i \cdot \bar{\psi}_1 \gamma_\mu (g_V - g_A \gamma_5) \psi_2$	$Z_\mu \leftarrow i \dots$
<i>F31</i>	$Z_\mu \leftarrow i \cdot [\gamma_\mu (g_V - g_A \gamma_5) \psi_2]_\alpha \bar{\psi}_{1,\alpha}$	$Z_\mu \leftarrow i \dots$
<i>F23</i>	$\psi_1 \leftarrow i \cdot \not{Z} (g_V - g_A \gamma_5) \psi_2$	$\psi_1 \leftarrow i \dots$
<i>F32</i>	$\psi_{1,\alpha} \leftarrow i \cdot \psi_{2,\beta} [\not{Z} (g_V - g_A \gamma_5)]_{\alpha\beta}$	$\psi_1 \leftarrow i \dots$
<i>FBF</i> ( <i>Psibar</i> , <i>VL</i> , <i>Psi</i> ): $\mathcal{L}_I = g_L \bar{\psi}_1 \not{Z} (1 - \gamma_5) \psi_2$		
<i>F12</i>	$\bar{\psi}_2 \leftarrow i \cdot g_L \bar{\psi}_1 \not{Z} (1 - \gamma_5)$	$\psi_2 \leftarrow i \dots$
<i>F21</i>	$\bar{\psi}_{2,\beta} \leftarrow i \cdot g_L [\not{Z} (1 - \gamma_5)]_{\alpha\beta} \bar{\psi}_{1,\alpha}$	$\psi_2 \leftarrow i \dots$
<i>F13</i>	$Z_\mu \leftarrow i \cdot g_L \bar{\psi}_1 \gamma_\mu (1 - \gamma_5) \psi_2$	$Z_\mu \leftarrow i \dots$
<i>F31</i>	$Z_\mu \leftarrow i \cdot g_L [\gamma_\mu (1 - \gamma_5) \psi_2]_\alpha \bar{\psi}_{1,\alpha}$	$Z_\mu \leftarrow i \dots$
<i>F23</i>	$\psi_1 \leftarrow i \cdot g_L \not{Z} (1 - \gamma_5) \psi_2$	$\psi_1 \leftarrow i \dots$
<i>F32</i>	$\psi_{1,\alpha} \leftarrow i \cdot g_L \psi_{2,\beta} [\not{Z} (1 - \gamma_5)]_{\alpha\beta}$	$\psi_1 \leftarrow i \dots$
<i>FBF</i> ( <i>Psibar</i> , <i>VR</i> , <i>Psi</i> ): $\mathcal{L}_I = g_R \bar{\psi}_1 \not{Z} (1 + \gamma_5) \psi_2$		
<i>F12</i>	$\bar{\psi}_2 \leftarrow i \cdot g_R \bar{\psi}_1 \not{Z} (1 + \gamma_5)$	$\psi_2 \leftarrow i \dots$
<i>F21</i>	$\bar{\psi}_{2,\beta} \leftarrow i \cdot g_R [\not{Z} (1 + \gamma_5)]_{\alpha\beta} \bar{\psi}_{1,\alpha}$	$\psi_2 \leftarrow i \dots$
<i>F13</i>	$Z_\mu \leftarrow i \cdot g_R \bar{\psi}_1 \gamma_\mu (1 + \gamma_5) \psi_2$	$Z_\mu \leftarrow i \dots$
<i>F31</i>	$Z_\mu \leftarrow i \cdot g_R [\gamma_\mu (1 + \gamma_5) \psi_2]_\alpha \bar{\psi}_{1,\alpha}$	$Z_\mu \leftarrow i \dots$
<i>F23</i>	$\psi_1 \leftarrow i \cdot g_R \not{Z} (1 + \gamma_5) \psi_2$	$\psi_1 \leftarrow i \dots$
<i>F32</i>	$\psi_{1,\alpha} \leftarrow i \cdot g_R \psi_{2,\beta} [\not{Z} (1 + \gamma_5)]_{\alpha\beta}$	$\psi_1 \leftarrow i \dots$
<i>FBF</i> ( <i>Psibar</i> , <i>VLR</i> , <i>Psi</i> ): $\mathcal{L}_I = g_L \bar{\psi}_1 \not{Z} (1 - \gamma_5) \psi_2 + g_R \bar{\psi}_1 \not{Z} (1 + \gamma_5) \psi_2$		

Table 9.6: Combined dimension-4 trilinear fermionic couplings continued.

<i>FBF</i> ( <i>Psibar</i> , <i>S</i> , <i>Chi</i> ): $\bar{\psi}S\chi$	
<i>F12</i> : $\chi \leftarrow \psi S$	<i>F21</i> : $\chi \leftarrow S\psi$
<i>F13</i> : $S \leftarrow \psi^T C\chi$	<i>F31</i> : $S \leftarrow \chi^T C\psi$
<i>F23</i> : $\psi \leftarrow S\chi$	<i>F32</i> : $\psi \leftarrow \chi S$
<i>FBF</i> ( <i>Psibar</i> , <i>P</i> , <i>Chi</i> ): $\bar{\psi}P\gamma_5\chi$	
<i>F12</i> : $\chi \leftarrow \gamma_5\psi P$	<i>F21</i> : $\chi \leftarrow P\gamma_5\psi$
<i>F13</i> : $P \leftarrow \psi^T C\gamma_5\chi$	<i>F31</i> : $P \leftarrow \chi^T C\gamma_5\psi$
<i>F23</i> : $\psi \leftarrow P\gamma_5\chi$	<i>F32</i> : $\psi \leftarrow \gamma_5\chi P$
<i>FBF</i> ( <i>Psibar</i> , <i>V</i> , <i>Chi</i> ): $\bar{\psi}\not{V}\chi$	
<i>F12</i> : $\chi_\alpha \leftarrow -\psi_\beta \not{V}_{\alpha\beta}$	<i>F21</i> : $\chi \leftarrow -\not{V}\psi$
<i>F13</i> : $V_\mu \leftarrow \psi^T C\gamma_\mu\chi$	<i>F31</i> : $V_\mu \leftarrow \chi^T C(-\gamma_\mu\psi)$
<i>F23</i> : $\psi \leftarrow \not{V}\chi$	<i>F32</i> : $\psi_\alpha \leftarrow \chi_\beta \not{V}_{\alpha\beta}$
<i>FBF</i> ( <i>Psibar</i> , <i>A</i> , <i>Chi</i> ): $\bar{\psi}\gamma^5\not{A}\chi$	
<i>F12</i> : $\chi_\alpha \leftarrow \psi_\beta [\gamma^5\not{A}]_{\alpha\beta}$	<i>F21</i> : $\chi \leftarrow \gamma^5\not{A}\psi$
<i>F13</i> : $A_\mu \leftarrow \psi^T C\gamma^5\gamma_\mu\chi$	<i>F31</i> : $A_\mu \leftarrow \chi^T C(\gamma^5\gamma_\mu\psi)$
<i>F23</i> : $\psi \leftarrow \gamma^5\not{A}\chi$	<i>F32</i> : $\psi_\alpha \leftarrow \chi_\beta [\gamma^5\not{A}]_{\alpha\beta}$

Table 9.7: Dimension-4 trilinear couplings including one Dirac and one Majorana fermion

<i>FBF</i> ( <i>Psibar</i> , <i>SP</i> , <i>Chi</i> ): $\bar{\psi}\phi(g_S + g_P\gamma_5)\chi$	
<i>F12</i> : $\chi \leftarrow (g_S + g_P\gamma_5)\psi\phi$	<i>F21</i> : $\chi \leftarrow \phi(g_S + g_P\gamma_5)\psi$
<i>F13</i> : $\phi \leftarrow \psi^T C(g_S + g_P\gamma_5)\chi$	<i>F31</i> : $\phi \leftarrow \chi^T C(g_S + g_P\gamma_5)\chi$
<i>F23</i> : $\psi \leftarrow \phi(g_S + g_P\gamma_5)\chi$	<i>F32</i> : $\psi \leftarrow (g_S + g_P\gamma_5)\chi\phi$
<i>FBF</i> ( <i>Psibar</i> , <i>VA</i> , <i>Chi</i> ): $\bar{\psi}\not{Z}(g_V - g_A\gamma_5)\chi$	
<i>F12</i> : $\chi_\alpha \leftarrow \psi_\beta [\not{Z}(-g_V - g_A\gamma_5)]_{\alpha\beta}$	<i>F21</i> : $\chi \leftarrow \not{Z}(-g_V - g_A\gamma_5)\psi$
<i>F13</i> : $Z_\mu \leftarrow \psi^T C\gamma_\mu(g_V - g_A\gamma_5)\chi$	<i>F31</i> : $Z_\mu \leftarrow \chi^T C\gamma_\mu(-g_V - g_A\gamma_5)\psi$
<i>F23</i> : $\psi \leftarrow \not{Z}(g_V - g_A\gamma_5)\chi$	<i>F32</i> : $\psi_\alpha \leftarrow \chi_\beta [\not{Z}(g_V - g_A\gamma_5)]_{\alpha\beta}$

Table 9.8: Combined dimension-4 trilinear fermionic couplings including one Dirac and one Majorana fermion.

<i>FBF (Chibar, S, Psi): <math>\bar{\chi}S\psi</math></i>	
<i>F12:</i> $\psi \leftarrow \chi S$	<i>F21:</i> $\psi \leftarrow S\chi$
<i>F13:</i> $S \leftarrow \chi^T C\psi$	<i>F31:</i> $S \leftarrow \psi^T C\chi$
<i>F23:</i> $\chi \leftarrow S\psi$	<i>F32:</i> $\chi \leftarrow \psi S$
<i>FBF (Chibar, P, Psi): <math>\bar{\chi}P\gamma_5\psi</math></i>	
<i>F12:</i> $\psi \leftarrow \gamma_5\chi P$	<i>F21:</i> $\psi \leftarrow P\gamma_5\chi$
<i>F13:</i> $P \leftarrow \chi^T C\gamma_5\psi$	<i>F31:</i> $P \leftarrow \psi^T C\gamma_5\chi$
<i>F23:</i> $\chi \leftarrow P\gamma_5\psi$	<i>F32:</i> $\chi \leftarrow \gamma_5\psi P$
<i>FBF (Chibar, V, Psi): <math>\bar{\chi}\not{V}\psi</math></i>	
<i>F12:</i> $\psi_\alpha \leftarrow -\chi_\beta \not{V}_{\alpha\beta}$	<i>F21:</i> $\psi \leftarrow -\not{V}\chi$
<i>F13:</i> $V_\mu \leftarrow \chi^T C\gamma_\mu\psi$	<i>F31:</i> $V_\mu \leftarrow \psi^T C(-\gamma_\mu\chi)$
<i>F23:</i> $\chi \leftarrow \not{V}\psi$	<i>F32:</i> $\chi_\alpha \leftarrow \psi_\beta \not{V}_{\alpha\beta}$
<i>FBF (Chibar, A, Psi): <math>\bar{\chi}\gamma^5\not{A}\psi</math></i>	
<i>F12:</i> $\psi_\alpha \leftarrow \chi_\beta [\gamma^5\not{A}]_{\alpha\beta}$	<i>F21:</i> $\psi \leftarrow \gamma^5\not{A}\chi$
<i>F13:</i> $A_\mu \leftarrow \chi^T C(\gamma^5\gamma_\mu\psi)$	<i>F31:</i> $A_\mu \leftarrow \psi^T C\gamma^5\gamma_\mu\chi$
<i>F23:</i> $\chi \leftarrow \gamma^5\not{A}\psi$	<i>F32:</i> $\chi_\alpha \leftarrow \psi_\beta [\gamma^5\not{A}]_{\alpha\beta}$

Table 9.9: Dimension-4 trilinear couplings including one Dirac and one Majorana fermion

<i>FBF (Chibar, SP, Psi): <math>\bar{\chi}\phi(g_S + g_P\gamma_5)\psi</math></i>	
<i>F12:</i> $\psi \leftarrow (g_S + g_P\gamma_5)\chi\phi$	<i>F21:</i> $\psi \leftarrow \phi(g_S + g_P\gamma_5)\chi$
<i>F13:</i> $\phi \leftarrow \chi^T C(g_S + g_P\gamma_5)\psi$	<i>F31:</i> $\phi \leftarrow \psi^T C(g_S + g_P\gamma_5)\chi$
<i>F23:</i> $\chi \leftarrow \phi(g_S + g_P\gamma_5)\psi$	<i>F32:</i> $\chi \leftarrow (g_S + g_P\gamma_5)\psi\phi$
<i>FBF (Chibar, VA, Psi): <math>\bar{\chi}\not{Z}(g_V - g_A\gamma_5)\psi</math></i>	
<i>F12:</i> $\psi_\alpha \leftarrow \chi_\beta [\not{Z}(-g_V - g_A\gamma_5)]_{\alpha\beta}$	<i>F21:</i> $\psi \leftarrow \not{Z}(-g_V - g_A\gamma_5)\chi$
<i>F13:</i> $Z_\mu \leftarrow \chi^T C\gamma_\mu(g_V - g_A\gamma_5)\psi$	<i>F31:</i> $Z_\mu \leftarrow \psi^T C\gamma_\mu(-g_V - g_A\gamma_5)\chi$
<i>F23:</i> $\chi \leftarrow \not{Z}(g_V - g_A\gamma_5)\psi$	<i>F32:</i> $\chi_\alpha \leftarrow \psi_\beta [\not{Z}(g_V - g_A\gamma_5)]_{\alpha\beta}$

Table 9.10: Combined dimension-4 trilinear fermionic couplings including one Dirac and one Majorana fermion.

<i>FBF (Chibar, S, Chi):</i> $\bar{\chi}_a S \chi_b$	
<i>F12:</i> $\chi_b \leftarrow \chi_a S$	<i>F21:</i> $\chi_b \leftarrow S \chi_a$
<i>F13:</i> $S \leftarrow \chi_a^T C \chi_b$	<i>F31:</i> $S \leftarrow \chi_b^T C \chi_a$
<i>F23:</i> $\chi_a \leftarrow S \chi_b$	<i>F32:</i> $\chi_a \leftarrow \chi S_b$
<i>FBF (Chibar, P, Chi):</i> $\bar{\chi}_a P \gamma_5 \psi_b$	
<i>F12:</i> $\chi_b \leftarrow \gamma_5 \chi_a P$	<i>F21:</i> $\chi_b \leftarrow P \gamma_5 \chi_a$
<i>F13:</i> $P \leftarrow \chi_a^T C \gamma_5 \chi_b$	<i>F31:</i> $P \leftarrow \chi_b^T C \gamma_5 \chi_a$
<i>F23:</i> $\chi_a \leftarrow P \gamma_5 \chi_b$	<i>F32:</i> $\chi_a \leftarrow \gamma_5 \chi_b P$
<i>FBF (Chibar, V, Chi):</i> $\bar{\chi}_a \not{V} \chi_b$	
<i>F12:</i> $\chi_{b,\alpha} \leftarrow -\chi_{a,\beta} \not{V}_{\alpha\beta}$	<i>F21:</i> $\chi_b \leftarrow -\not{V} \chi_a$
<i>F13:</i> $V_\mu \leftarrow \chi_a^T C \gamma_\mu \chi_b$	<i>F31:</i> $V_\mu \leftarrow -\chi_b^T C \gamma_\mu \chi_a$
<i>F23:</i> $\chi_a \leftarrow \not{V} \chi_b$	<i>F32:</i> $\chi_{a,\alpha} \leftarrow \chi_{b,\beta} \not{V}_{\alpha\beta}$
<i>FBF (Chibar, A, Chi):</i> $\bar{\chi}_a \gamma^5 \not{A} \chi_b$	
<i>F12:</i> $\chi_{b,\alpha} \leftarrow \chi_{a,\beta} [\gamma^5 \not{A}]_{\alpha\beta}$	<i>F21:</i> $\chi_b \leftarrow \gamma^5 \not{A} \chi_a$
<i>F13:</i> $A_\mu \leftarrow \chi_a^T C \gamma^5 \gamma_\mu \chi_b$	<i>F31:</i> $A_\mu \leftarrow \chi_b^T C (\gamma^5 \gamma_\mu \chi_a)$
<i>F23:</i> $\chi_a \leftarrow \gamma^5 \not{A} \chi_b$	<i>F32:</i> $\chi_{a,\alpha} \leftarrow \chi_{b,\beta} [\gamma^5 \not{A}]_{\alpha\beta}$

Table 9.11: Dimension-4 trilinear couplings of two Majorana fermions

<i>FBF (Chibar, SP, Chi):</i> $\bar{\chi} \phi_a (g_S + g_P \gamma_5) \chi_b$	
<i>F12:</i> $\chi_b \leftarrow (g_S + g_P \gamma_5) \chi_a \phi$	<i>F21:</i> $\chi_b \leftarrow \phi (g_S + g_P \gamma_5) \chi_a$
<i>F13:</i> $\phi \leftarrow \chi_a^T C (g_S + g_P \gamma_5) \chi_b$	<i>F31:</i> $\phi \leftarrow \chi_b^T C (g_S + g_P \gamma_5) \chi_a$
<i>F23:</i> $\chi_a \leftarrow \phi (g_S + g_P \gamma_5) \chi_b$	<i>F32:</i> $\chi_a \leftarrow (g_S + g_P \gamma_5) \chi_b \phi$
<i>FBF (Chibar, VA, Chi):</i> $\bar{\chi}_a \not{Z} (g_V - g_A \gamma_5) \chi_b$	
<i>F12:</i> $\chi_{b,\alpha} \leftarrow \chi_{a,\beta} [\not{Z} (-g_V - g_A \gamma_5)]_{\alpha\beta}$	<i>F21:</i> $\chi_b \leftarrow \not{Z} (-g_V - g_A \gamma_5) \chi_a$
<i>F13:</i> $Z_\mu \leftarrow \chi_a^T C \gamma_\mu (g_V - g_A \gamma_5) \chi_b$	<i>F31:</i> $Z_\mu \leftarrow \chi_b^T C \gamma_\mu (-g_V - g_A \gamma_5) \chi_a$
<i>F23:</i> $\chi_a \leftarrow \not{Z} (g_V - g_A \gamma_5) \chi_b$	<i>F32:</i> $\chi_{a,\alpha} \leftarrow \chi_{b,\beta} [\not{Z} (g_V - g_A \gamma_5)]_{\alpha\beta}$

Table 9.12: Combined dimension-4 trilinear fermionic couplings of two Majorana fermions.

<i>Gauge_Gauge_Gauge</i> : $\mathcal{L}_I = gf_{abc}A_a^\mu A_b^\nu \partial_\mu A_{c,\nu}$
$\therefore A_a^\mu \leftarrow i \cdot (-ig/2) \cdot C_{abc}^{\mu\rho\sigma}(-k_2 - k_3, k_2, k_3) A_\rho^b A_\sigma^c$
<i>Aux_Gauge_Gauge</i> : $\mathcal{L}_I = gf_{abc}X_{a,\mu\nu}(k_1)(A_b^\mu(k_2)A_c^\nu(k_3) - A_b^\nu(k_2)A_c^\mu(k_3))$
<i>F23</i> $\vee$ <i>F32</i> : $X_a^{\mu\nu}(k_2 + k_3) \leftarrow i \cdot gf_{abc}(A_b^\mu(k_2)A_c^\nu(k_3) - A_b^\nu(k_2)A_c^\mu(k_3))$
<i>F12</i> $\vee$ <i>F13</i> : $A_{a,\mu}(k_1 + k_{2/3}) \leftarrow i \cdot gf_{abc}X_{b,\nu\mu}(k_1)A_c^\nu(k_{2/3})$
<i>F21</i> $\vee$ <i>F31</i> : $A_{a,\mu}(k_{2/3} + k_1) \leftarrow i \cdot gf_{abc}A_b^\nu(k_{2/3})X_{c,\mu\nu}(k_1)$

Table 9.13: Dimension-4 Vector Boson couplings with *outgoing* momenta. See (11.1b) and (9.6b) for the definition of the antisymmetric tensor  $C^{\mu_1\mu_2\mu_3}(k_1, k_2, k_3)$ .

<i>Scalar_Vector_Vector</i> : $\mathcal{L}_I = g\phi V_1^\mu V_{2,\mu}$	
<i>F13</i> : $\leftarrow i \cdot g \cdots$	<i>F31</i> : $\leftarrow i \cdot g \cdots$
<i>F12</i> : $\leftarrow i \cdot g \cdots$	<i>F21</i> : $\leftarrow i \cdot g \cdots$
<i>F23</i> : $\phi \leftarrow i \cdot g V_1^\mu V_{2,\mu}$	<i>F32</i> : $\phi \leftarrow i \cdot g V_{2,\mu} V_1^\mu$
<i>Aux_Vector_Vector</i> : $\mathcal{L}_I = gX V_1^\mu V_{2,\mu}$	
<i>F13</i> : $\leftarrow i \cdot g \cdots$	<i>F31</i> : $\leftarrow i \cdot g \cdots$
<i>F12</i> : $\leftarrow i \cdot g \cdots$	<i>F21</i> : $\leftarrow i \cdot g \cdots$
<i>F23</i> : $X \leftarrow i \cdot g V_1^\mu V_{2,\mu}$	<i>F32</i> : $X \leftarrow i \cdot g V_{2,\mu} V_1^\mu$
<i>Aux_Scalar_Vector</i> : $\mathcal{L}_I = gX^\mu \phi V_\mu$	
<i>F13</i> : $\leftarrow i \cdot g \cdots$	<i>F31</i> : $\leftarrow i \cdot g \cdots$
<i>F12</i> : $\leftarrow i \cdot g \cdots$	<i>F21</i> : $\leftarrow i \cdot g \cdots$
<i>F23</i> : $\leftarrow i \cdot g \cdots$	<i>F32</i> : $\leftarrow i \cdot g \cdots$

Table 9.14: ...

<i>Scalar_Scalar_Scalar</i> : $\mathcal{L}_I = g\phi_1\phi_2\phi_3$	
<i>F13</i> : $\phi_2 \leftarrow i \cdot g\phi_1\phi_3$	<i>F31</i> : $\phi_2 \leftarrow i \cdot g\phi_3\phi_1$
<i>F12</i> : $\phi_3 \leftarrow i \cdot g\phi_1\phi_2$	<i>F21</i> : $\phi_3 \leftarrow i \cdot g\phi_2\phi_1$
<i>F23</i> : $\phi_1 \leftarrow i \cdot g\phi_2\phi_3$	<i>F32</i> : $\phi_1 \leftarrow i \cdot g\phi_3\phi_2$
<i>Aux_Scalar_Scalar</i> : $\mathcal{L}_I = gX\phi_1\phi_2$	
<i>F13</i> : $\leftarrow i \cdot g \cdots$	<i>F31</i> : $\leftarrow i \cdot g \cdots$
<i>F12</i> : $\leftarrow i \cdot g \cdots$	<i>F21</i> : $\leftarrow i \cdot g \cdots$
<i>F23</i> : $X \leftarrow i \cdot g\phi_1\phi_2$	<i>F32</i> : $X \leftarrow i \cdot g\phi_2\phi_1$

Table 9.15: ...

<i>Vector_Scalar_Scalar</i> : $\mathcal{L}_I = gV^\mu\phi_1\overset{\leftrightarrow}{\partial}_\mu\phi_2$	
<i>F23</i> :	$V^\mu(k_2 + k_3) \leftarrow i \cdot g(k_2^\mu - k_3^\mu)\phi_1(k_2)\phi_2(k_3)$
<i>F32</i> :	$V^\mu(k_2 + k_3) \leftarrow i \cdot g(k_2^\mu - k_3^\mu)\phi_2(k_3)\phi_1(k_2)$
<i>F12</i> :	$\phi_2(k_1 + k_2) \leftarrow i \cdot g(k_1^\mu + 2k_2^\mu)V_\mu(k_1)\phi_1(k_2)$
<i>F21</i> :	$\phi_2(k_1 + k_2) \leftarrow i \cdot g(k_1^\mu + 2k_2^\mu)\phi_1(k_2)V_\mu(k_1)$
<i>F13</i> :	$\phi_1(k_1 + k_3) \leftarrow i \cdot g(-k_1^\mu - 2k_3^\mu)V_\mu(k_1)\phi_2(k_3)$
<i>F31</i> :	$\phi_1(k_1 + k_3) \leftarrow i \cdot g(-k_1^\mu - 2k_3^\mu)\phi_2(k_3)V_\mu(k_1)$

Table 9.16: ...

<i>Aux_DScalar_DScalar</i> : $\mathcal{L}_I = g\chi(i\partial_\mu\phi_1)(i\partial^\mu\phi_2)$	
<i>F23</i> :	$\chi(k_2 + k_3) \leftarrow i \cdot g(k_2 \cdot k_3)\phi_1(k_2)\phi_2(k_3)$
<i>F32</i> :	$\chi(k_2 + k_3) \leftarrow i \cdot g(k_3 \cdot k_2)\phi_2(k_3)\phi_1(k_2)$
<i>F12</i> :	$\phi_2(k_1 + k_2) \leftarrow i \cdot g((-k_1 - k_2) \cdot k_2)\chi(k_1)\phi_1(k_2)$
<i>F21</i> :	$\phi_2(k_1 + k_2) \leftarrow i \cdot g(k_2 \cdot (-k_1 - k_2))\phi_1(k_2)\chi(k_1)$
<i>F13</i> :	$\phi_1(k_1 + k_3) \leftarrow i \cdot g((-k_1 - k_3) \cdot k_3)\chi(k_1)\phi_2(k_3)$
<i>F31</i> :	$\phi_1(k_1 + k_3) \leftarrow i \cdot g(k_3 \cdot (-k_1 - k_3))\phi_2(k_3)\chi(k_1)$

Table 9.17: ...

<i>Aux_Vector_DScalar</i> : $\mathcal{L}_I = g\chi V_\mu(i\partial^\mu\phi)$	
<i>F23</i> :	$\chi(k_2 + k_3) \leftarrow i \cdot gk_3^\mu V_\mu(k_2)\phi(k_3)$
<i>F32</i> :	$\chi(k_2 + k_3) \leftarrow i \cdot g\phi(k_3)k_3^\mu V_\mu(k_2)$
<i>F12</i> :	$\phi(k_1 + k_2) \leftarrow i \cdot g\chi(k_1)(-k_1 - k_2)^\mu V_\mu(k_2)$
<i>F21</i> :	$\phi(k_1 + k_2) \leftarrow i \cdot g(-k_1 - k_2)^\mu V_\mu(k_2)\chi(k_1)$
<i>F13</i> :	$V_\mu(k_1 + k_3) \leftarrow i \cdot g(-k_1 - k_3)_\mu\chi(k_1)\phi(k_3)$
<i>F31</i> :	$V_\mu(k_1 + k_3) \leftarrow i \cdot g(-k_1 - k_3)_\mu\phi(k_3)\chi(k_1)$

Table 9.18: ...



As an important example, we can rewrite the dimension-4 “anomalous” triple gauge couplings

$$\begin{aligned} i\mathcal{L}_{\text{TGC}}(g_1, \kappa, g_4)/g_{VWW} = & g_1 V^\mu (W_{\mu\nu}^- W^{+\nu} - W_{\mu\nu}^+ W^{-\nu}) \\ & + \kappa W_\mu^+ W_\nu^- V^{\mu\nu} + g_4 W_\mu^+ W_\nu^- (\partial^\mu V^\nu + \partial^\nu V^\mu) \end{aligned} \quad (9.9)$$

as

$$\begin{aligned} \mathcal{L}_{\text{TGC}}(g_1, \kappa, g_4) = & g_1 \mathcal{L}_T(V, W^-, W^+) \\ & - \frac{\kappa + g_1 - g_4}{2} \mathcal{L}_T(W^-, V, W^+) + \frac{\kappa + g_1 + g_4}{2} \mathcal{L}_T(W^+, V, W^-) \\ & - \frac{\kappa - g_1 - g_4}{2} \mathcal{L}_L(W^-, V, W^+) + \frac{\kappa - g_1 + g_4}{2} \mathcal{L}_L(W^+, V, W^-) \end{aligned} \quad (9.10)$$

### CP Violation

$$\mathcal{L}_{\tilde{T}}(V_1, V_2, V_3) = V_{1,\mu} (V_{2,\rho} i \overleftrightarrow{\partial}_\nu V_{3,\sigma}) \epsilon^{\mu\nu\rho\sigma} = +\mathcal{L}_T(V_1, V_3, V_2) \quad (9.11a)$$

$$\mathcal{L}_{\tilde{L}}(V_1, V_2, V_3) = (i\partial_\mu V_{1,\nu}) V_{2,\rho} V_{3,\sigma} \epsilon^{\mu\nu\rho\sigma} = -\mathcal{L}_L(V_1, V_3, V_2) \quad (9.11b)$$

Here the notations  $\tilde{T}$  and  $\tilde{L}$  are clearly *abuse de langage*, because  $\mathcal{L}_{\tilde{L}}(V_1, V_2, V_3)$  is actually the transversal combination, due to the antisymmetry of  $\epsilon$ . Using partial integration in  $\mathcal{L}_{\tilde{L}}$ , we could again find combinations

$$\mathcal{L}_{\tilde{T}}(V_1, V_2, V_3) + \mathcal{L}_{\tilde{L}}(V_1, V_2, V_3) = -2V_{1,\mu} V_{2,\nu} i\partial_\rho V_{3,\sigma} \epsilon^{\mu\nu\rho\sigma} \quad (9.12a)$$

$$\mathcal{L}_{\tilde{T}}(V_1, V_2, V_3) - \mathcal{L}_{\tilde{L}}(V_1, V_2, V_3) = -2V_{1,\mu} i\partial_\nu V_{2,\rho} V_{3,\sigma} \epsilon^{\mu\nu\rho\sigma} \quad (9.12b)$$

but we don't need them, since

$$\begin{aligned} i\mathcal{L}_{\text{TGC}}(g_5, \tilde{\kappa})/g_{VWW} = & g_5 \epsilon_{\mu\nu\rho\sigma} (W^{+,\mu} i \overleftrightarrow{\partial}^\rho W^{-,\nu}) V^\sigma \\ & - \frac{\tilde{\kappa}_V}{2} W_\mu^- W_\nu^+ \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} \end{aligned} \quad (9.13)$$

is immediately recognizable as

$$\mathcal{L}_{\text{TGC}}(g_5, \tilde{\kappa})/g_{VWW} = -ig_5 \mathcal{L}_{\tilde{L}}(V, W^-, W^+) + \tilde{\kappa} \mathcal{L}_{\tilde{T}}(V, W^-, W^+) \quad (9.14)$$

### 9.1.4 SU(2) Gauge Bosons

An important special case for table 9.13 are the two usual coordinates of SU(2)

$$W_\pm = \frac{1}{\sqrt{2}} (W_1 \mp iW_2) \quad (9.15)$$

i. e.

$$W_1 = \frac{1}{\sqrt{2}} (W_+ + W_-) \quad (9.16a)$$

$$W_2 = \frac{i}{\sqrt{2}} (W_+ - W_-) \quad (9.16b)$$

<i>Dim4_Vector_Vector_Vector-T</i> : $\mathcal{L}_I = gV_1^\mu V_{2,\nu} i \overleftrightarrow{\partial}_\mu V_3^\nu$
<i>F23</i> : $V_1^\mu(k_2 + k_3) \leftarrow i \cdot g(k_2^\mu - k_3^\mu) V_{2,\nu}(k_2) V_3^\nu(k_3)$
<i>F32</i> : $V_1^\mu(k_2 + k_3) \leftarrow i \cdot g(k_2^\mu - k_3^\mu) V_3^\nu(k_3) V_{2,\nu}(k_2)$
<i>F12</i> : $V_3^\mu(k_1 + k_2) \leftarrow i \cdot g(2k_2^\nu + k_1^\nu) V_{1,\nu}(k_1) V_2^\mu(k_2)$
<i>F21</i> : $V_3^\mu(k_1 + k_2) \leftarrow i \cdot g(2k_2^\nu + k_1^\nu) V_2^\mu(k_2) V_{1,\nu}(k_1)$
<i>F13</i> : $V_2^\mu(k_1 + k_3) \leftarrow i \cdot g(-k_1^\nu - 2k_3^\nu) V_1^\nu(k_1) V_3^\mu(k_3)$
<i>F31</i> : $V_2^\mu(k_1 + k_3) \leftarrow i \cdot g(-k_1^\nu - 2k_3^\nu) V_3^\mu(k_3) V_1^\nu(k_1)$
<i>Dim4_Vector_Vector_Vector-L</i> : $\mathcal{L}_I = gi\partial_\mu V_1^\mu V_{2,\nu} V_3^\nu$
<i>F23</i> : $V_1^\mu(k_2 + k_3) \leftarrow i \cdot g(k_2^\mu + k_3^\mu) V_{2,\nu}(k_2) V_3^\nu(k_3)$
<i>F32</i> : $V_1^\mu(k_2 + k_3) \leftarrow i \cdot g(k_2^\mu + k_3^\mu) V_3^\nu(k_3) V_{2,\nu}(k_2)$
<i>F12</i> : $V_3^\mu(k_1 + k_2) \leftarrow i \cdot g(-k_1^\nu) V_{1,\nu}(k_1) V_2^\mu(k_2)$
<i>F21</i> : $V_3^\mu(k_1 + k_2) \leftarrow i \cdot g(-k_1^\nu) V_2^\mu(k_2) V_{1,\nu}(k_1)$
<i>F13</i> : $V_2^\mu(k_1 + k_3) \leftarrow i \cdot g(-k_1^\nu) V_1^\nu(k_1) V_3^\mu(k_3)$
<i>F31</i> : $V_2^\mu(k_1 + k_3) \leftarrow i \cdot g(-k_1^\nu) V_3^\mu(k_3) V_1^\nu(k_1)$

Table 9.19: ...

<i>Dim4_Vector_Vector_Vector-T5</i> : $\mathcal{L}_I = gV_{1,\mu} V_{2,\rho} i \overleftrightarrow{\partial}_\nu V_{3,\sigma} \epsilon^{\mu\nu\rho\sigma}$
<i>F23</i> : $V_1^\mu(k_2 + k_3) \leftarrow i \cdot g\epsilon^{\mu\nu\rho\sigma}(k_{2,\nu} - k_{3,\nu}) V_{2,\rho}(k_2) V_{3,\sigma}(k_3)$
<i>F32</i> : $V_1^\mu(k_2 + k_3) \leftarrow i \cdot g\epsilon^{\mu\nu\rho\sigma}(k_{2,\nu} - k_{3,\nu}) V_{3,\sigma}(k_3) V_{2,\rho}(k_2)$
<i>F12</i> : $V_3^\mu(k_1 + k_2) \leftarrow i \cdot g\epsilon^{\mu\nu\rho\sigma}(2k_{2,\nu} + k_{1,\nu}) V_{1,\rho}(k_1) V_{2,\sigma}(k_2)$
<i>F21</i> : $V_3^\mu(k_1 + k_2) \leftarrow i \cdot g\epsilon^{\mu\nu\rho\sigma}(2k_{2,\nu} + k_{1,\nu}) V_{2,\sigma}(k_2) V_{1,\rho}(k_1)$
<i>F13</i> : $V_2^\mu(k_1 + k_3) \leftarrow i \cdot g\epsilon^{\mu\nu\rho\sigma}(-k_{1,\nu} - 2k_{3,\nu}) V_{1,\rho}(k_1) V_{3,\sigma}(k_3)$
<i>F31</i> : $V_2^\mu(k_1 + k_3) \leftarrow i \cdot g\epsilon^{\mu\nu\rho\sigma}(-k_{1,\nu} - 2k_{3,\nu}) V_{3,\sigma}(k_3) V_{1,\rho}(k_1)$
<i>Dim4_Vector_Vector_Vector-L5</i> : $\mathcal{L}_I = gi\partial_\mu V_{1,\nu} V_{2,\nu} V_{3,\sigma} \epsilon^{\mu\nu\rho\sigma}$
<i>F23</i> : $V_1^\mu(k_2 + k_3) \leftarrow i \cdot g\epsilon^{\mu\nu\rho\sigma}(k_{2,\nu} + k_{3,\nu}) V_{2,\rho}(k_2) V_{3,\sigma}(k_3)$
<i>F32</i> : $V_1^\mu(k_2 + k_3) \leftarrow i \cdot g\epsilon^{\mu\nu\rho\sigma}(k_{2,\nu} + k_{3,\nu}) V_{2,\rho}(k_2) V_{3,\sigma}(k_3)$
<i>F12</i> : $V_3^\mu(k_1 + k_2) \leftarrow i \cdot g\epsilon^{\mu\nu\rho\sigma}(-k_{1,\nu}) V_{1,\rho}(k_1) V_{2,\sigma}(k_2)$
<i>F21</i> : $V_3^\mu(k_1 + k_2) \leftarrow i \cdot g\epsilon^{\mu\nu\rho\sigma}(-k_{1,\nu}) V_{2,\sigma}(k_2) V_{1,\rho}(k_1)$
<i>F13</i> : $V_2^\mu(k_1 + k_3) \leftarrow i \cdot g\epsilon^{\mu\nu\rho\sigma}(-k_{1,\nu}) V_{1,\rho}(k_1) V_{3,\sigma}(k_3)$
<i>F31</i> : $V_2^\mu(k_1 + k_3) \leftarrow i \cdot g\epsilon^{\mu\nu\rho\sigma}(-k_{1,\nu}) V_{3,\sigma}(k_3) V_{1,\rho}(k_1)$

Table 9.20: ...

<i>Dim6_Gauge_Gauge_Gauge</i> : $\mathcal{L}_I = g F_1^{\mu\nu} F_{2,\nu\rho} F_{3,\rho\mu}$
$\therefore A_1^\mu(k_2 + k_3) \leftarrow -i \cdot \Lambda^{\mu\rho\sigma}(-k_2 - k_3, k_2, k_3) A_{2,\rho} A_{3,\sigma}$

Table 9.21: ...

<i>Dim6_Gauge_Gauge_Gauge_5</i> : $\mathcal{L}_I = g/2 \cdot \epsilon^{\mu\nu\lambda\tau} F_{1,\mu\nu} F_{2,\tau\rho} F_{3,\rho\lambda}$
<i>F23</i> : $A_1^\mu(k_2 + k_3) \leftarrow -i \cdot \Lambda_5^{\mu\rho\sigma}(-k_2 - k_3, k_2, k_3) A_{2,\rho} A_{3,\sigma}$
<i>F32</i> : $A_1^\mu(k_2 + k_3) \leftarrow -i \cdot \Lambda_5^{\mu\rho\sigma}(-k_2 - k_3, k_2, k_3) A_{3,\sigma} A_{2,\rho}$
<i>F12</i> : $A_3^\mu(k_1 + k_2) \leftarrow -i \cdot$
<i>F21</i> : $A_3^\mu(k_1 + k_2) \leftarrow -i \cdot$
<i>F13</i> : $A_2^\mu(k_1 + k_3) \leftarrow -i \cdot$
<i>F31</i> : $A_2^\mu(k_1 + k_3) \leftarrow -i \cdot$

Table 9.22: ...

and

$$W_1^\mu W_2^\nu - W_2^\mu W_1^\nu = i(W_-^\mu W_+^\nu - W_+^\mu W_-^\nu) \quad (9.17)$$

Thus the symmtry remains after the change of basis:

$$\begin{aligned} \epsilon^{abc} W_a^{\mu_1} W_b^{\mu_2} W_c^{\mu_3} &= i W_-^{\mu_1} (W_+^{\mu_2} W_3^{\mu_3} - W_3^{\mu_2} W_+^{\mu_3}) \\ &\quad + i W_+^{\mu_1} (W_3^{\mu_2} W_-^{\mu_3} - W_-^{\mu_2} W_3^{\mu_3}) + i W_3^{\mu_1} (W_-^{\mu_2} W_+^{\mu_3} - W_+^{\mu_2} W_-^{\mu_3}) \end{aligned} \quad (9.18)$$

### 9.1.5 Quartic Couplings and Auxiliary Fields

Quartic couplings can be replaced by cubic couplings to a non-propagating auxiliary field. The quartic term should get a negative sign so that the energy is bounded from below for identical fields. In the language of functional integrals

$$\begin{aligned} \mathcal{L}_{\phi^4} &= -g^2 \phi_1 \phi_2 \phi_3 \phi_4 \implies \\ \mathcal{L}_{X\phi^2} &= X^* X \pm g X \phi_1 \phi_2 \pm g X^* \phi_3 \phi_4 = (X^* \pm g \phi_1 \phi_2)(X \pm g \phi_3 \phi_4) - g^2 \phi_1 \phi_2 \phi_3 \phi_4 \end{aligned} \quad (9.19a)$$

and in the language of Feynman diagrams

The diagram shows a transformation of a quartic vertex. On the left, a single vertex (black dot) with four external lines (two solid, two dashed) is labeled  $-ig^2$ . An arrow points to the right, where two vertices (black dots) are connected by a horizontal dashed line. Each vertex has two external lines (one solid, one dashed). The left vertex is labeled  $\pm ig$  and the right vertex is labeled  $\pm ig$ . The dashed line connecting them is labeled  $+i$ . The entire transformation is labeled (9.19b).

The other choice of signs

$$\mathcal{L}'_{X\phi^2} = -X^* X \pm g X \phi_1 \phi_2 \mp g X^* \phi_3 \phi_4 = -(X^* \pm g \phi_1 \phi_2)(X \mp g \phi_3 \phi_4) - g^2 \phi_1 \phi_2 \phi_3 \phi_4 \quad (9.20)$$

$$\begin{aligned}
 & p \longrightarrow \text{vertex} = +ig\gamma_\mu T_a \quad (9.22a) \\
 & 2 \longrightarrow \text{vertex} = gf_{a_1 a_2 a_3} C^{\mu_1 \mu_2 \mu_3}(k_1, k_2, k_3) \quad (9.22b) \\
 & 2 \longrightarrow \text{vertex} = \begin{aligned} & -ig^2 f_{a_1 a_2 b} f_{a_3 a_4 b} (g_{\mu_1 \mu_3} g_{\mu_4 \mu_2} - g_{\mu_1 \mu_4} g_{\mu_2 \mu_3}) \\ & -ig^2 f_{a_1 a_3 b} f_{a_4 a_2 b} (g_{\mu_1 \mu_4} g_{\mu_2 \mu_3} - g_{\mu_1 \mu_2} g_{\mu_3 \mu_4}) \\ & -ig^2 f_{a_1 a_4 b} f_{a_2 a_3 b} (g_{\mu_1 \mu_2} g_{\mu_3 \mu_4} - g_{\mu_1 \mu_3} g_{\mu_4 \mu_2}) \end{aligned} \quad (9.22c)
 \end{aligned}$$

Figure 9.1: Gauge couplings. See (11.1b) for the definition of the antisymmetric tensor  $C^{\mu_1 \mu_2 \mu_3}(k_1, k_2, k_3)$ .

can not be extended easily to identical particles and is therefore not used. For identical particles we have

$$\begin{aligned}
 \mathcal{L}_{\phi^4} &= -\frac{g^2}{4!} \phi^4 \implies \\
 \mathcal{L}_{X\phi^2} &= \frac{1}{2} X^2 \pm \frac{g}{2} X \phi^2 \pm \frac{g}{2} X \phi^2 = \frac{1}{2} \left( X \pm \frac{g}{2} \phi^2 \right) \left( X \pm \frac{g}{2} \phi^2 \right) - \frac{g^2}{4!} \phi^4 \quad (9.21)
 \end{aligned}$$

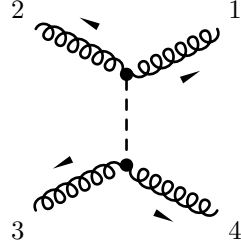
⚡ Explain the factor 1/3 in the functional setting and its relation to the three diagrams in the graphical setting?

### Quartic Gauge Couplings

The three crossed versions of figure 9.2 reproduces the quartic coupling in figure 9.1, because

$$\begin{aligned}
 & -ig^2 f_{a_1 a_2 b} f_{a_3 a_4 b} (g_{\mu_1 \mu_3} g_{\mu_4 \mu_2} - g_{\mu_1 \mu_4} g_{\mu_2 \mu_3}) \\
 & = (ig f_{a_1 a_2 b} T_{\mu_1 \mu_2, \nu_1 \nu_2}) \left( \frac{ig^{\nu_1 \nu_3} g^{\nu_2 \nu_4}}{2} \right) (ig f_{a_3 a_4 b} T_{\mu_3 \mu_4, \nu_3 \nu_4}) \quad (9.24)
 \end{aligned}$$

with  $T_{\mu_1 \mu_2, \mu_3 \mu_4} = g_{\mu_1 \mu_3} g_{\mu_4 \mu_2} - g_{\mu_1 \mu_4} g_{\mu_2 \mu_3}$ .



$$= -ig^2 f_{a_1 a_2 b} f_{a_3 a_4 b} (g_{\mu_1 \mu_3} g_{\mu_4 \mu_2} - g_{\mu_1 \mu_4} g_{\mu_2 \mu_3}) \quad (9.23)$$

Figure 9.2: Gauge couplings.

### 9.1.6 Gravitinos and supersymmetric currents

In supergravity theories there is a fermionic partner of the graviton, the gravitino. Therefore we have introduced the Lorentz type *Vectorspinor*.

### 9.1.7 Perturbative Quantum Gravity and Kaluza-Klein Interactions

The gravitational coupling constant and the relative strength of the dilaton coupling are abbreviated as

$$\kappa = \sqrt{16\pi G_N} \quad (9.25a)$$

$$\omega = \sqrt{\frac{2}{3(n+2)}} = \sqrt{\frac{2}{3(d-2)}}, \quad (9.25b)$$

where  $n = d - 4$  is the number of extra space dimensions.

In (9.27-9.34), we use the notation of [13]:

$$C_{\mu\nu,\rho\sigma} = g_{\mu\rho}g_{\nu\sigma} + g_{\mu\sigma}g_{\nu\rho} - g_{\mu\nu}g_{\rho\sigma} \quad (9.26a)$$

$$D_{\mu\nu,\rho\sigma}(k_1, k_2) = g_{\mu\nu}k_{1,\sigma}k_{2,\rho} - (g_{\mu\sigma}k_{1,\nu}k_{2,\rho} + g_{\mu\rho}k_{1,\sigma}k_{2,\nu} - g_{\rho\sigma}k_{1,\mu}k_{2,\nu} + (\mu \leftrightarrow \nu)) \quad (9.26b)$$

$$E_{\mu\nu,\rho\sigma}(k_1, k_2) = g_{\mu\nu}(k_{1,\rho}k_{1,\sigma} + k_{2,\rho}k_{2,\sigma} + k_{1,\rho}k_{2,\sigma}) - (g_{\nu\sigma}k_{1,\mu}k_{1,\rho} + g_{\nu\rho}k_{2,\mu}k_{2,\sigma} + (\mu \leftrightarrow \nu)) \quad (9.26c)$$

$$F_{\mu\nu,\rho\sigma\lambda}(k_1, k_2, k_3) = g_{\mu\rho}g_{\sigma\lambda}(k_2 - k_3)_\nu + g_{\mu\sigma}g_{\lambda\rho}(k_3 - k_1)_\nu + g_{\mu\lambda}g_{\rho\sigma}(k_1 - k_2)_\nu + (\mu \leftrightarrow \nu) \quad (9.26d)$$

$$G_{\mu\nu,\rho\sigma\lambda\delta} = g_{\mu\nu}(g_{\rho\sigma}g_{\lambda\delta} - g_{\rho\delta}g_{\lambda\sigma}) + (g_{\mu\rho}g_{\nu\delta}g_{\lambda\sigma} + g_{\mu\lambda}g_{\nu\sigma}g_{\rho\delta} - g_{\mu\rho}g_{\nu\sigma}g_{\lambda\delta} - g_{\mu\lambda}g_{\nu\delta}g_{\rho\sigma} + (\mu \leftrightarrow \nu)) \quad (9.26e)$$

Derivation of (9.27a)

<i>GBG (Fermbar, MOM, Ferm):</i> $\bar{\psi}_1(i\cancel{\partial} \pm m)\phi\psi_2$	
<i>F12:</i> $\psi_2 \leftarrow -(\cancel{k} \mp m)\psi_1 S$	<i>F21:</i> $\psi_2 \leftarrow -S(\cancel{k} \mp m)\psi_1$
<i>F13:</i> $S \leftarrow \psi_1^T C(\cancel{k} \pm m)\psi_2$	<i>F31:</i> $S \leftarrow \psi_2^T C(-(\cancel{k} \mp m)\psi_1)$
<i>F23:</i> $\psi_1 \leftarrow S(\cancel{k} \pm m)\psi_2$	<i>F32:</i> $\psi_1 \leftarrow (\cancel{k} \pm m)\psi_2 S$
<i>GBG (Fermbar, MOM5, Ferm):</i> $\bar{\psi}_1(i\cancel{\partial} \pm m)\phi\gamma^5\psi_2$	
<i>F12:</i> $\psi_2 \leftarrow (\cancel{k} \pm m)\gamma^5\psi_1 P$	<i>F21:</i> $\psi_2 \leftarrow P(\cancel{k} \pm m)\gamma^5\psi_1$
<i>F13:</i> $P \leftarrow \psi_1^T C(\cancel{k} \pm m)\gamma^5\psi_2$	<i>F31:</i> $P \leftarrow \psi_2^T C(\cancel{k} \pm m)\gamma^5\psi_1$
<i>F23:</i> $\psi_1 \leftarrow P(\cancel{k} \pm m)\gamma^5\psi_2$	<i>F32:</i> $\psi_1 \leftarrow (\cancel{k} \pm m)\gamma^5\psi_2 P$
<i>GBG (Fermbar, MOML, Ferm):</i> $\bar{\psi}_1(i\cancel{\partial} \pm m)\phi(1 - \gamma^5)\psi_2$	
<i>F12:</i> $\psi_2 \leftarrow -(1 - \gamma^5)(\cancel{k} \mp m)\psi_1\phi$	<i>F21:</i> $\psi_2 \leftarrow -\phi(1 - \gamma^5)(\cancel{k} \mp m)\psi_1$
<i>F13:</i> $\phi \leftarrow \psi_1^T C(\cancel{k} \pm m)(1 - \gamma^5)\psi_2$	<i>F31:</i> $\phi \leftarrow \psi_2^T C(1 - \gamma^5)(-(\cancel{k} \mp m)\psi_1)$
<i>F23:</i> $\psi_1 \leftarrow \phi(\cancel{k} \pm m)(1 - \gamma^5)\psi_2$	<i>F32:</i> $\psi_1 \leftarrow (\cancel{k} \pm m)(1 - \gamma^5)\psi_2\phi$
<i>GBG (Fermbar, LMOM, Ferm):</i> $\bar{\psi}_1\phi(1 - \gamma^5)(i\cancel{\partial} \pm m)\psi_2$	
<i>F12:</i> $\psi_2 \leftarrow -(\cancel{k} \mp m)\psi_1(1 - \gamma^5)\phi$	<i>F21:</i> $\psi_2 \leftarrow -\phi(\cancel{k} \mp m)(1 - \gamma^5)\psi_1$
<i>F13:</i> $\phi \leftarrow \psi_1^T C(1 - \gamma^5)(\cancel{k} \pm m)\psi_2$	<i>F31:</i> $\phi \leftarrow \psi_2^T C(-(\cancel{k} \mp m)(1 - \gamma^5)\psi_1)$
<i>F23:</i> $\psi_1 \leftarrow \phi(1 - \gamma^5)(\cancel{k} \pm m)\psi_2$	<i>F32:</i> $\psi_1 \leftarrow (1 - \gamma^5)(\cancel{k} \pm m)\psi_2\phi$
<i>GBG (Fermbar, VMOM, Ferm):</i> $\bar{\psi}_1 i\cancel{\partial}_\alpha V_\beta[\gamma^\alpha, \gamma^\beta]\psi_2$	
<i>F12:</i> $\psi_2 \leftarrow -[\cancel{k}, \gamma^\alpha]\psi_1 V_\alpha$	<i>F21:</i> $\psi_2 \leftarrow -[\cancel{k}, V]\psi_1$
<i>F13:</i> $V_\alpha \leftarrow \psi_1^T C[\cancel{k}, \gamma_\alpha]\psi_2$	<i>F31:</i> $V_\alpha \leftarrow \psi_2^T C(-[\cancel{k}, \gamma_\alpha]\psi_1)$
<i>F23:</i> $\psi_1 \leftarrow [\cancel{k}, V]\psi_2$	<i>F32:</i> $\psi_1 \leftarrow [\cancel{k}, \gamma^\alpha]\psi_2 V_\alpha$

Table 9.23: Combined dimension-4 trilinear fermionic couplings including a momentum. *Ferm* stands for *Psi* and *Chi*. The case of *MOMR* is identical to *MOML* if one substitutes  $1 + \gamma^5$  for  $1 - \gamma^5$ , as well as for *LMOM* and *RMOM*. The mass term forces us to keep the chiral projector always on the left after "inverting the line" for *MOML* while on the right for *LMOM*.

<i>GBBG (Fermbar, S2LR, Ferm):</i> $\bar{\psi}_1 S_1 S_2 (g_L P_L + g_R P_R) \psi_2$	
<i>F123 F213 F132 F231 F312 F321:</i>	$\psi_2 \leftarrow S_1 S_2 (g_R P_L + g_L P_R) \psi_1$
<i>F423 F243 F432 F234 F342 F324:</i>	$\psi_1 \leftarrow S_1 S_2 (g_L P_L + g_R P_R) \psi_2$
<i>F134 F143 F314:</i>	$S_1 \leftarrow \psi_1^T C S_2 (g_L P_L + g_R P_R) \psi_2$
<i>F124 F142 F214:</i>	$S_2 \leftarrow \psi_1^T C S_1 (g_L P_L + g_R P_R) \psi_2$
<i>F413 F431 F341:</i>	$S_1 \leftarrow \psi_2^T C S_2 (g_R P_L + g_L P_R) \psi_1$
<i>F412 F421 F241:</i>	$S_2 \leftarrow \psi_2^T C S_1 (g_R P_L + g_L P_R) \psi_1$
<i>GBBG (Fermbar, S2, Ferm):</i> $\bar{\psi}_1 S_1 S_2 \gamma^5 \psi_2$	
<i>F123 F213 F132 F231 F312 F321:</i>	$\psi_2 \leftarrow S_1 S_2 \gamma^5 \psi_1$
<i>F423 F243 F432 F234 F342 F324:</i>	$\psi_1 \leftarrow S_1 S_2 \gamma^5 \psi_2$
<i>F134 F143 F314:</i>	$S_1 \leftarrow \psi_1^T C S_2 \gamma^5 \psi_2$
<i>F124 F142 F214:</i>	$S_2 \leftarrow \psi_1^T C S_1 \gamma^5 \psi_2$
<i>F413 F431 F341:</i>	$S_1 \leftarrow \psi_2^T C S_2 \gamma^5 \psi_1$
<i>F412 F421 F241:</i>	$S_2 \leftarrow \psi_2^T C S_1 \gamma^5 \psi_1$
<i>GBBG (Fermbar, V2, Ferm):</i> $\bar{\psi}_1 [\mathbb{V}_1, \mathbb{V}_2] \psi_2$	
<i>F123 F213 F132 F231 F312 F321:</i>	$\psi_2 \leftarrow -[\mathbb{V}_1, \mathbb{V}_2] \psi_1$
<i>F423 F243 F432 F234 F342 F324:</i>	$\psi_1 \leftarrow [\mathbb{V}_1, \mathbb{V}_2] \psi_2$
<i>F134 F143 F314:</i>	$V_{1\alpha} \leftarrow \psi_1^T C [\gamma_\alpha, \mathbb{V}_2] \psi_2$
<i>F124 F142 F214:</i>	$V_{2\alpha} \leftarrow \psi_1^T C (-[\gamma_\alpha, \mathbb{V}_1]) \psi_2$
<i>F413 F431 F341:</i>	$V_{1\alpha} \leftarrow \psi_2^T C (-[\gamma_\alpha, \mathbb{V}_2]) \psi_1$
<i>F412 F421 F241:</i>	$V_{2\alpha} \leftarrow \psi_2^T C [\gamma_\alpha, \mathbb{V}_1] \psi_1$

Table 9.24: Vertices with two fermions (*Ferm* stands for *Psi* and *Chi*, but not for *Grav*) and two bosons (two scalars, scalar/vector, two vectors) for the BRST transformations. Part I

<i>GBBG (Fermbar, SV, Ferm): <math>\bar{\psi}_1 \not{V} S \psi_2</math></i>	
<i>F123 F213 F132 F231 F312 F321:</i>	$\psi_2 \leftarrow -\not{V} S \psi_1$
<i>F423 F243 F432 F234 F342 F324:</i>	$\psi_1 \leftarrow \not{V} S \psi_2$
<i>F134 F143 F314:</i>	$V_\alpha \leftarrow \psi_1^T C \gamma_\alpha S \psi_2$
<i>F124 F142 F214:</i>	$S \leftarrow \psi_1^T C \not{V} \psi_2$
<i>F413 F431 F341:</i>	$V_\alpha \leftarrow \psi_2^T C (-\gamma_\alpha S \psi_1)$
<i>F412 F421 F241:</i>	$S \leftarrow \psi_2^T C (-\not{V} \psi_1)$
<i>GBBG (Fermbar, PV, Ferm): <math>\bar{\psi}_1 \not{V} \gamma^5 P \psi_2</math></i>	
<i>F123 F213 F132 F231 F312 F321:</i>	$\psi_2 \leftarrow \not{V} \gamma^5 P \psi_1$
<i>F423 F243 F432 F234 F342 F324:</i>	$\psi_1 \leftarrow \not{V} \gamma^5 P \psi_2$
<i>F134 F143 F314:</i>	$V_\alpha \leftarrow \psi_1^T C \gamma_\alpha \gamma^5 P \psi_2$
<i>F124 F142 F214:</i>	$P \leftarrow \psi_1^T C \not{V} \gamma^5 \psi_2$
<i>F413 F431 F341:</i>	$V_\alpha \leftarrow \psi_2^T C \gamma_\alpha \gamma^5 P \psi_1$
<i>F412 F421 F241:</i>	$P \leftarrow \psi_2^T C \not{V} \gamma^5 \psi_1$
<i>GBBG (Fermbar, S(L/R)V, Ferm): <math>\bar{\psi}_1 \not{V} (1 \mp \gamma^5) \phi \psi_2</math></i>	
<i>F123 F213 F132 F231 F312 F321:</i>	$\psi_2 \leftarrow -\not{V} (1 \pm \gamma^5) \phi \psi_1$
<i>F423 F243 F432 F234 F342 F324:</i>	$\psi_1 \leftarrow \not{V} (1 \mp \gamma^5) \phi \psi_2$
<i>F134 F143 F314:</i>	$V_\alpha \leftarrow \psi_1^T C \gamma_\alpha (1 \mp \gamma^5) \phi \psi_2$
<i>F124 F142 F214:</i>	$\phi \leftarrow \psi_1^T C \not{V} (1 \mp \gamma^5) \psi_2$
<i>F413 F431 F341:</i>	$V_\alpha \leftarrow \psi_2^T C \gamma_\alpha (-(1 \pm \gamma^5) \phi \psi_1)$
<i>F412 F421 F241:</i>	$\phi \leftarrow \psi_2^T C \not{V} (-(1 \pm \gamma^5) \psi_1)$

Table 9.25: Vertices with two fermions (*Ferm* stands for *Psi* and *Chi*, but not for *Grav*) and two bosons (two scalars, scalar/vector, two vectors) for the BRST transformations. Part II



<i>GBG (Gravbar, POT, Psi): <math>\bar{\psi}_\mu S \gamma^\mu \psi</math></i>	
<i>F12:</i> $\psi \leftarrow -\gamma^\mu \psi_\mu S$	<i>F21:</i> $\psi \leftarrow -S \gamma^\mu \psi_\mu$
<i>F13:</i> $S \leftarrow \psi_\mu^T C \gamma^\mu \psi$	<i>F31:</i> $S \leftarrow \psi^T C (-\gamma^\mu) \psi_\mu$
<i>F23:</i> $\psi_\mu \leftarrow S \gamma_\mu \psi$	<i>F32:</i> $\psi_\mu \leftarrow \gamma_\mu \psi S$
<i>GBG (Gravbar, S, Psi): <math>\bar{\psi}_\mu \not{k}_S S \gamma^\mu \psi</math></i>	
<i>F12:</i> $\psi \leftarrow \gamma^\mu \not{k}_S \psi_\mu S$	<i>F21:</i> $\psi \leftarrow S \gamma^\mu \not{k}_S \psi_\mu$
<i>F13:</i> $S \leftarrow \psi_\mu^T C \not{k}_S \gamma^\mu \psi$	<i>F31:</i> $S \leftarrow \psi^T C \gamma^\mu \not{k}_S \psi_\mu$
<i>F23:</i> $\psi_\mu \leftarrow S \not{k}_S \gamma_\mu \psi$	<i>F32:</i> $\psi_\mu \leftarrow \not{k}_S \gamma_\mu \psi S$
<i>GBG (Gravbar, P, Psi): <math>\bar{\psi}_\mu \not{k}_P P \gamma^\mu \gamma_5 \psi</math></i>	
<i>F12:</i> $\psi \leftarrow \gamma^\mu \not{k}_P \gamma_5 \psi_\mu P$	<i>F21:</i> $\psi \leftarrow P \gamma^\mu \not{k}_P \gamma_5 \psi_\mu$
<i>F13:</i> $P \leftarrow \psi_\mu^T C \not{k}_P \gamma^\mu \gamma_5 \psi$	<i>F31:</i> $P \leftarrow \psi^T C \gamma^\mu \not{k}_P \gamma_5 \psi_\mu$
<i>F23:</i> $\psi_\mu \leftarrow P \not{k}_P \gamma_\mu \gamma_5 \psi$	<i>F32:</i> $\psi_\mu \leftarrow \not{k}_P \gamma_\mu \gamma_5 \psi P$
<i>GBG (Gravbar, V, Psi): <math>\bar{\psi}_\mu [\not{k}_V, \gamma^\mu] \gamma^\mu \gamma^5 \psi</math></i>	
<i>F12:</i> $\psi \leftarrow \gamma^5 \gamma^\mu [\not{k}_V, \gamma^\alpha] \psi_\mu V_\alpha$	<i>F21:</i> $\psi \leftarrow \gamma^5 \gamma^\mu [\not{k}_V, V] \psi_\mu$
<i>F13:</i> $V_\mu \leftarrow \psi_\rho^T C [\not{k}_V, \gamma_\mu] \gamma^\rho \gamma^5 \psi$	<i>F31:</i> $V_\mu \leftarrow \psi^T C \gamma^5 \gamma^\rho [\not{k}_V, \gamma_\mu] \psi_\rho$
<i>F23:</i> $\psi_\mu \leftarrow [\not{k}_V, V] \gamma_\mu \gamma^5 \psi$	<i>F32:</i> $\psi_\mu \leftarrow [\not{k}_V, \gamma^\alpha] \gamma_\mu \gamma^5 \psi V_\alpha$

Table 9.26: Dimension-5 trilinear couplings including one Dirac, one Gravitino fermion and one additional particle. The option *POT* is for the coupling of the supersymmetric current to the derivative of the quadratic terms in the superpotential.

<i>GBG</i> ( <i>Psibar</i> , <i>POT</i> , <i>Grav</i> ): $\bar{\psi}\gamma^\mu S\psi_\mu$	
<i>F12</i> : $\psi_\mu \leftarrow -\gamma_\mu \psi S$	<i>F21</i> : $\psi_\mu \leftarrow -S\gamma_\mu \psi$
<i>F13</i> : $S \leftarrow \psi^T C\gamma^\mu \psi_\mu$	<i>F31</i> : $S \leftarrow \psi_\mu^T C(-\gamma^\mu)\psi$
<i>F23</i> : $\psi \leftarrow S\gamma^\mu \psi_\mu$	<i>F32</i> : $\psi \leftarrow \gamma^\mu \psi_\mu S$
<i>GBG</i> ( <i>Psibar</i> , <i>S</i> , <i>Grav</i> ): $\bar{\psi}\gamma^\mu \not{k}_S S\psi_\mu$	
<i>F12</i> : $\psi_\mu \leftarrow \not{k}_S \gamma_\mu \psi S$	<i>F21</i> : $\psi_\mu \leftarrow S \not{k}_S \gamma_\mu \psi$
<i>F13</i> : $S \leftarrow \psi^T C\gamma^\mu \not{k}_S \psi_\mu$	<i>F31</i> : $S \leftarrow \psi_\mu^T C \not{k}_S \gamma^\mu \psi$
<i>F23</i> : $\psi \leftarrow S\gamma^\mu \not{k}_S \psi_\mu$	<i>F32</i> : $\psi \leftarrow \gamma^\mu \not{k}_S \psi_\mu S$
<i>GBG</i> ( <i>Psibar</i> , <i>P</i> , <i>Grav</i> ): $\bar{\psi}\gamma^\mu \gamma^5 P \not{k}_P \psi_\mu$	
<i>F12</i> : $\psi_\mu \leftarrow -\not{k}_P \gamma_\mu \gamma^5 \psi P$	<i>F21</i> : $\psi_\mu \leftarrow -P \not{k}_P \gamma_\mu \gamma^5 \psi$
<i>F13</i> : $P \leftarrow \psi^T C\gamma^\mu \gamma^5 \not{k}_P \psi_\mu$	<i>F31</i> : $P \leftarrow -\psi_\mu^T C \not{k}_P \gamma^\mu \gamma^5 \psi$
<i>F23</i> : $\psi \leftarrow P\gamma^\mu \gamma^5 \not{k}_P \psi_\mu$	<i>F32</i> : $\psi \leftarrow \gamma^\mu \gamma^5 \not{k}_P \psi_\mu P$
<i>GBG</i> ( <i>Psibar</i> , <i>V</i> , <i>Grav</i> ): $\bar{\psi}\gamma^5 \gamma^\mu [\not{k}_V, V]\psi_\mu$	
<i>F12</i> : $\psi_\mu \leftarrow [\not{k}_V, \gamma^\alpha] \gamma_\mu \gamma^5 \psi V_\alpha$	<i>F21</i> : $\psi_\mu \leftarrow [\not{k}_V, V] \gamma_\mu \gamma^5 \psi$
<i>F13</i> : $V_\mu \leftarrow \psi^T C\gamma^5 \gamma^\rho [\not{k}_V, \gamma_\mu] \psi_\rho$	<i>F31</i> : $V_\mu \leftarrow \psi_\rho^T C [\not{k}_V, \gamma_\mu] \gamma^\rho \gamma^5 \psi$
<i>F23</i> : $\psi \leftarrow \gamma^5 \gamma^\mu [\not{k}_V, V] \psi_\mu$	<i>F32</i> : $\psi \leftarrow \gamma^5 \gamma^\mu [\not{k}_V, \gamma^\alpha] \psi_\mu V_\alpha$

Table 9.27: Dimension-5 trilinear couplings including one conjugated Dirac, one Gravitino fermion and one additional particle.

<i>GBG (Gravbar, POT, Chi): <math>\bar{\psi}_\mu S \gamma^\mu \chi</math></i>	
<i>F12:</i> $\chi \leftarrow -\gamma^\mu \psi_\mu S$	<i>F21:</i> $\chi \leftarrow -S \gamma^\mu \psi_\mu$
<i>F13:</i> $S \leftarrow \psi_\mu^T C \gamma^\mu \chi$	<i>F31:</i> $S \leftarrow \chi^T C (-\gamma^\mu) \psi_\mu$
<i>F23:</i> $\psi_\mu \leftarrow S \gamma_\mu \chi$	<i>F32:</i> $\psi_\mu \leftarrow \gamma_\mu \chi S$
<i>GBG (Gravbar, S, Chi): <math>\bar{\psi}_\mu \not{k}_S S \gamma^\mu \chi</math></i>	
<i>F12:</i> $\chi \leftarrow \gamma^\mu \not{k}_S \psi_\mu S$	<i>F21:</i> $\chi \leftarrow S \gamma^\mu \not{k}_S \psi_\mu$
<i>F13:</i> $S \leftarrow \psi_\mu^T C \not{k}_S \gamma^\mu \chi$	<i>F31:</i> $S \leftarrow \chi^T C \gamma^\mu \not{k}_S \psi_\mu$
<i>F23:</i> $\psi_\mu \leftarrow S \not{k}_S \gamma_\mu \chi$	<i>F32:</i> $\psi_\mu \leftarrow \not{k}_S \gamma_\mu \chi S$
<i>GBG (Gravbar, P, Chi): <math>\bar{\psi}_\mu \not{k}_P P \gamma^\mu \gamma_5 \chi</math></i>	
<i>F12:</i> $\chi \leftarrow \gamma^\mu \not{k}_P \gamma_5 \psi_\mu P$	<i>F21:</i> $\chi \leftarrow P \gamma^\mu \not{k}_P \gamma_5 \psi_\mu$
<i>F13:</i> $P \leftarrow \psi_\mu^T C \not{k}_P \gamma^\mu \gamma_5 \chi$	<i>F31:</i> $P \leftarrow \chi^T C \gamma^\mu \not{k}_P \gamma_5 \psi_\mu$
<i>F23:</i> $\psi_\mu \leftarrow P \not{k}_P \gamma_\mu \gamma_5 \chi$	<i>F32:</i> $\psi_\mu \leftarrow \not{k}_P \gamma_\mu \gamma_5 \chi P$
<i>GBG (Gravbar, V, Chi): <math>\bar{\psi}_\mu [\not{k}_V, V] \gamma^\mu \gamma^5 \chi</math></i>	
<i>F12:</i> $\chi \leftarrow \gamma^5 \gamma^\mu [\not{k}_V, \gamma^\alpha] \psi_\mu V_\alpha$	<i>F21:</i> $\chi \leftarrow \gamma^5 \gamma^\mu [\not{k}_V, V] \psi_\mu$
<i>F13:</i> $V_\mu \leftarrow \psi_\rho^T C [\not{k}_V, \gamma_\mu] \gamma^\rho \gamma^5 \chi$	<i>F31:</i> $V_\mu \leftarrow \chi^T C \gamma^5 \gamma^\rho [\not{k}_V, \gamma_\mu] \psi_\rho$
<i>F23:</i> $\psi_\mu \leftarrow [\not{k}_V, V] \gamma_\mu \gamma^5 \chi$	<i>F32:</i> $\psi_\mu \leftarrow [\not{k}_V, \gamma^\alpha] \gamma_\mu \gamma^5 \chi V_\alpha$

Table 9.28: Dimension-5 trilinear couplings including one Majorana, one Gravitino fermion and one additional particle. The table is essentially the same as the one with the Dirac fermion and only written for the sake of completeness.

<i>GBG (Chibar, POT, Grav): <math>\bar{\chi}\gamma^\mu S\psi_\mu</math></i>	
<i>F12:</i> $\psi_\mu \leftarrow -\gamma_\mu \chi S$	<i>F21:</i> $\psi_\mu \leftarrow -S\gamma_\mu \chi$
<i>F13:</i> $S \leftarrow \chi^T C\gamma^\mu \psi_\mu$	<i>F31:</i> $S \leftarrow \psi_\mu^T C(-\gamma^\mu)\chi$
<i>F23:</i> $\chi \leftarrow S\gamma^\mu \psi_\mu$	<i>F32:</i> $\chi \leftarrow \gamma^\mu \psi_\mu S$
<i>GBG (Chibar, S, Grav): <math>\bar{\chi}\gamma^\mu \not{k}_S S\psi_\mu</math></i>	
<i>F12:</i> $\psi_\mu \leftarrow \not{k}_S \gamma_\mu \chi S$	<i>F21:</i> $\psi_\mu \leftarrow S \not{k}_S \gamma_\mu \chi$
<i>F13:</i> $S \leftarrow \chi^T C\gamma^\mu \not{k}_S \psi_\mu$	<i>F31:</i> $S \leftarrow \psi_\mu^T C \not{k}_S \gamma^\mu \chi$
<i>F23:</i> $\chi \leftarrow S\gamma^\mu \not{k}_S \psi_\mu$	<i>F32:</i> $\chi \leftarrow \gamma^\mu \not{k}_S \psi_\mu S$
<i>GBG (Chibar, P, Grav): <math>\bar{\chi}\gamma^\mu \gamma^5 P \not{k}_P \psi_\mu</math></i>	
<i>F12:</i> $\psi_\mu \leftarrow -\not{k}_P \gamma_\mu \gamma^5 \chi P$	<i>F21:</i> $\psi_\mu \leftarrow -P \not{k}_P \gamma_\mu \gamma^5 \chi$
<i>F13:</i> $P \leftarrow \chi^T C\gamma^\mu \gamma^5 \not{k}_P \psi_\mu$	<i>F31:</i> $P \leftarrow -\psi_\mu^T C \not{k}_P \gamma^\mu \gamma^5 \chi$
<i>F23:</i> $\chi \leftarrow P\gamma^\mu \gamma^5 \not{k}_P \psi_\mu$	<i>F32:</i> $\chi \leftarrow \gamma^\mu \gamma^5 \not{k}_P \psi_\mu P$
<i>GBG (Chibar, V, Grav): <math>\bar{\chi}\gamma^5 \gamma^\mu [\not{k}_V, V]\psi_\mu</math></i>	
<i>F12:</i> $\psi_\mu \leftarrow [\not{k}_V, \gamma^\alpha] \gamma_\mu \gamma^5 \chi V_\alpha$	<i>F21:</i> $\psi_\mu \leftarrow [\not{k}_V, V] \gamma_\mu \gamma^5 \chi$
<i>F13:</i> $V_\mu \leftarrow \chi^T C\gamma^5 \gamma^\rho [\not{k}_V, \gamma_\mu] \psi_\rho$	<i>F31:</i> $V_\mu \leftarrow \psi_\rho^T C [\not{k}_V, \gamma_\mu] \gamma^\rho \gamma^5 \chi$
<i>F23:</i> $\chi \leftarrow \gamma^5 \gamma^\mu [\not{k}_V, V] \psi_\mu$	<i>F32:</i> $\chi \leftarrow \gamma^5 \gamma^\mu [\not{k}_V, \gamma^\alpha] \psi_\mu V_\alpha$

Table 9.29: Dimension-5 trilinear couplings including one conjugated Majorana, one Gravitino fermion and one additional particle. This table is not only the same as the one with the conjugated Dirac fermion but also the same part of the Lagrangian density as the one with the Majorana particle on the right of the gravitino.

<i>GBBG</i> ( <i>Gravbar</i> , <i>S2</i> , <i>Psi</i> ): $\bar{\psi}_\mu S_1 S_2 \gamma^\mu \psi$						
<i>F123</i>	<i>F213</i>	<i>F132</i>	<i>F231</i>	<i>F312</i>	<i>F321</i> :	$\psi \leftarrow -\gamma^\mu S_1 S_2 \psi_\mu$
<i>F423</i>	<i>F243</i>	<i>F432</i>	<i>F234</i>	<i>F342</i>	<i>F324</i> :	$\psi_\mu \leftarrow \gamma_\mu S_1 S_2 \psi$
	<i>F134</i>	<i>F143</i>	<i>F314</i> :	$S_1 \leftarrow \psi_\mu^T C S_2 \gamma^\mu \psi$		
	<i>F124</i>	<i>F142</i>	<i>F214</i> :	$S_2 \leftarrow \psi_\mu^T C S_1 \gamma^\mu \psi$		
	<i>F413</i>	<i>F431</i>	<i>F341</i> :	$S_1 \leftarrow -\psi^T C S_2 \gamma^\mu \psi_\mu$		
	<i>F412</i>	<i>F421</i>	<i>F241</i> :	$S_2 \leftarrow -\psi^T C S_1 \gamma^\mu \psi_\mu$		
<i>GBBG</i> ( <i>Gravbar</i> , <i>SV</i> , <i>Psi</i> ): $\bar{\psi}_\mu S \mathbb{V} \gamma^\mu \gamma^5 \psi$						
<i>F123</i>	<i>F213</i>	<i>F132</i>	<i>F231</i>	<i>F312</i>	<i>F321</i> :	$\psi \leftarrow \gamma^5 \gamma^\mu S \mathbb{V} \psi_\mu$
<i>F423</i>	<i>F243</i>	<i>F432</i>	<i>F234</i>	<i>F342</i>	<i>F324</i> :	$\psi_\mu \leftarrow \mathbb{V} S \gamma_\mu \gamma^5 \psi$
	<i>F134</i>	<i>F143</i>	<i>F314</i> :	$S \leftarrow \psi_\mu^T C \mathbb{V} \gamma^\mu \gamma^5 \psi$		
	<i>F124</i>	<i>F142</i>	<i>F214</i> :	$V_\mu \leftarrow \psi_\rho^T C S \gamma_\mu \gamma^\rho \gamma^5 \psi$		
	<i>F413</i>	<i>F431</i>	<i>F341</i> :	$S \leftarrow \psi^T C \gamma^5 \gamma^\mu \mathbb{V} \psi_\mu$		
	<i>F412</i>	<i>F421</i>	<i>F241</i> :	$V_\mu \leftarrow \psi^T C S \gamma^5 \gamma^\rho \gamma_\mu \psi_\rho$		
<i>GBBG</i> ( <i>Gravbar</i> , <i>PV</i> , <i>Psi</i> ): $\bar{\psi}_\mu P \mathbb{V} \gamma^\mu \psi$						
<i>F123</i>	<i>F213</i>	<i>F132</i>	<i>F231</i>	<i>F312</i>	<i>F321</i> :	$\psi \leftarrow \gamma^\mu P \mathbb{V} \psi_\mu$
<i>F423</i>	<i>F243</i>	<i>F432</i>	<i>F234</i>	<i>F342</i>	<i>F324</i> :	$\psi_\mu \leftarrow \mathbb{V} P \gamma_\mu \psi$
	<i>F134</i>	<i>F143</i>	<i>F314</i> :	$P \leftarrow \psi_\mu^T C \mathbb{V} \gamma^\mu \psi$		
	<i>F124</i>	<i>F142</i>	<i>F214</i> :	$V_\mu \leftarrow \psi_\rho^T C P \gamma_\mu \gamma^\rho \psi$		
	<i>F413</i>	<i>F431</i>	<i>F341</i> :	$P \leftarrow \psi^T C \gamma^\mu \mathbb{V} \psi_\mu$		
	<i>F412</i>	<i>F421</i>	<i>F241</i> :	$V_\mu \leftarrow \psi^T C P \gamma^\rho \gamma_\mu \psi_\rho$		
<i>GBBG</i> ( <i>Gravbar</i> , <i>V2</i> , <i>Psi</i> ): $\bar{\psi}_\mu f_{abc} [V^a, \mathbb{V}^b] \gamma^\mu \gamma^5 \psi$						
<i>F123</i>	<i>F213</i>	<i>F132</i>	<i>F231</i>	<i>F312</i>	<i>F321</i> :	$\psi \leftarrow f_{abc} \gamma^5 \gamma^\mu [V^a, \mathbb{V}^b] \psi_\mu$
<i>F423</i>	<i>F243</i>	<i>F432</i>	<i>F234</i>	<i>F342</i>	<i>F324</i> :	$\psi_\mu \leftarrow f_{abc} [V^a, \mathbb{V}^b] \gamma_\mu \gamma^5 \psi$
<i>F134</i>	<i>F143</i>	<i>F314</i>	<i>F124</i>	<i>F142</i>	<i>F214</i> :	$V_\mu^a \leftarrow \psi_\rho^T C f_{abc} [\gamma_\mu, \mathbb{V}^b] \gamma^\rho \gamma^5 \psi$
<i>F413</i>	<i>F431</i>	<i>F341</i>	<i>F412</i>	<i>F421</i>	<i>F241</i> :	$V_\mu^a \leftarrow \psi^T C f_{abc} \gamma^5 \gamma^\rho [\gamma_\mu, \mathbb{V}^b] \psi_\rho$

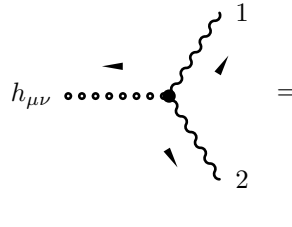
Table 9.30: Dimension-5 trilinear couplings including one Dirac, one Gravitino fermion and two additional bosons. In each lines we list the fusion possibilities with the same order of the fermions, but the order of the bosons is arbitrary (of course, one has to take care of this order in the mapping of the wave functions in *fusion*).

<i>GBBG</i> ( <i>Psibar</i> , <i>S2</i> , <i>Grav</i> ): $\bar{\psi}S_1S_2\gamma^\mu\psi_\mu$	
$F123\ F213\ F132\ F231\ F312\ F321$ :	$\psi_\mu \leftarrow -\gamma_\mu S_1S_2\psi$
$F423\ F243\ F432\ F234\ F342\ F324$ :	$\psi \leftarrow \gamma^\mu S_1S_2\psi_\mu$
$F134\ F143\ F314$ :	$S_1 \leftarrow \psi^T C S_2 \gamma^\mu \psi_\mu$
$F124\ F142\ F214$ :	$S_2 \leftarrow \psi^T C S_1 \gamma^\mu \psi_\mu$
$F413\ F431\ F341$ :	$S_1 \leftarrow -\psi_\mu^T C S_2 \gamma^\mu \psi$
$F412\ F421\ F241$ :	$S_2 \leftarrow -\psi_\mu^T C S_1 \gamma^\mu \psi$
<i>GBBG</i> ( <i>Psibar</i> , <i>SV</i> , <i>Grav</i> ): $\bar{\psi}S\gamma^\mu\gamma^5V\psi_\mu$	
$F123\ F213\ F132\ F231\ F312\ F321$ :	$\psi_\mu \leftarrow V S \gamma^5 \gamma^\mu \psi$
$F423\ F243\ F432\ F234\ F342\ F324$ :	$\psi \leftarrow \gamma^\mu \gamma^5 S V \psi_\mu$
$F134\ F143\ F314$ :	$S \leftarrow \psi^T C \gamma^\mu \gamma^5 V \psi$
$F124\ F142\ F214$ :	$V_\mu \leftarrow \psi^T C \gamma^\rho \gamma^5 S \gamma_\mu \psi_\rho$
$F413\ F431\ F341$ :	$S \leftarrow \psi_\mu^T C V \gamma^5 \gamma^\mu \psi$
$F412\ F421\ F241$ :	$V_\mu \leftarrow \psi_\rho^T C S \gamma_\mu \gamma^5 \gamma^\rho \psi$
<i>GBBG</i> ( <i>Psibar</i> , <i>PV</i> , <i>Grav</i> ): $\bar{\psi}P\gamma^\mu V\psi_\mu$	
$F123\ F213\ F132\ F231\ F312\ F321$ :	$\psi_\mu \leftarrow V \gamma_\mu P \psi$
$F423\ F243\ F432\ F234\ F342\ F324$ :	$\psi \leftarrow \gamma^\mu V P \psi_\mu$
$F134\ F143\ F314$ :	$P \leftarrow \psi^T C \gamma^\mu V \psi_\mu$
$F124\ F142\ F214$ :	$V_\mu \leftarrow \psi^T C P \gamma^\rho \gamma_\mu \psi_\rho$
$F413\ F431\ F341$ :	$P \leftarrow \psi_\mu^T C V \gamma^\mu \psi$
$F412\ F421\ F241$ :	$V_\mu \leftarrow \psi_\rho^T C P \gamma_\mu \gamma^\rho \psi$
<i>GBBG</i> ( <i>Psibar</i> , <i>V2</i> , <i>Grav</i> ): $\bar{\psi}f_{abc}\gamma^5\gamma^\mu[V^a, V^b]\psi_\mu$	
$F123\ F213\ F132\ F231\ F312\ F321$ :	$\psi_\mu \leftarrow f_{abc}[V^a, V^b]\gamma_\mu\gamma^5\psi$
$F423\ F243\ F432\ F234\ F342\ F324$ :	$\psi \leftarrow f_{abc}\gamma^5\gamma^\mu[V^a, V^b]\psi_\mu$
$F134\ F143\ F314\ F124\ F142\ F214$ :	$V_\mu^a \leftarrow \psi^T C f_{abc}\gamma^5\gamma^\rho[\gamma_\mu, V^b]\psi_\rho$
$F413\ F431\ F341\ F412\ F421\ F241$ :	$V_\mu^a \leftarrow \psi_\rho^T C f_{abc}[\gamma_\mu, V^b]\gamma^\rho\gamma^5\psi$

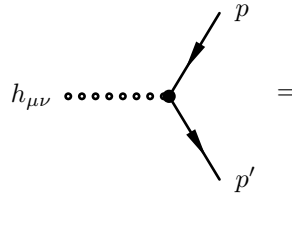
Table 9.31: Dimension-5 trilinear couplings including one conjugated Dirac, one Gravitino fermion and two additional bosons. The couplings of Majorana fermions to the gravitino and two bosons are essentially the same as for Dirac fermions and they are omitted here.



$$= -i\frac{\kappa}{2}g_{\mu\nu}m^2 + i\frac{\kappa}{2}C_{\mu\nu,\mu_1\mu_2}k_1^{\mu_1}k_2^{\mu_2} \quad (9.27a)$$



$$= -i\frac{\kappa}{2}m^2C_{\mu\nu,\mu_1\mu_2} - i\frac{\kappa}{2}(k_1k_2C_{\mu\nu,\mu_1\mu_2} + D_{\mu\nu,\mu_1\mu_2}(k_1,k_2) + \xi^{-1}E_{\mu\nu,\mu_1\mu_2}(k_1,k_2)) \quad (9.27b)$$



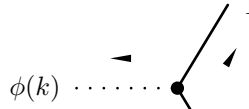
$$= -i\frac{\kappa}{2}mg_{\mu\nu} - i\frac{\kappa}{8}(\gamma_\mu(p+p')_\nu + \gamma_\nu(p+p')_\mu - 2g_{\mu\nu}(\not{p} + \not{p}')) \quad (9.27c)$$

Figure 9.3: Three-point graviton couplings.

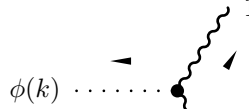
<i>Graviton_Scalar_Scalar:</i> $h_{\mu\nu}C_0^{\mu\nu}(k_1, k_2)\phi_1\phi_2$	
<i>F12</i>   <i>F21:</i>	$\phi_2 \leftarrow i \cdot h_{\mu\nu}C_0^{\mu\nu}(k_1, -k - k_1)\phi_1$
<i>F13</i>   <i>F31:</i>	$\phi_1 \leftarrow i \cdot h_{\mu\nu}C_0^{\mu\nu}(-k - k_2, k_2)\phi_2$
<i>F23</i>   <i>F32:</i>	$h^{\mu\nu} \leftarrow i \cdot C_0^{\mu\nu}(k_1, k_2)\phi_1\phi_2$
<i>Graviton_Vector_Vector:</i> $h_{\mu\nu}C_1^{\mu\nu, \mu_1\mu_2}(k_1, k_2, \xi)V_{\mu_1}V_{\mu_2}$	
<i>F12</i>   <i>F21:</i>	$V_2^\mu \leftarrow i \cdot h_{\kappa\lambda}C_1^{\kappa\lambda, \mu\nu}(-k - k_1, k_1\xi)V_{1,\nu}$
<i>F13</i>   <i>F31:</i>	$V_1^\mu \leftarrow i \cdot h_{\kappa\lambda}C_1^{\kappa\lambda, \mu\nu}(-k - k_2, k_2, \xi)V_{2,\nu}$
<i>F23</i>   <i>F32:</i>	$h^{\mu\nu} \leftarrow i \cdot C_1^{\mu\nu, \mu_1\mu_2}(k_1, k_2, \xi)V_{1,\mu_1}V_{2,\mu_2}$
<i>Graviton_Spinor_Spinor:</i> $h_{\mu\nu}\bar{\psi}_1C_{\frac{1}{2}}^{\mu\nu}(k_1, k_2)\psi_2$	
<i>F12:</i>	$\bar{\psi}_2 \leftarrow i \cdot h_{\mu\nu}\bar{\psi}_1C_{\frac{1}{2}}^{\mu\nu}(k_1, -k - k_1)$
<i>F21:</i>	$\bar{\psi}_2 \leftarrow i \cdot \dots$
<i>F13:</i>	$\psi_1 \leftarrow i \cdot h_{\mu\nu}C_{\frac{1}{2}}^{\mu\nu}(-k - k_2, k_2)\psi_2$
<i>F31:</i>	$\psi_1 \leftarrow i \cdot \dots$
<i>F23:</i>	$h^{\mu\nu} \leftarrow i \cdot \bar{\psi}_1C_{\frac{1}{2}}^{\mu\nu}(k_1, k_2)\psi_2$
<i>F32:</i>	$h^{\mu\nu} \leftarrow i \cdot \dots$

Table 9.32: ...

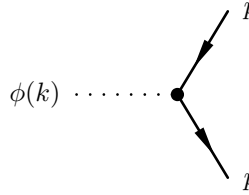




$$= -i\omega\kappa 2m^2 - i\omega\kappa k_1 k_2 \quad (9.30a)$$



$$= -i\omega\kappa g_{\mu_1\mu_2} m^2 - i\omega\kappa \xi^{-1} (k_{1,\mu_1} k_{\mu_2} + k_{2,\mu_2} k_{\mu_1}) \quad (9.30b)$$



$$= -i\omega\kappa 2m + i\omega\kappa \frac{3}{4} (\not{p} + \not{p}') \quad (9.30c)$$

Figure 9.4: Three-point dilaton couplings.

$$L = \frac{1}{2} (\partial_\mu \phi) (\partial^\mu \phi) - \frac{m^2}{2} \phi^2 \quad (9.28a)$$

$$(\partial_\mu \phi) \frac{\partial L}{\partial (\partial^\nu \phi)} = (\partial_\mu \phi) (\partial_\nu \phi) \quad (9.28b)$$

$$T_{\mu\nu} = -g_{\mu\nu} L + (\partial_\mu \phi) \frac{\partial L}{\partial (\partial^\nu \phi)} + \quad (9.28c)$$

$$C_0^{\mu\nu}(k_1, k_2) = C^{\mu\nu, \mu_1 \mu_2} k_{1, \mu_1} k_{2, \mu_2} \quad (9.29a)$$

$$C_1^{\mu\nu, \mu_1 \mu_2}(k_1, k_2, \xi) = k_1 k_2 C^{\mu\nu, \mu_1 \mu_2} + D^{\mu\nu, \mu_1 \mu_2}(k_1, k_2) + \xi^{-1} E^{\mu\nu, \mu_1 \mu_2}(k_1, k_2) \quad (9.29b)$$

$$C_{\frac{1}{2}, \alpha\beta}^{\mu\nu}(p, p') = \gamma_{\alpha\beta}^\mu (p + p')^\nu + \gamma_{\alpha\beta}^\nu (p + p')^\mu - 2g^{\mu\nu} (\not{p} + \not{p}')_{\alpha\beta} \quad (9.29c)$$

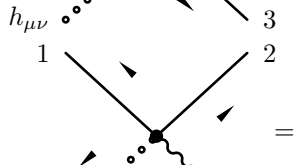
### 9.1.8 Dependent Parameters

This is a simple abstract syntax for parameter dependencies. Later, there will be a parser for a convenient concrete syntax as a part of a concrete syntax for models. There is no intention to do *any* symbolic manipulation with this. The expressions will be translated directly by *Targets* to the target language.

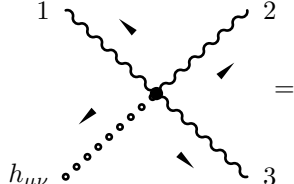
<i>Dilaton_Scalar_Scalar</i> : $\phi \dots k_1 k_2 \phi_1 \phi_2$
$F12 \mid F21$ : $\phi_2 \leftarrow i \cdot k_1 (-k - k_1) \phi \phi_1$
$F13 \mid F31$ : $\phi_1 \leftarrow i \cdot (-k - k_2) k_2 \phi \phi_2$
$F23 \mid F32$ : $\phi \leftarrow i \cdot k_1 k_2 \phi_1 \phi_2$
<i>Dilaton_Vector_Vector</i> : $\phi \dots$
$F12$ : $V_{2,\mu} \leftarrow i \dots$
$F21$ : $V_{2,\mu} \leftarrow i \dots$
$F13$ : $V_{1,\mu} \leftarrow i \dots$
$F31$ : $V_{1,\mu} \leftarrow i \dots$
$F23$ : $\phi \leftarrow i \dots$
$F32$ : $\phi \leftarrow i \dots$
<i>Dilaton_Spinor_Spinor</i> : $\phi \dots$
$F12$ : $\bar{\psi}_2 \leftarrow i \dots$
$F21$ : $\bar{\psi}_2 \leftarrow i \dots$
$F13$ : $\psi_1 \leftarrow i \dots$
$F31$ : $\psi_1 \leftarrow i \dots$
$F23$ : $\phi \leftarrow i \dots$
$F32$ : $\phi \leftarrow i \dots$

Table 9.33: ...


 $???$  (9.31a)


 $= -ig\frac{\kappa}{2}C_{\mu\nu,\mu_3\rho}(k_1-k_2)^\rho T_{n_2n_1}^{a_3}$  (9.31b)


 $???$  (9.31c)


 $= -g\frac{\kappa}{2}f^{a_1a_2a_3}(C_{\mu\nu,\mu_1\mu_2}(k_1-k_2)_{\mu_3}$   
 $+ C_{\mu\nu,\mu_2\mu_3}(k_2-k_3)_{\mu_1}$   
 $+ C_{\mu\nu,\mu_3\mu_1}(k_3-k_1)_{\mu_2}$   
 $+ F_{\mu\nu,\mu_1\mu_2\mu_3}(k_1,k_2,k_3))$  (9.31d)


 $???$  (9.31e)

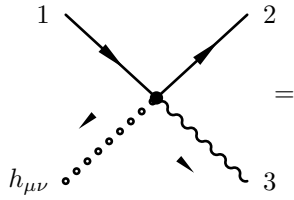

 $= ig\frac{\kappa}{4}(C_{\mu\nu,\mu_3\rho} - g_{\mu\nu}g_{\mu_3\rho})\gamma^\rho T_{n_2n_1}^{a_3}$  (9.31f)

Figure 9.5: Four-point graviton couplings. (9.31a), (9.31c), and (?? are missing in [13], but should be generated by standard model Higgs selfcouplings, Higgs-gaugeboson couplings, and Yukawa couplings.

(9.32a)

(9.32b)

(9.32c)

(9.32d)

(9.32e)

(9.32f)

Figure 9.6: Four-point dilaton couplings. (9.32a), (9.32c) and (9.32e) are missing in [13], but could be generated by standard model Higgs selfcouplings, Higgs-gaugeboson couplings, and Yukawa couplings.

$$\begin{array}{ccc}
\begin{array}{c} 1 \\ \diagup \\ \bullet \\ \diagdown \\ 4 \end{array} & \begin{array}{c} \diagdown \\ \bullet \\ \diagup \\ 3 \end{array} & = \\
h_{\mu\nu} \cdots \cdots & & ??? \\
\end{array}
\quad (9.33a)$$

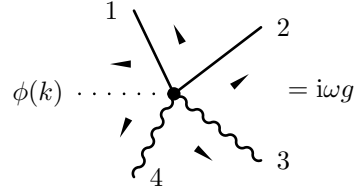
$$\begin{array}{ccc}
\begin{array}{c} 1 \\ \diagup \\ \bullet \\ \diagdown \\ 4 \end{array} & \begin{array}{c} \diagdown \\ \bullet \\ \diagup \\ 3 \end{array} & = \\
h_{\mu\nu} \cdots \cdots & & -ig^2 \frac{\kappa}{2} C_{\mu\nu, \mu_3 \mu_4} (T^{a_3} T^{a_4} + T^{a_4} T^{a_3})_{n_2 n_1} \\
\end{array}
\quad (9.33b)$$

$$\begin{array}{ccc}
\begin{array}{c} 1 \\ \diagup \\ \bullet \\ \diagdown \\ 4 \end{array} & \begin{array}{c} \diagdown \\ \bullet \\ \diagup \\ 3 \end{array} & = \\
h_{\mu\nu} \cdots \cdots & & -ig^2 \frac{\kappa}{2} (f^{ba_1 a_3} f^{ba_2 a_4} G_{\mu\nu, \mu_1 \mu_2 \mu_3 \mu_4} \\
& & + f^{ba_1 a_2} f^{ba_3 a_4} G_{\mu\nu, \mu_1 \mu_3 \mu_2 \mu_4} \\
& & + f^{ba_1 a_4} f^{ba_2 a_3} G_{\mu\nu, \mu_1 \mu_2 \mu_4 \mu_3}) \\
\end{array}
\quad (9.33c)$$

Figure 9.7: Five-point graviton couplings. (9.33a) is missing in [13], but should be generated by standard model Higgs selfcouplings.



$$\phi(k) \cdots \cdots = ??? \quad (9.34a)$$



$$\phi(k) \cdots \cdots = i\omega g^2 \kappa g_{\mu_3 \mu_4} (T^{a_3} T^{a_4} + T^{a_4} T^{a_3})_{n_2 n_1} \quad (9.34b)$$



$$\phi(k) \cdots \cdots = 0 \quad (9.34c)$$

Figure 9.8: Five-point dilaton couplings. (9.34a) is missing in [13], but could be generated by standard model Higgs selfcouplings.

```

type  $\alpha$  expr =
  | I | Const of int
  | Atom of  $\alpha$ 
  | Sum of  $\alpha$  expr list
  | Diff of  $\alpha$  expr  $\times$   $\alpha$  expr
  | Neg of  $\alpha$  expr
  | Prod of  $\alpha$  expr list
  | Quot of  $\alpha$  expr  $\times$   $\alpha$  expr
  | Rec of  $\alpha$  expr
  | Pow of  $\alpha$  expr  $\times$  int
  | Sqrt of  $\alpha$  expr
  | Sin of  $\alpha$  expr
  | Cos of  $\alpha$  expr
  | Tan of  $\alpha$  expr
  | Cot of  $\alpha$  expr
  | Atan2 of  $\alpha$  expr  $\times$   $\alpha$  expr
  | Conj of  $\alpha$  expr

type  $\alpha$  variable = Real of  $\alpha$  | Complex of  $\alpha$ 
type  $\alpha$  variable_array = Real_Array of  $\alpha$  | Complex_Array of  $\alpha$ 

type  $\alpha$  parameters =
  { input : ( $\alpha \times$  float) list;
    derived : ( $\alpha$  variable  $\times$   $\alpha$  expr) list;
    derived_arrays : ( $\alpha$  variable_array  $\times$   $\alpha$  expr list) list }

```

<i>Dim5_Scalar_Vector_Vector_T</i> : $\mathcal{L}_I = g\phi(i\partial_\mu V_1^\nu)(i\partial_\nu V_2^\mu)$
<i>F23</i> : $\phi(k_2 + k_3) \leftarrow i \cdot g k_3^\mu V_{1,\mu}(k_2) k_2^\nu V_{2,\nu}(k_3)$
<i>F32</i> : $\phi(k_2 + k_3) \leftarrow i \cdot g k_2^\mu V_{2,\mu}(k_3) k_3^\nu V_{1,\nu}(k_2)$
<i>F12</i> : $V_2^\mu(k_1 + k_2) \leftarrow i \cdot g k_2^\mu \phi(k_1) (-k_1^\nu - k_2^\nu) V_{1,\nu}(k_2)$
<i>F21</i> : $V_2^\mu(k_1 + k_2) \leftarrow i \cdot g k_2^\mu (-k_1^\nu - k_2^\nu) V_{1,\nu}(k_2) \phi(k_1)$
<i>F13</i> : $V_1^\mu(k_1 + k_3) \leftarrow i \cdot g k_3^\mu \phi(k_1) (-k_1^\nu - k_3^\nu) V_{2,\nu}(k_3)$
<i>F31</i> : $V_1^\mu(k_1 + k_3) \leftarrow i \cdot g k_3^\mu (-k_1^\nu - k_3^\nu) V_{2,\nu}(k_3) \phi(k_1)$

Table 9.34: ...

<i>Dim6_Vector_Vector_Vector_T</i> : $\mathcal{L}_I = gV_1^\mu((i\partial_\nu V_2^\rho) \overleftrightarrow{\partial}_\mu (i\partial_\rho V_3^\nu))$
<i>F23</i> : $V_1^\mu(k_2 + k_3) \leftarrow i \cdot g(k_2^\mu - k_3^\mu) k_3^\nu V_{2,\nu}(k_2) k_2^\rho V_{3,\rho}(k_3)$
<i>F32</i> : $V_1^\mu(k_2 + k_3) \leftarrow i \cdot g(k_2^\mu - k_3^\mu) k_2^\nu V_{3,\nu}(k_3) k_3^\rho V_{2,\rho}(k_2)$
<i>F12</i> : $V_3^\mu(k_1 + k_2) \leftarrow i \cdot g k_2^\mu (k_1^\nu + 2k_2^\nu) V_{1,\nu}(k_1) (-k_1^\rho - k_2^\rho) V_{2,\rho}(k_2)$
<i>F21</i> : $V_3^\mu(k_1 + k_2) \leftarrow i \cdot g k_2^\mu (-k_1^\rho - k_2^\rho) V_{2,\rho}(k_2) (k_1^\nu + 2k_2^\nu) V_{1,\nu}(k_1)$
<i>F13</i> : $V_2^\mu(k_1 + k_3) \leftarrow i \cdot g k_3^\mu (k_1^\nu + 2k_3^\nu) V_{1,\nu}(k_1) (-k_1^\rho - k_3^\rho) V_{3,\rho}(k_3)$
<i>F31</i> : $V_2^\mu(k_1 + k_3) \leftarrow i \cdot g k_3^\mu (-k_1^\rho - k_3^\rho) V_{3,\rho}(k_3) (k_1^\nu + 2k_3^\nu) V_{1,\nu}(k_1)$

Table 9.35: ...

### 9.1.9 More Exotic Couplings

## 9.2 Interface of *Model*

### 9.2.1 General Quantum Field Theories

module type *T* =

sig

*flavor* abstractly encodes all quantum numbers.

type *flavor*

*Color.t* encodes the (SU(*N*)) color representation.

val *color* : *flavor* → *Color.t*

The set of conserved charges.

module *Ch* : *Charges.T*

val *charges* : *flavor* → *Ch.t*

The PDG particle code for interfacing with Monte Carlos.

val *pdg* : *flavor* → *int*

The Lorentz representation of the particle.

<i>Tensor_2_Vector_Vector</i> : $\mathcal{L}_I = gT^{\mu\nu}(V_{1,\mu}V_{2,\nu} + V_{1,\nu}V_{2,\mu})$
<i>F23</i> : $T^{\mu\nu}(k_2 + k_3) \leftarrow i \cdot g(V_{1,\mu}(k_2)V_{2,\nu}(k_3) + V_{1,\nu}(k_2)V_{2,\mu}(k_3))$
<i>F32</i> : $T^{\mu\nu}(k_2 + k_3) \leftarrow i \cdot g(V_{2,\nu}(k_3)V_{1,\mu}(k_2) + V_{2,\mu}(k_3)V_{1,\nu}(k_2))$
<i>F12</i> : $V_2^\mu(k_1 + k_2) \leftarrow i \cdot g(T^{\mu\nu}(k_1) + T^{\nu\mu}(k_1))V_{1,\nu}(k_2)$
<i>F21</i> : $V_2^\mu(k_1 + k_2) \leftarrow i \cdot gV_{1,\nu}(k_2)(T^{\mu\nu}(k_1) + T^{\nu\mu}(k_1))$
<i>F13</i> : $V_1^\mu(k_1 + k_3) \leftarrow i \cdot g(T^{\mu\nu}(k_1) + T^{\nu\mu}(k_1))V_{2,\nu}(k_3)$
<i>F31</i> : $V_1^\mu(k_1 + k_3) \leftarrow i \cdot gV_{2,\nu}(k_3)(T^{\mu\nu}(k_1) + T^{\nu\mu}(k_1))$

Table 9.36: ...

<i>Dim5_Tensor_2_Vector_Vector_1</i> : $\mathcal{L}_I = gT^{\alpha\beta}(V_1^\mu i \overleftrightarrow{\partial}_\alpha i \overleftrightarrow{\partial}_\beta V_{2,\mu})$
<i>F23</i> : $T^{\alpha\beta}(k_2 + k_3) \leftarrow i \cdot g(k_2^\alpha - k_3^\alpha)(k_2^\beta - k_3^\beta)V_1^\mu(k_2)V_{2,\mu}(k_3)$
<i>F32</i> : $T^{\alpha\beta}(k_2 + k_3) \leftarrow i \cdot g(k_2^\alpha - k_3^\alpha)(k_2^\beta - k_3^\beta)V_{2,\mu}(k_3)V_1^\mu(k_2)$
<i>F12</i> : $V_2^\mu(k_1 + k_2) \leftarrow i \cdot g(k_1^\alpha + 2k_2^\alpha)(k_1^\beta + 2k_2^\beta)T_{\alpha\beta}(k_1)V_1^\mu(k_2)$
<i>F21</i> : $V_2^\mu(k_1 + k_2) \leftarrow i \cdot g(k_1^\alpha + 2k_2^\alpha)(k_1^\beta + 2k_2^\beta)V_1^\mu(k_2)T_{\alpha\beta}(k_1)$
<i>F13</i> : $V_1^\mu(k_1 + k_3) \leftarrow i \cdot g(k_1^\alpha + 2k_3^\alpha)(k_1^\beta + 2k_3^\beta)T_{\alpha\beta}(k_1)V_2^\mu(k_3)$
<i>F31</i> : $V_1^\mu(k_1 + k_3) \leftarrow i \cdot g(k_1^\alpha + 2k_3^\alpha)(k_1^\beta + 2k_3^\beta)V_2^\mu(k_3)T_{\alpha\beta}(k_1)$

Table 9.37: ...

<i>Dim5_Tensor_2_Vector_Vector_2</i> : $\mathcal{L}_I = gT^{\alpha\beta}(V_1^\mu i \overleftrightarrow{\partial}_\beta (i\partial_\mu V_{2,\alpha}) + V_1^\mu i \overleftrightarrow{\partial}_\alpha (i\partial_\mu V_{2,\beta}))$
<i>F23</i> : $T^{\alpha\beta}(k_2 + k_3) \leftarrow i \cdot g(k_3^\beta - k_2^\beta)k_3^\mu V_{1,\mu}(k_2)V_2^\alpha(k_3) + (\alpha \leftrightarrow \beta)$
<i>F32</i> : $T^{\alpha\beta}(k_2 + k_3) \leftarrow i \cdot g(k_3^\beta - k_2^\beta)V_2^\alpha(k_3)k_3^\mu V_{1,\mu}(k_2) + (\alpha \leftrightarrow \beta)$
<i>F12</i> : $V_2^\alpha(k_1 + k_2) \leftarrow i \cdot g(k_1^\beta + 2k_2^\beta)(T^{\alpha\beta}(k_1) + T^{\beta\alpha}(k_1))(k_1^\mu + k_2^\mu)V_{1,\mu}(k_2)$
<i>F21</i> : $V_2^\alpha(k_1 + k_2) \leftarrow i \cdot g(k_1^\mu + k_2^\mu)V_{1,\mu}(k_2)(k_1^\beta + 2k_2^\beta)(T^{\alpha\beta}(k_1) + T^{\beta\alpha}(k_1))$
<i>F13</i> : $V_1^\alpha(k_1 + k_3) \leftarrow i \cdot g(k_1^\beta + 2k_3^\beta)(T^{\alpha\beta}(k_1) + T^{\beta\alpha}(k_1))(k_1^\mu + k_3^\mu)V_{2,\mu}(k_3)$
<i>F31</i> : $V_1^\alpha(k_1 + k_3) \leftarrow i \cdot g(k_1^\mu + k_3^\mu)V_{2,\mu}(k_3)(k_1^\beta + 2k_3^\beta)(T^{\alpha\beta}(k_1) + T^{\beta\alpha}(k_1))$

Table 9.38: ...



<i>Dim7_Tensor_2_Vector_Vector_T</i> : $\mathcal{L}_I = gT^{\alpha\beta}((i\partial^\mu V_1^\nu)i\overleftrightarrow{\partial}_\alpha i\overleftrightarrow{\partial}_\beta(i\partial_\nu V_{2,\mu}))$
<i>F23</i> : $T^{\alpha\beta}(k_2 + k_3) \leftarrow i \cdot g(k_2^\alpha - k_3^\alpha)(k_2^\beta - k_3^\beta)k_3^\mu V_{1,\mu}(k_2)k_2^\nu V_{2,\nu}(k_3)$
<i>F32</i> : $T^{\alpha\beta}(k_2 + k_3) \leftarrow i \cdot g(k_2^\alpha - k_3^\alpha)(k_2^\beta - k_3^\beta)k_2^\mu V_{2,\nu}(k_3)k_3^\mu V_{1,\mu}(k_2)$
<i>F12</i> : $V_2^\mu(k_1 + k_2) \leftarrow i \cdot gk_2^\mu(k_1^\alpha + 2k_2^\alpha)(k_1^\beta + 2k_2^\beta)T_{\alpha\beta}(k_1)(-k_1^\nu - k_2^\nu)V_{1,\nu}(k_2)$
<i>F21</i> : $V_2^\mu(k_1 + k_2) \leftarrow i \cdot gk_2^\mu(-k_1^\nu - k_2^\nu)V_{1,\nu}(k_2)(k_1^\alpha + 2k_2^\alpha)(k_1^\beta + 2k_2^\beta)T_{\alpha\beta}(k_1)$
<i>F13</i> : $V_1^\mu(k_1 + k_3) \leftarrow i \cdot gk_3^\mu(k_1^\alpha + 2k_3^\alpha)(k_1^\beta + 2k_3^\beta)T_{\alpha\beta}(k_1)(-k_1^\nu - k_3^\nu)V_{2,\nu}(k_3)$
<i>F31</i> : $V_1^\mu(k_1 + k_3) \leftarrow i \cdot gk_3^\mu(-k_1^\nu - k_3^\nu)V_{2,\nu}(k_3)(k_1^\alpha + 2k_3^\alpha)(k_1^\beta + 2k_3^\beta)T_{\alpha\beta}(k_1)$

Table 9.39: ...

`val lorentz : flavor → Coupling.lorentz`

The propagator for the particle, which *can* depend on a gauge parameter.

`type gauge`

`val propagator : flavor → gauge Coupling.propagator`

*Not* the symbol for the numerical value, but the scheme or strategy.

`val width : flavor → Coupling.width`

Charge conjugation, with and without color.

`val conjugate : flavor → flavor`

Returns 1 for fermions, -1 for anti-fermions, 2 for Majoranas and 0 otherwise.

`val fermion : flavor → int`

The Feynman rules. *vertices* and (*fuse2*, *fuse3*, *fusen*) are redundant, of course. However, *vertices* is required for building functors for models and *vertices* can be recovered from (*fuse2*, *fuse3*, *fusen*) only at great cost.



Nevertheless: *vertices* is a candidate for removal, b/c we can build a smarter *Colorize* functor acting on (*fuse2*, *fuse3*, *fusen*). It can support an arbitrary number of color lines. But we have to test whether it is efficient enough.

`type constant`

Later: `type orders` to count orders of couplings

`val max_degree : unit → int`

`val vertices : unit →`

`(((((flavor × flavor × flavor) × constant Coupling.vertex3 × constant) list)`  
`× (((flavor × flavor × flavor × flavor) × constant Coupling.vertex4 ×`  
`constant) list)`  
`× (((flavor list) × constant Coupling.vertexn × constant) list))`

`val fuse2 : flavor → flavor → (flavor × constant Coupling.t) list`

`val fuse3 : flavor → flavor → flavor → (flavor × constant Coupling.t) list`

`val fuse : flavor list → (flavor × constant Coupling.t) list`

Later: `val orders : constant → orders` counting orders of couplings

The list of all known flavors.

```
val flavors : unit → flavor list
```

The flavors that can appear in incoming or outgoing states, grouped in a way that is useful for user interfaces.

```
val external_flavors : unit → (string × flavor list) list
```

The Goldstone bosons corresponding to a gauge field, if any.

```
val goldstone : flavor → (flavor × constant Coupling.expr) option
```

The dependent parameters.

```
val parameters : unit → constant Coupling.parameters
```

Translate from and to convenient textual representations of flavors.

```
val flavor_of_string : string → flavor
```

```
val flavor_to_string : flavor → string
```

TeX and L<sup>A</sup>T<sub>E</sub>X

```
val flavor_to_TeX : flavor → string
```

The following must return unique symbols that are acceptable as symbols in all programming languages under consideration as targets. Strings of alphanumeric characters (starting with a letter) should be safe. Underscores are also usable, but would violate strict Fortran77.

```
val flavor_symbol : flavor → string
```

```
val gauge_symbol : gauge → string
```

```
val mass_symbol : flavor → string
```

```
val width_symbol : flavor → string
```

```
val constant_symbol : constant → string
```

Model specific options.

```
val options : Options.t
```

Revision control information.

```
val rcs : RCS.t
```

end

In addition to hardcoded models, we can have models that are initialized at run time.

### 9.2.2 Mutable Quantum Field Theories

```
module type Mutable =
```

```
sig
```

```
include T
```

Export only one big initialization function to discourage partial initializations. Labels make this usable.

```
val setup :
```

```

color : (flavor → Color.t) →
pdg : (flavor → int) →
lorentz : (flavor → Coupling.lorentz) →
propagator : (flavor → gauge Coupling.propagator) →
width : (flavor → Coupling.width) →
goldstone : (flavor → (flavor × constant Coupling.expr) option) →
conjugate : (flavor → flavor) →
fermion : (flavor → int) →
max_degree : int →
vertices : (unit →
  (((flavor × flavor × flavor) × constant Coupling.vertex3 ×
  constant) list)
  × (((flavor × flavor × flavor × flavor) × constant Coupling.vertex4 ×
  constant) list)
  × (((flavor list) × constant Coupling.vertexn × constant) list))) →

fuse : ((flavor → flavor → (flavor × constant Coupling.t) list)
  × (flavor → flavor → flavor →
    (flavor × constant Coupling.t) list)
  × (flavor list → (flavor × constant Coupling.t) list)) →
flavors : ((string × flavor list) list) →
parameters : (unit → constant Coupling.parameters) →
flavor_of_string : (string → flavor) →
flavor_to_string : (flavor → string) →
flavor_to_TeX : (flavor → string) →
flavor_symbol : (flavor → string) →
gauge_symbol : (gauge → string) →
mass_symbol : (flavor → string) →
width_symbol : (flavor → string) →
constant_symbol : (constant → string) →
unit
end

```

### 9.2.3 Gauge Field Theories

The following signatures are used only for model building. The diagrammatics and numerics is supposed to be completely ignorant about the detail of the models and expected to rely on the interface *T* exclusively.



In the end, we might have functors  $(M : T) \rightarrow \text{Gauge}$ , but we will need to add the quantum numbers to *T*.

```

module type Gauge =
sig
  include T

```

Matter field carry conserved quantum numbers and can be replicated in generations without changing the gauge sector.

```

type matter_field

```

Gauge bosons proper.

```
type gauge_boson
```

Higgses, Goldstones and all the rest:

```
type other
```

We can query the kind of field

```
type field =
  | Matter of matter_field
  | Gauge of gauge_boson
  | Other of other
val field : flavor → field
```

and we can build new fields of a given kind:

```
val matter_field : matter_field → flavor
val gauge_boson : gauge_boson → flavor
val other : other → flavor
end
```

#### 9.2.4 *Gauge Field Theories with Broken Gauge Symmetries*

Both are carefully crafted as subtypes of *Gauge* so that they can be used in place of *Gauge* and *T* everywhere:

```
module type Broken_Gauge =
sig
  include Gauge

  type massless
  type massive
  type goldstone

  type kind =
    | Massless of massless
    | Massive of massive
    | Goldstone of goldstone
  val kind : gauge_boson → kind

  val massless : massive → gauge_boson
  val massive : massive → gauge_boson
  val goldstone : goldstone → gauge_boson
end
```

```
module type Unitarity_Gauge =
sig
  include Gauge

  type massless
  type massive

  type kind =
    | Massless of massless
    | Massive of massive
  val kind : gauge_boson → kind
```

```

    val massless : massive → gauge_boson
    val massive : massive → gauge_boson

end

module type Colorized =
sig
    include T

    type flavor_sans_color
    val flavor_sans_color : flavor → flavor_sans_color
    val conjugate_sans_color : flavor_sans_color → flavor_sans_color

    val nc : unit → int
    val amplitude : flavor_sans_color list → flavor_sans_color list →
        (flavor list × flavor list) list
    val flow : flavor list → flavor list → Color.Flow.t

end

module type Colorized_Gauge =
sig
    include Gauge

    type flavor_sans_color
    val flavor_sans_color : flavor → flavor_sans_color
    val conjugate_sans_color : flavor_sans_color → flavor_sans_color

    val nc : unit → int
    val amplitude : flavor_sans_color list → flavor_sans_color list →
        (flavor list × flavor list) list
    val flow : flavor list → flavor list → Color.Flow.t

end

```



Interface *vertex.mli* unavailable!



Implementation *vertex.ml* unavailable!

### 9.3 Interface of *Target*

```

module type T =
sig
    type amplitudes

    val options : Options.t
    type diagnostic = All | Arguments | Momenta | Gauge

```

Format the amplitudes as a sequence of strings.

```

    val amplitudes_to_channel : string → out_channel →
        (diagnostic × bool) list → amplitudes → unit
    val parameters_to_channel : out_channel → unit

```

```
    val rsc_list : RCS.t list
  end

module type Maker =
  functor (F : Fusion.Maker) →
    functor (P : Momentum.T) → functor (M : Model.T) →
      T with type amplitudes = Fusion.Multi(F)(P)(M).amplitudes
```

---

# —10—

## CONSERVED QUANTUM NUMBERS

### *10.1 Interface of Charges*

#### *10.1.1 Abstract Type*

```
module type T =
  sig
```

The abstract type of the set of conserved charges or additive quantum numbers.

```
  type t
```

Add the quantum numbers of a pair or a list of particles.

```
  val add : t → t → t
  val sum : t list → t
```

Test the charge conservation.

```
  val is_null : t → bool
end
```

#### *10.1.2 Trivial Realisation*

```
module Null : T with type t = unit
```

#### *10.1.3 Nontrivial Realisations*

**Z**

```
module Z : T with type t = int
```

**Z** × **Z** × ... × **Z**

```
module ZZ : T with type t = int list
```

**Q**

```
module Q : T with type t = Algebra.Small_Rational.t
```

**Q × Q × ⋯ × Q**

```
module QQ : T with type t = Algebra.Small_Rational.t list
```

## 10.2 Implementation of *Charges*

```
module type T =
  sig
    type t
    val add : t → t → t
    val sum : t list → t
    val is_null : t → bool
  end

module Null : T with type t = unit =
  struct
    type t = unit
    let add () () = ()
    let sum _ = ()
    let is_null _ = true
  end

module Z : T with type t = int =
  struct
    type t = int
    let add = ( + )
    let sum = List.fold_left add 0
    let is_null n = (n = 0)
  end

module ZZ : T with type t = int list =
  struct
    type t = int list
    let add = List.map2 ( + )
    let sum = function
      | [] → []
      | [charges] → charges
      | charges :: rest → List.fold_left add charges rest
    let is_null = List.for_all (fun n → n = 0)
  end

module Rat = Algebra.Small_Rational

module Q : T with type t = Rat.t =
  struct
    type t = Rat.t
    let add = Rat.add
```



```

    let sum = List.fold_left Rat.add Rat.null
    let is_null = Rat.is_null
  end

module QQ : T with type t = Rat.t list =
  struct
    type t = Rat.t list
    let add = List.map2 Rat.add
    let sum = function
      | [] → []
      | [charges] → charges
      | charges :: rest → List.fold_left add charges rest
    let is_null = List.for_all Rat.is_null
  end

```

---

# —11—

## COLORIZATION

### 11.1 Interface of Colorize

#### 11.1.1 ...

```
module It (M : Model.T) :  
  Model.Colorized with type flavor_sans_color = M.flavor  
  and type constant = M.constant  
  
module Gauge (M : Model.Gauge) :  
  Model.Colorized_Gauge with type flavor_sans_color = M.flavor  
  and type constant = M.constant
```

### 11.2 Implementation of Colorize

```
let rcs_file = RCS.parse "Colorize" ["Colorizing_Monochrome_Models"]  
{ RCS.revision = "$Revision: 5864$";  
  RCS.date = "$Date: 2014-06-02 15:12:47 +0200 (Mon, 02 Jun 2014)$";  
  RCS.author = "$Author: ohl$";  
  RCS.source  
    = "$URL: svn+ssh://jr_reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/s"
```

#### 11.2.1 Colorizing a Monochrome Model

```
module It (M : Model.T) =  
  struct  
    let rcs = RCS.rename rcs_file "Colorize.It()"  
      [ "Colorizing_Generic_Monochrome_Models"]  
    open Coupling  
    module C = Color  
    let incomplete s =  
      failwith ("Colorize.It()." ^ s ^ "_not_done_yet!")  
    let invalid s =  
      invalid_arg ("Colorize.It()." ^ s ^ "_must_not_be_evaluated!")
```

```

let impossible s =
  invalid_arg ("Colorize.It()." ^ s ^ "can't happen!(but_just_did...)")

let su0 s =
  invalid_arg ("Colorize.It()." ^ s ^ ":_found_SU(0)!")

let colored_vertex s =
  invalid_arg ("Colorize.It()." ^ s ^ ":_colored_vertex!")

let baryonic_vertex s =
  invalid_arg ("Colorize.It()." ^ s ^
    ":_baryonic_(i.e._eps_ijk)_vertices_not_supported_yet!")

let color_flow_ambiguous s =
  invalid_arg ("Colorize.It()." ^ s ^ ":_ambiguous_color_flow!")

let color_flow_of_string s =
  let c = int_of_string s in
  if c < 1 then
    invalid_arg ("Colorize.It()." ^ s ^ ":_color_flow_#_<_1!")
  else
    c

type cf_in = int
type cf_out = int

type flavor =
  | White of M.flavor
  | CF_in of M.flavor × cf_in
  | CF_out of M.flavor × cf_out
  | CF_io of M.flavor × cf_in × cf_out
  | CF_aux of M.flavor

type flavor_sans_color = M.flavor

let flavor_sans_color = function
  | White f → f
  | CF_in (f, _) → f
  | CF_out (f, _) → f
  | CF_io (f, -, _) → f
  | CF_aux f → f

let pullback f arg1 =
  f (flavor_sans_color arg1)

type gauge = M.gauge
type constant = M.constant
let options = M.options

let color = pullback M.color
let pdg = pullback M.pdg
let lorentz = pullback M.lorentz

module Ch = M.Ch
let charges = pullback M.charges

```

For the propagator we cannot use pullback because we have to add the case of the color singlet propagator by hand.

```

let cf_aux_propagator = function
  | Prop_Scalar → Prop_Col_Scalar (* Spin 0 octets. *)
  | Prop_Majorana → Prop_Col_Majorana (* Spin 1/2 octets. *)
  | Prop_Feynman → Prop_Col_Feynman (* Spin 1 states, massless. *)
  | Prop_Unitarity → Prop_Col_Unitarity (* Spin 1 states, massive. *)
  | Aux_Scalar → Aux_Col_Scalar (* constant colored scalar propagator
*)
  | Aux_Vector → Aux_Col_Vector (* constant colored vector propaga-
tor *)
  | Aux_Tensor_1 → Aux_Col_Tensor_1 (* constant colored tensor
propagator *)
  | Prop_Col_Scalar | Prop_Col_Feynman
  | Prop_Col_Majorana | Prop_Col_Unitarity
  | Aux_Col_Scalar | Aux_Col_Vector | Aux_Col_Tensor_1
  → failwith ("Colorize.It().colorize_propagator: already colored particle!")
  | _ → failwith ("Colorize.It().colorize_propagator: impossible!")

let propagator = function
  | CF_aux f → cf_aux_propagator (M.propagator f)
  | White f → M.propagator f
  | CF_in (f, _) → M.propagator f
  | CF_out (f, _) → M.propagator f
  | CF_io (f, -, _) → M.propagator f

let width = pullback M.width

let goldstone = function
  | White f →
    begin match M.goldstone f with
    | None → None
    | Some (f', g) → Some (White f', g)
    end
  | CF_in (f, c) →
    begin match M.goldstone f with
    | None → None
    | Some (f', g) → Some (CF_in (f', c), g)
    end
  | CF_out (f, c) →
    begin match M.goldstone f with
    | None → None
    | Some (f', g) → Some (CF_out (f', c), g)
    end
  | CF_io (f, c1, c2) →
    begin match M.goldstone f with
    | None → None
    | Some (f', g) → Some (CF_io (f', c1, c2), g)
    end
  | CF_aux f →
    begin match M.goldstone f with
    | None → None
    | Some (f', g) → Some (CF_aux f', g)
    end

```

```

let conjugate = function
| White f → White (M.conjugate f)
| CF_in (f, c) → CF_out (M.conjugate f, c)
| CF_out (f, c) → CF_in (M.conjugate f, c)
| CF_io (f, c1, c2) → CF_io (M.conjugate f, c2, c1)
| CF_aux f → CF_aux (M.conjugate f)

let conjugate_sans_color = M.conjugate

let fermion = pullback M.fermion

let max_degree = M.max_degree

let flavors () =
  invalid "flavors"

let external_flavors () =
  invalid "external_flavors"

let parameters = M.parameters

module ISet = Set.Make (struct type t = int let compare = compare end)

let nc_value =
  let nc_set =
    List.fold_left
      (fun nc_set f →
        match M.color f with
        | C.Singlet → nc_set
        | C.SUN nc → ISet.add (abs nc) nc_set
        | C.AdjSUN nc → ISet.add (abs nc) nc_set)
      ISet.empty (M.flavors ()) in
  match ISet.elements nc_set with
  | [] → 0
  | [n] → n
  | nc_list →
    invalid_arg
      ("Colorize.It(): more than one value of N_C: " ^
       String.concat ", " (List.map string_of_int nc_list))

let nc () =
  nc_value

let split_color_string s =
  try
    let i1 = String.index s '/' in
    let i2 = String.index_from s (succ i1) '/' in
    let sf = String.sub s 0 i1
    and sc1 = String.sub s (succ i1) (i2 - i1 - 1)
    and sc2 = String.sub s (succ i2) (String.length s - i2 - 1) in
    (sf, sc1, sc2)
  with
  | Not_found → (s, "", "")

let flavor_of_string s =
  try

```

```

let sf, sc1, sc2 = split_color_string s in
let f = M.flavor_of_string sf in
match M.color f with
| C.Singlet → White f
| C.SUN nc →
    if nc > 0 then
        CF_in (f, color_flow_of_string sc1)
    else
        CF_out (f, color_flow_of_string sc2)
| C.AdjSUN _ →
    begin match sc1, sc2 with
    | "", "" → CF_aux f
    | -, - → CF_io (f, color_flow_of_string sc1, color_flow_of_string sc2)
    end
with
| Failure "int_of_string" →
    invalid_arg "Colorize().flavor_of_string: expecting integer"
let flavor_to_string = function
| White f →
    M.flavor_to_string f
| CF_in (f, c) →
    M.flavor_to_string f ^ "/" ^ string_of_int c ^ "/"
| CF_out (f, c) →
    M.flavor_to_string f ^ "/" ^ string_of_int c
| CF_io (f, c1, c2) →
    M.flavor_to_string f ^ "/" ^ string_of_int c1 ^ "/" ^ string_of_int c2
| CF_aux f →
    M.flavor_to_string f ^ "/"
let flavor_to_TeX = function
| White f →
    M.flavor_to_TeX f
| CF_in (f, c) →
    "{" ^ M.flavor_to_TeX f ^ "}-{\mathstrut} ^ string_of_int c ^ {"
| CF_out (f, c) →
    "{" ^ M.flavor_to_TeX f ^ "}-{\mathstrut\overline{" ^
    string_of_int c ^ "}}"
| CF_io (f, c1, c2) →
    "{" ^ M.flavor_to_TeX f ^ "}-{\mathstrut} ^
    string_of_int c1 ^ "\overline{" ^ string_of_int c2 ^ "}}"
| CF_aux f →
    "{" ^ M.flavor_to_TeX f ^ "}-{\mathstrut}0{"
let flavor_symbol = function
| White f →
    M.flavor_symbol f
| CF_in (f, c) →
    M.flavor_symbol f ^ "-" ^ string_of_int c ^ "-"
| CF_out (f, c) →
    M.flavor_symbol f ^ "--" ^ string_of_int c
| CF_io (f, c1, c2) →

```

```

      M.flavor_symbol f ^ "-" ^ string_of_int c1 ^ "-" ^ string_of_int c2
| CF_aux f →
      M.flavor_symbol f ^ "--"

```

```
let gauge_symbol = M.gauge_symbol
```

Masses and widths must not depend on the colors anyway!

```

let mass_symbol = pullback M.mass_symbol
let width_symbol = pullback M.width_symbol
let constant_symbol = M.constant_symbol

```

### Vertices

#### Auxiliary functions

```

let mult_vertex3 x = function
| FBF (c, fb, coup, f) →
      FBF ((x × c), fb, coup, f)
| PBP (c, fb, coup, f) →
      PBP ((x × c), fb, coup, f)
| BBB (c, fb, coup, f) →
      BBB ((x × c), fb, coup, f)
| GBG (c, fb, coup, f) →
      GBG ((x × c), fb, coup, f)
| Gauge_Gauge_Gauge c →
      Gauge_Gauge_Gauge (x × c)
| Aux_Gauge_Gauge c →
      Aux_Gauge_Gauge (x × c)
| Scalar_Vector_Vector c →
      Scalar_Vector_Vector (x × c)
| Aux_Vector_Vector c →
      Aux_Vector_Vector (x × c)
| Aux_Scalar_Vector c →
      Aux_Scalar_Vector (x × c)
| Scalar_Scalar_Scalar c →
      Scalar_Scalar_Scalar (x × c)
| Aux_Scalar_Scalar c →
      Aux_Scalar_Scalar (x × c)
| Vector_Scalar_Scalar c →
      Vector_Scalar_Scalar (x × c)
| Graviton_Scalar_Scalar c →
      Graviton_Scalar_Scalar (x × c)
| Graviton_Vector_Vector c →
      Graviton_Vector_Vector (x × c)
| Graviton_Spinor_Spinor c →
      Graviton_Spinor_Spinor (x × c)
| Dim4_Vector_Vector_Vector_T c →
      Dim4_Vector_Vector_Vector_T (x × c)

```

---

```

| Dim4_Vector_Vector_Vector_L c →
  Dim4_Vector_Vector_Vector_L (x × c)
| Dim4_Vector_Vector_Vector_T5 c →
  Dim4_Vector_Vector_Vector_T5 (x × c)
| Dim4_Vector_Vector_Vector_L5 c →
  Dim4_Vector_Vector_Vector_L5 (x × c)
| Dim6_Gauge_Gauge_Gauge c →
  Dim6_Gauge_Gauge_Gauge (x × c)
| Dim6_Gauge_Gauge_Gauge_5 c →
  Dim6_Gauge_Gauge_Gauge_5 (x × c)
| Aux_DScalar_DScalar c →
  Aux_DScalar_DScalar (x × c)
| Aux_Vector_DScalar c →
  Aux_Vector_DScalar (x × c)
| Dim5_Scalar_Gauge2 c →
  Dim5_Scalar_Gauge2 (x × c)
| Dim5_Scalar_Gauge2_Skew c →
  Dim5_Scalar_Gauge2_Skew (x × c)
| Dim5_Scalar_Vector_Vector_T c →
  Dim5_Scalar_Vector_Vector_T (x × c)
| Dim5_Scalar_Vector_Vector_U c →
  Dim5_Scalar_Vector_Vector_U (x × c)
| Dim5_Scalar_Vector_Vector_TU c →
  Dim5_Scalar_Vector_Vector_TU (x × c)
| Scalar_Vector_Vector_t c →
  Scalar_Vector_Vector_t (x × c)
| Dim6_Vector_Vector_Vector_T c →
  Dim6_Vector_Vector_Vector_T (x × c)
| Tensor_2_Vector_Vector c →
  Tensor_2_Vector_Vector (x × c)
| Tensor_2_Vector_Vector_1 c →
  Tensor_2_Vector_Vector_1 (x × c)
| Tensor_2_Vector_Vector_t c →
  Tensor_2_Vector_Vector_t (x × c)
| Dim5_Tensor_2_Vector_Vector_1 c →
  Dim5_Tensor_2_Vector_Vector_1 (x × c)
| Dim5_Tensor_2_Vector_Vector_2 c →
  Dim5_Tensor_2_Vector_Vector_2 (x × c)
| Dim7_Tensor_2_Vector_Vector_T c →
  Dim7_Tensor_2_Vector_Vector_T (x × c)

let mult_vertex4 x = function
| Scalar4 c →
  Scalar4 (x × c)
| Scalar2_Vector2 c →
  Scalar2_Vector2 (x × c)
| Vector4 ic4_list →
  Vector4 (List.map (fun (c, icl) → (x × c, icl)) ic4_list)
| DScalar4 ic4_list →
  DScalar4 (List.map (fun (c, icl) → (x × c, icl)) ic4_list)

```



```

| DScalar2_Vector2 ic4_list →
  DScalar2_Vector2 (List.map (fun (c, icl) → (x × c, icl)) ic4_list)
| GBBG (c, fb, b2, f) →
  GBBG ((x × c), fb, b2, f)
| Vector4_K_Matrix_tho (c, ic4_list) →
  Vector4_K_Matrix_tho ((x × c), ic4_list)
| Vector4_K_Matrix_jr (c, ch2_list) →
  Vector4_K_Matrix_jr ((x × c), ch2_list)

let mult_vertexn x = function
| foo → ignore (incomplete "mult_vertexn"); foo

let mult_vertex x = function
| V3 (v, fuse, c) → V3 (mult_vertex3 x v, fuse, c)
| V4 (v, fuse, c) → V4 (mult_vertex4 x v, fuse, c)
| Vn (v, fuse, c) → Vn (mult_vertexn x v, fuse, c)

```

Below, we will need to permute Lorentz structures. The following permutes the three possible contractions of four vectors. We permute the first three indices, as they correspond to the particles entering the fusion.

```

type permutation4 =
| P123 | P231 | P312
| P213 | P321 | P132

let permute_contract4 = function
| P123 →
  begin function
  | C_12_34 → C_12_34
  | C_13_42 → C_13_42
  | C_14_23 → C_14_23
  end
| P231 →
  begin function
  | C_12_34 → C_14_23
  | C_13_42 → C_12_34
  | C_14_23 → C_13_42
  end
| P312 →
  begin function
  | C_12_34 → C_13_42
  | C_13_42 → C_14_23
  | C_14_23 → C_12_34
  end
| P213 →
  begin function
  | C_12_34 → C_12_34
  | C_13_42 → C_14_23
  | C_14_23 → C_13_42
  end
| P321 →
  begin function
  | C_12_34 → C_14_23

```

```

      | C_13_42 → C_13_42
      | C_14_23 → C_12_34
    end
  | P132 →
    begin function
      | C_12_34 → C_13_42
      | C_13_42 → C_12_34
      | C_14_23 → C_14_23
    end

let permute_contract4_list perm ic4_list =
  List.map (fun (i, c4) → (i, permute_contract4 perm c4)) ic4_list

let permute_vertex4' perm = function
  | Scalar4 c →
    Scalar4 c
  | Vector4 ic4_list →
    Vector4 (permute_contract4_list perm ic4_list)
  | Vector4_K_Matrix_jr (c, ic4_list) →
    Vector4_K_Matrix_jr (c, permute_contract4_list perm ic4_list)
  | Scalar2_Vector2 c →
    incomplete "permute_vertex4'␣Scalar2_Vector2"
  | DScalar4 ic4_list →
    incomplete "permute_vertex4'␣DScalar4"
  | DScalar2_Vector2 ic4_list →
    incomplete "permute_vertex4'␣DScalar2_Vector2"
  | GBBG (c, fb, b2, f) →
    incomplete "permute_vertex4'␣GBBG"
  | Vector4_K_Matrix_tho (c, ch2_list) →
    incomplete "permute_vertex4'␣Vector4_K_Matrix_tho"

let permute_vertex4 perm = function
  | V3 (v, fuse, c) → V3 (v, fuse, c)
  | V4 (v, fuse, c) → V4 (permute_vertex4' perm v, fuse, c)
  | Vn (v, fuse, c) → Vn (v, fuse, c)

```

*vertices* are *only* used by functor applications and for indexing a cache of pre-computed fusion rules, which is not used for colorized models.

```

let vertices () =
  invalid "vertices"

```

### Cubic Vertices



The following pattern matches could eventually become quite long. The O'Caml compiler will (hopefully) optimize them aggressively (<http://pauillac.inria.fr/~maranget/papers/opat/>).

```

let colorize_fusion2 f1 f2 (f, v) =
  match M.color f with
  | C.Singlet →

```

```

begin match f1, f2 with
| White -, White - →
  [White f, v]
| CF_in (_, c1), CF_out (_, c2')
| CF_out (_, c1), CF_in (_, c2') →
  if c1 = c2' then
    [White f, v]
  else
    []
| CF_io (f1, c1, c1'), CF_io (f2, c2, c2') →
  if c1 = c2' ∧ c2 = c1' then
    [White f, v]
  else
    []
| CF_aux f1, CF_aux f2 →
  [White f, mult_vertex (- (nc ())) v]
| CF_aux -, CF_io - | CF_io -, CF_aux - →
  []
| (CF_in - | CF_out - | CF_io - | CF_aux -), White -
| White -, (CF_in - | CF_out - | CF_io - | CF_aux -)
| (CF_io - | CF_aux -), (CF_in - | CF_out -)
| (CF_in - | CF_out -), (CF_io - | CF_aux -)
| CF_in -, CF_in - | CF_out -, CF_out - →
  colored_vertex "colorize_fusion2"

end

| C.SUN nc1 →
  begin match f1, f2 with
  | CF_in (_, c1), (White - | CF_aux -)
  | (White - | CF_aux -), CF_in (_, c1) →
    if nc1 > 0 then
      [CF_in (f, c1), v]
    else
      colored_vertex "colorize_fusion2"
  | CF_out (_, c1'), (White - | CF_aux -)
  | (White - | CF_aux -), CF_out (_, c1') →
    if nc1 < 0 then
      [CF_out (f, c1'), v]
    else
      colored_vertex "colorize_fusion2"
  | CF_in (_, c1), CF_io (_, c2, c2')
  | CF_io (_, c2, c2'), CF_in (_, c1) →
    if nc1 > 0 then begin
      if c1 = c2' then
        [CF_in (f, c2), v]
      else

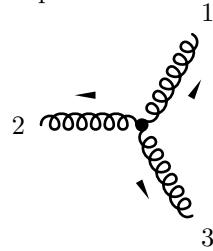
```

```

    []
  end else
    colored_vertex "colorize-fusion2"
  | CF_out (_, c1'), CF_io (_, c2, c2')
  | CF_io (_, c2, c2'), CF_out (_, c1') →
    if nc1 < 0 then begin
      if c1' = c2 then
        [CF_out (f, c2'), v]
      else
        []
      end else
        colored_vertex "colorize-fusion2"
    | CF_in _, CF_in _ →
      if nc1 > 0 then
        baryonic_vertex "colorize-fusion2"
      else
        colored_vertex "colorize-fusion2"
    | CF_out _, CF_out _ →
      if nc1 < 0 then
        baryonic_vertex "colorize-fusion2"
      else
        colored_vertex "colorize-fusion2"
    | CF_in _, CF_out _ | CF_out _, CF_in _
    | (White _ | CF_io _ | CF_aux _),
      (White _ | CF_io _ | CF_aux _) →
      colored_vertex "colorize-fusion2"
  end
| C.AdjSUN _ →
  begin match f1, f2 with
  | White _, CF_io (_, c1, c2') | CF_io (_, c1, c2'), White _ →
    [CF_io (f, c1, c2'), v]
  | White _, CF_aux _ | CF_aux _, White _ →
    [CF_aux f, mult_vertex (- (nc ())) v]
  | CF_in (_, c1), CF_out (_, c2')
  | CF_out (_, c2'), CF_in (_, c1) →
    if c1 ≠ c2' then
      [CF_io (f, c1, c2'), v]
    else
      [CF_aux f, v]
  end

```

In the adjoint representation



$$= g f_{a_1 a_2 a_3} C^{\mu_1 \mu_2 \mu_3}(k_1, k_2, k_3) \quad (11.1a)$$

with

$$C^{\mu_1\mu_2\mu_3}(k_1, k_2, k_3) = (g^{\mu_1\mu_2}(k_1^{\mu_3} - k_2^{\mu_3}) + g^{\mu_2\mu_3}(k_2^{\mu_1} - k_3^{\mu_1}) + g^{\mu_3\mu_1}(k_3^{\mu_2} - k_1^{\mu_2})) \quad (11.1b)$$

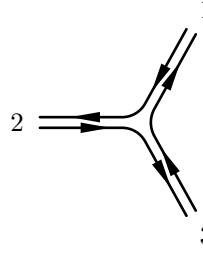
while in the color flow basis find from

$$if_{a_1a_2a_3} = \text{tr}(T_{a_1}[T_{a_2}, T_{a_3}]) = \text{tr}(T_{a_1}T_{a_2}T_{a_3}) - \text{tr}(T_{a_1}T_{a_3}T_{a_2}) \quad (11.2)$$

the decomposition

$$if_{a_1a_2a_3} T_{a_1}^{i_1j_1} T_{a_2}^{i_2j_2} T_{a_3}^{i_3j_3} = \delta^{i_1j_2} \delta^{i_2j_3} \delta^{i_3j_1} - \delta^{i_1j_3} \delta^{i_3j_2} \delta^{i_2j_1}. \quad (11.3)$$

The resulting Feynman rule is



$$= ig (\delta^{i_1j_3} \delta^{i_2j_1} \delta^{i_3j_2} - \delta^{i_1j_2} \delta^{i_2j_3} \delta^{i_3j_1}) C^{\mu_1\mu_2\mu_3}(k_1, k_2, k_3) \quad (11.4)$$



We have to generalize this for cases of three particles in the adjoint that are not all gluons (gluinos, scalar octets):

- scalar-scalar-scalar
- scalar-scalar-vector
- scalar-vector-vector
- scalar-fermion-fermion
- vector-fermion-fermion



We could use a better understanding of the signs for the gaugino-gaugino-gaugeboson couplings!!!

```

| CF_io (f1, c1, c1'), CF_io (f2, c2, c2') →
  let sign =
    begin match v with
    | V3 (Gauge_Gauge_Gauge -, -, -)
    | V3 (Aux_Gauge_Gauge -, -, -) → 1
    | V3 (FBF (-, -, -, -), fuse2, -) →
      begin match fuse2 with
      | F12 → 1 (* works, but needs theoretical underpinning
*)
      | F21 → -1 (* dto. *)
      | F31 → 1 (* dto. *)
      | F32 → -1 (* transposition of F12 (no testcase) *)
      | F23 → 1 (* transposition of F21 (no testcase) *)
      | F13 → -1 (* transposition of F12 (no testcase) *)
      end
    end

```

```

| V3 _ → incomplete "colorize_fusion2□(V3□-)"
| V4 _ → impossible "colorize_fusion2□(V4□-)"
| Vn _ → impossible "colorize_fusion2□(Vn□-)"
end in
if c1' = c2 then
  [CF_io (f, c1, c2'), mult_vertex (-sign) v]
else if c2' = c1 then
  [CF_io (f, c2, c1'), mult_vertex (sign) v]
else
  []
| CF_aux _ , CF_io _
| CF_io _ , CF_aux _
| CF_aux _ , CF_aux _ →
  []
| White _ , White _
| (White _ | CF_io _ | CF_aux _), (CF_in _ | CF_out _)
| (CF_in _ | CF_out _), (White _ | CF_io _ | CF_aux _)
| CF_in _ , CF_in _ | CF_out _ , CF_out _ →
  colored_vertex "colorize_fusion2"
end
end

```

#### Quartic Vertices

```

let colorize_fusion3 f1 f2 f3 (f, v) =
  match M.color f with
  | C.Singlet →
    begin match f1, f2, f3 with
    | White _ , White _ , White _ →
      [White f, v]
    | (White _ | CF_aux _), CF_in (_, c1), CF_out (_, c2')
    | (White _ | CF_aux _), CF_out (_, c1), CF_in (_, c2')
    | CF_in (_, c1), (White _ | CF_aux _), CF_out (_, c2')
    | CF_out (_, c1), (White _ | CF_aux _), CF_in (_, c2')
    | CF_in (_, c1), CF_out (_, c2'), (White _ | CF_aux _)
    | CF_out (_, c1), CF_in (_, c2'), (White _ | CF_aux _) →
      if c1 = c2' then
        [White f, v]
      else
        []
    | White _ , CF_io (_, c1, c1'), CF_io (_, c2, c2')
    | CF_io (_, c1, c1'), White _ , CF_io (_, c2, c2')
    | CF_io (_, c1, c1'), CF_io (_, c2, c2'), White _ →
      if c1 = c2' ∧ c2 = c1' then
        [White f, v]
      else
        []
    end
  end

```

```

| White -, CF_aux -, CF_aux -
| CF_aux -, White -, CF_aux -
| CF_aux -, CF_aux -, White - →
  [White f, mult_vertex (- (nc ())) v]

| White -, CF_io -, CF_aux -
| White -, CF_aux -, CF_io -
| CF_io -, White -, CF_aux -
| CF_aux -, White -, CF_io -
| CF_io -, CF_aux -, White -
| CF_aux -, CF_io -, White - →
  []

| CF_io (-, c1, c1'), CF_in (-, c2), CF_out (-, c3')
| CF_io (-, c1, c1'), CF_out (-, c3'), CF_in (-, c2)
| CF_in (-, c2), CF_io (-, c1, c1'), CF_out (-, c3')
| CF_out (-, c3'), CF_io (-, c1, c1'), CF_in (-, c2)
| CF_in (-, c2), CF_out (-, c3'), CF_io (-, c1, c1')
| CF_out (-, c3'), CF_in (-, c2), CF_io (-, c1, c1') →
  if c1 = c3' ∧ c1' = c2 then
    [White f, v]
  else
    []

| CF_io (-, c1, c1'), CF_io (-, c2, c2'), CF_io (-, c3, c3') →
  if c1' = c2 ∧ c2' = c3 ∧ c3' = c1 then
    [White f, mult_vertex (-1) v]
  else if c1' = c3 ∧ c2' = c1 ∧ c3' = c2 then
    [White f, mult_vertex (1) v]
  else
    []

| CF_io -, CF_io -, CF_aux -
| CF_io -, CF_aux -, CF_io -
| CF_aux -, CF_io -, CF_io -
| CF_io -, CF_aux -, CF_aux -
| CF_aux -, CF_io -, CF_aux -
| CF_aux -, CF_aux -, CF_io -
| CF_aux -, CF_aux -, CF_aux - →
  []

| CF_in -, CF_in -, CF_in -
| CF_out -, CF_out -, CF_out - →
  baryonic_vertex "colorize_fusion3"

| CF_in -, CF_in -, CF_out -
| CF_in -, CF_out -, CF_in -
| CF_out -, CF_in -, CF_in -
| CF_in -, CF_out -, CF_out -
| CF_out -, CF_in -, CF_out -
| CF_out -, CF_out -, CF_in -

| White -, White -, (CF_io - | CF_aux -)
| White -, (CF_io - | CF_aux -), White -

```

---

```

| (CF_io - | CF_aux -), White -, White -
| (White - | CF_io - | CF_aux -), CF_in -, CF_in -
| CF_in -, (White - | CF_io - | CF_aux -), CF_in -
| CF_in -, CF_in -, (White - | CF_io - | CF_aux -)

| (White - | CF_io - | CF_aux -), CF_out -, CF_out -
| CF_out -, (White - | CF_io - | CF_aux -), CF_out -
| CF_out -, CF_out -, (White - | CF_io - | CF_aux -)

| (CF_in - | CF_out -),
  (White - | CF_io - | CF_aux -),
  (White - | CF_io - | CF_aux -)
| (White - | CF_io - | CF_aux -),
  (CF_in - | CF_out -),
  (White - | CF_io - | CF_aux -)
| (White - | CF_io - | CF_aux -),
  (White - | CF_io - | CF_aux -),
  (CF_in - | CF_out -) →
  colored_vertex "colorize_fusion3"

end

| C.SUN nc1 →
  begin match f1, f2, f3 with
  | CF_in (-, c1), CF_io (-, c2, c2'), CF_io (-, c3, c3')
  | CF_io (-, c2, c2'), CF_in (-, c1), CF_io (-, c3, c3')
  | CF_io (-, c2, c2'), CF_io (-, c3, c3'), CF_in (-, c1) →
    if nc1 > 0 then
      if c1 = c2' ∧ c2 = c3' then
        [CF_in (f, c3), v]
      else if c1 = c3' ∧ c3 = c2' then
        [CF_in (f, c2), v]
      else
        []
    else
      colored_vertex "colorize_fusion3"

  | CF_out (-, c1'), CF_io (-, c2, c2'), CF_io (-, c3, c3')
  | CF_io (-, c2, c2'), CF_out (-, c1'), CF_io (-, c3, c3')
  | CF_io (-, c2, c2'), CF_io (-, c3, c3'), CF_out (-, c1') →
    if nc1 < 0 then
      if c1' = c2 ∧ c2' = c3 then
        [CF_out (f, c3'), v]
      else if c1' = c3 ∧ c3' = c2 then
        [CF_out (f, c2'), v]
      else
        []
    else
      colored_vertex "colorize_fusion3"

  | CF_aux -, CF_in (-, c1), CF_io (-, c2, c2')
  | CF_aux -, CF_io (-, c2, c2'), CF_in (-, c1)

```



---

```

| CF_in (_, c1), CF_aux -, CF_io (_, c2, c2')
| CF_io (_, c2, c2'), CF_aux -, CF_in (_, c1)
| CF_in (_, c1), CF_io (_, c2, c2'), CF_aux -
| CF_io (_, c2, c2'), CF_in (_, c1), CF_aux - →
  if nc1 > 0 then
    if c1 = c2' then
      [CF_in (f, c2), mult_vertex (2) v]
    else
      []
  else
    colored_vertex "colorize_fusion3"
| CF_aux -, CF_out (_, c1'), CF_io (_, c2, c2')
| CF_aux -, CF_io (_, c2, c2'), CF_out (_, c1')
| CF_out (_, c1'), CF_aux -, CF_io (_, c2, c2')
| CF_io (_, c2, c2'), CF_aux -, CF_out (_, c1')
| CF_out (_, c1'), CF_io (_, c2, c2'), CF_aux -
| CF_io (_, c2, c2'), CF_out (_, c1'), CF_aux - →
  if nc1 < 0 then
    if c1' = c2 then
      [CF_out (f, c2'), mult_vertex (2) v]
    else
      []
  else
    colored_vertex "colorize_fusion3"
| White -, CF_in (_, c1), CF_io (_, c2, c2')
| White -, CF_io (_, c2, c2'), CF_in (_, c1)
| CF_in (_, c1), White -, CF_io (_, c2, c2')
| CF_io (_, c2, c2'), White -, CF_in (_, c1)
| CF_in (_, c1), CF_io (_, c2, c2'), White -
| CF_io (_, c2, c2'), CF_in (_, c1), White - →
  if nc1 > 0 then
    if c1 = c2' then
      [CF_in (f, c2), v]
    else
      []
  else
    colored_vertex "colorize_fusion3"
| White -, CF_out (_, c1'), CF_io (_, c2, c2')
| White -, CF_io (_, c2, c2'), CF_out (_, c1')
| CF_out (_, c1'), White -, CF_io (_, c2, c2')
| CF_io (_, c2, c2'), White -, CF_out (_, c1')
| CF_out (_, c1'), CF_io (_, c2, c2'), White -
| CF_io (_, c2, c2'), CF_out (_, c1'), White - →
  if nc1 < 0 then
    if c2 = c1' then
      [CF_out (f, c2'), v]
    else
      []
  else
    colored_vertex "colorize_fusion3"

```

```

    colored_vertex "colorize-fusion3"
| CF_in (_, c1), CF_aux -, CF_aux -
| CF_aux -, CF_in (_, c1), CF_aux -
| CF_aux -, CF_aux -, CF_in (_, c1) →
  if nc1 > 0 then
    [CF_in (f, c1), mult_vertex (2) v]
  else
    colored_vertex "colorize-fusion3"
| CF_in (_, c1), CF_aux -, White -
| CF_in (_, c1), White -, CF_aux -
| CF_in (_, c1), White -, White -
| CF_aux -, CF_in (_, c1), White -
| White -, CF_in (_, c1), CF_aux -
| White -, CF_in (_, c1), White -
| CF_aux -, White -, CF_in (_, c1)
| White -, CF_aux -, CF_in (_, c1)
| White -, White -, CF_in (_, c1) →
  if nc1 > 0 then
    [CF_in (f, c1), v]
  else
    colored_vertex "colorize-fusion3"
| CF_out (_, c1'), CF_aux -, CF_aux -
| CF_aux -, CF_out (_, c1'), CF_aux -
| CF_aux -, CF_aux -, CF_out (_, c1') →
  if nc1 < 0 then
    [CF_out (f, c1'), mult_vertex (2) v]
  else
    colored_vertex "colorize-fusion3"
| CF_out (_, c1'), CF_aux -, White -
| CF_out (_, c1'), White -, CF_aux -
| CF_out (_, c1'), White -, White -
| CF_aux -, CF_out (_, c1'), White -
| White -, CF_out (_, c1'), CF_aux -
| White -, CF_out (_, c1'), White -
| CF_aux -, White -, CF_out (_, c1')
| White -, CF_aux -, CF_out (_, c1')
| White -, White -, CF_out (_, c1') →
  if nc1 < 0 then
    [CF_out (f, c1'), v]
  else
    colored_vertex "colorize-fusion3"
| CF_in -, CF_in -, CF_out -
| CF_in -, CF_out -, CF_in -
| CF_out -, CF_in -, CF_in - →
  if nc1 > 0 then
    color_flow_ambiguous "colorize-fusion3"
  else
    colored_vertex "colorize-fusion3"

```

---

```

| CF_in -, CF_out -, CF_out -
| CF_out -, CF_in -, CF_out -
| CF_out -, CF_out -, CF_in - →
  if nc1 < 0 then
    color_flow_ambiguous "colorize-fusion3"
  else
    colored_vertex "colorize-fusion3"

| CF_in -, CF_in -, CF_in -
| CF_out -, CF_out -, CF_out -

| (White - | CF_io - | CF_aux -),
  (White - | CF_io - | CF_aux -),
  (White - | CF_io - | CF_aux -)

| (CF_in - | CF_out -),
  (CF_in - | CF_out -),
  (White - | CF_io - | CF_aux -)
| (CF_in - | CF_out -),
  (White - | CF_io - | CF_aux -),
  (CF_in - | CF_out -)
| (White - | CF_io - | CF_aux -),
  (CF_in - | CF_out -),
  (CF_in - | CF_out -) →
  colored_vertex "colorize-fusion3"

end

| C.AdjSUN nc →
  begin match f1, f2, f3 with

    | CF_in (-, c1), CF_out (-, c1'), White -
    | CF_out (-, c1'), CF_in (-, c1), White -
    | CF_in (-, c1), White -, CF_out (-, c1')
    | CF_out (-, c1'), White -, CF_in (-, c1)
    | White -, CF_in (-, c1), CF_out (-, c1')
    | White -, CF_out (-, c1'), CF_in (-, c1) →
      if c1 ≠ c1' then
        [CF_io (f, c1, c1'), v]
      else
        [CF_aux f, v]

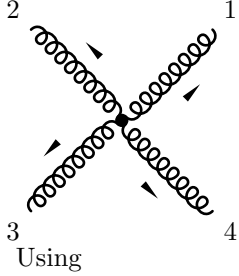
    | CF_in (-, c1), CF_out (-, c1'), CF_aux -
    | CF_out (-, c1'), CF_in (-, c1), CF_aux -
    | CF_in (-, c1), CF_aux -, CF_out (-, c1')
    | CF_out (-, c1'), CF_aux -, CF_in (-, c1)
    | CF_aux -, CF_in (-, c1), CF_out (-, c1')
    | CF_aux -, CF_out (-, c1'), CF_in (-, c1) →
      if c1 ≠ c1' then
        [CF_io (f, c1, c1'), mult_vertex (2) v]
      else
        [CF_aux f, mult_vertex (2) v]

    | CF_in (-, c1), CF_out (-, c1'), CF_io (-, c2, c2')

```

```

| CF_out (-, c1'), CF_in (-, c1), CF_io (-, c2, c2')
| CF_in (-, c1), CF_io (-, c2, c2'), CF_out (-, c1')
| CF_out (-, c1'), CF_io (-, c2, c2'), CF_in (-, c1)
| CF_io (-, c2, c2'), CF_in (-, c1), CF_out (-, c1')
| CF_io (-, c2, c2'), CF_out (-, c1'), CF_in (-, c1) →
  if c1 = c2' ∧ c2 = c1' then
    [CF_aux f, mult_vertex ( 2) v]
  else if c1 = c2' then
    [CF_io (f, c2, c1'), v]
  else if c2 = c1' then
    [CF_io (f, c1, c2'), v]
  else
    []
    
```

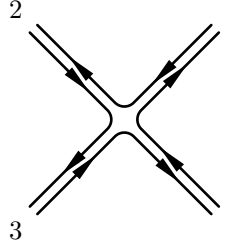


$$\begin{aligned}
 &= -ig^2 f_{a_1 a_2 b} f_{a_3 a_4 b} (g_{\mu_1 \mu_3} g_{\mu_4 \mu_2} - g_{\mu_1 \mu_4} g_{\mu_2 \mu_3}) \\
 &\quad -ig^2 f_{a_1 a_3 b} f_{a_4 a_2 b} (g_{\mu_1 \mu_4} g_{\mu_2 \mu_3} - g_{\mu_1 \mu_2} g_{\mu_3 \mu_4}) \\
 &\quad -ig^2 f_{a_1 a_4 b} f_{a_2 a_3 b} (g_{\mu_1 \mu_2} g_{\mu_3 \mu_4} - g_{\mu_1 \mu_3} g_{\mu_4 \mu_2})
 \end{aligned} \tag{11.5}$$

Using

$$\mathcal{P}_4 = \{\{1, 2, 3, 4\}, \{1, 3, 4, 2\}, \{1, 4, 2, 3\}, \{1, 2, 4, 3\}, \{1, 4, 3, 2\}, \{1, 3, 2, 4\}\} \tag{11.6}$$

as the set of permutations of  $\{1, 2, 3, 4\}$  with the cyclic permutations factored out, we have:



$$\begin{aligned}
 &= ig^2 \sum_{\{\alpha_k\}_{k=1,2,3,4} \in \mathcal{P}_4} \delta^{i_{\alpha_1} j_{\alpha_2}} \delta^{i_{\alpha_2} j_{\alpha_3}} \delta^{i_{\alpha_3} j_{\alpha_4}} \delta^{i_{\alpha_4} j_{\alpha_1}} \\
 &\quad (2g_{\mu_{\alpha_1} \mu_{\alpha_3}} g_{\mu_{\alpha_4} \mu_{\alpha_2}} - g_{\mu_{\alpha_1} \mu_{\alpha_4}} g_{\mu_{\alpha_2} \mu_{\alpha_3}} - g_{\mu_{\alpha_1} \mu_{\alpha_2}} g_{\mu_{\alpha_3} \mu_{\alpha_4}})
 \end{aligned} \tag{11.7}$$

The different color connections correspond to permutations of the particles entering the fusion and have to be matched by a corresponding permutation of the Lorentz structure:



We have to generalize this for cases of four particles in the adjoint that are not all gluons:

- scalar-scalar-scalar-scalar
- scalar-scalar-vector-vector

and even ones including fermions (gluinos) if higher dimensional operators are involved.

```

| CF_io (-, c1, c1'), CF_io (-, c2, c2'), CF_io (-, c3, c3') →
    
```

```

    if  $c1' = c2 \wedge c2' = c3$  then
      [CF_io (f, c1, c3'), permute_vertex4 P123 v]
    else if  $c1' = c3 \wedge c3' = c2$  then
      [CF_io (f, c1, c2'), permute_vertex4 P132 v]
    else if  $c2' = c3 \wedge c3' = c1$  then
      [CF_io (f, c2, c1'), permute_vertex4 P231 v]
    else if  $c2' = c1 \wedge c1' = c3$  then
      [CF_io (f, c2, c3'), permute_vertex4 P213 v]
    else if  $c3' = c1 \wedge c1' = c2$  then
      [CF_io (f, c3, c2'), permute_vertex4 P312 v]
    else if  $c3' = c2 \wedge c2' = c1$  then
      [CF_io (f, c3, c1'), permute_vertex4 P321 v]
    else
      []
  | CF_io -, CF_io -, CF_aux -
  | CF_io -, CF_aux -, CF_io -
  | CF_aux -, CF_io -, CF_io -
  | CF_io -, CF_aux -, CF_aux -
  | CF_aux -, CF_aux -, CF_io -
  | CF_aux -, CF_io -, CF_aux -
  | CF_aux -, CF_aux -, CF_aux - →
  | []
  | CF_io (-, c1, c1'), CF_io (-, c2, c2'), White -
  | CF_io (-, c1, c1'), White -, CF_io (-, c2, c2')
  | White -, CF_io (-, c1, c1'), CF_io (-, c2, c2') →
    if  $c1' = c2$  then
      [CF_io (f, c1, c2'), mult_vertex (-1) v]
    else if  $c2' = c1$  then
      [CF_io (f, c2, c1'), mult_vertex (1) v]
    else
      []
  | CF_io (-, c1, c1'), CF_aux -, White -
  | CF_aux -, CF_io (-, c1, c1'), White -
  | CF_io (-, c1, c1'), White -, CF_aux -
  | CF_aux -, White -, CF_io (-, c1, c1')
  | White -, CF_io (-, c1, c1'), CF_aux -
  | White -, CF_aux -, CF_io (-, c1, c1') →
  | []
  | CF_aux -, CF_aux -, White -
  | CF_aux -, White -, CF_aux -
  | White -, CF_aux -, CF_aux - →
  | []
  | White -, White -, CF_io (-, c1, c1')
  | White -, CF_io (-, c1, c1'), White -
  | CF_io (-, c1, c1'), White -, White - →
    [CF_io (f, c1, c1'), v]
  | White -, White -, CF_aux -
  | White -, CF_aux -, White -

```

```

| CF_aux -, White -, White - →
  []
| White -, White -, White -
| (White - | CF_io - | CF_aux -),
  (White - | CF_io - | CF_aux -),
  (CF_in - | CF_out -)
| (White - | CF_io - | CF_aux -),
  (CF_in - | CF_out -),
  (White - | CF_io - | CF_aux -)
| (CF_in - | CF_out -),
  (White - | CF_io - | CF_aux -),
  (White - | CF_io - | CF_aux -)

| CF_in -, CF_in -, (White - | CF_io - | CF_aux -)
| CF_in -, (White - | CF_io - | CF_aux -), CF_in -
| (White - | CF_io - | CF_aux -), CF_in -, CF_in -

| CF_out -, CF_out -, (White - | CF_io - | CF_aux -)
| CF_out -, (White - | CF_io - | CF_aux -), CF_out -
| (White - | CF_io - | CF_aux -), CF_out -, CF_out -

| (CF_in - | CF_out -),
  (CF_in - | CF_out -),
  (CF_in - | CF_out -) →
  colored_vertex "colorize_fusion3"
end

```

### Quintic and Higher Vertices

```

let is_white = function
| White - → true
| - → false

let colorize_fusionn flist (f, v) =
  let incomplete_match () =
    incomplete
    ("colorize_fusionn{␣" ^
     String.concat ",␣" (List.map flavor_to_string flist) ^
     "␣}>␣" ^ M.flavor_to_string f) in
  match M.color f with
  | C.Singlet →
    if List.for_all is_white flist then
      [White f, v]
    else
      incomplete_match ()
  | C.SUN - →
    if List.for_all is_white flist then
      colored_vertex "colorize_fusionn"
    else
      incomplete_match ()

```

```

| C.AdjSUN _ →
  if List.for_all is_white flist then
    colored_vertex "colorize_fusionn"
  else
    incomplete_match ()

let fuse2 f1 f2 =
  ThoList.flatmap
    (colorize_fusion2 f1 f2)
    (M.fuse2 (flavor_sans_color f1) (flavor_sans_color f2))

let fuse3 f1 f2 f3 =
  ThoList.flatmap
    (colorize_fusion3 f1 f2 f3)
    (M.fuse3 (flavor_sans_color f1) (flavor_sans_color f2) (flavor_sans_color f3))

let fuse_list flist =
  ThoList.flatmap
    (colorize_fusionn flist)
    (M.fuse (List.map flavor_sans_color flist))

let fuse = function
| [] | [-] → invalid_arg "Colorize.It().fuse"
| [f1; f2] → fuse2 f1 f2
| [f1; f2; f3] → fuse3 f1 f2 f3
| flist → fuse_list flist

let max_degree = M.max_degree

```

### Adding Color to External Particles

```

let count_color_strings f_list =
  let rec count_color_strings' n_in n_out n_glue = function
    | f :: rest →
      begin match M.color f with
      | C.Singlet → count_color_strings' n_in n_out n_glue rest
      | C.SUN nc →
        if nc > 0 then
          count_color_strings' (succ n_in) n_out n_glue rest
        else if nc < 0 then
          count_color_strings' n_in (succ n_out) n_glue rest
        else
          su0 "count_color_strings"
      | C.AdjSUN _ →
          count_color_strings' (succ n_in) (succ n_out) (succ n_glue) rest
      end
    | [] → (n_in, n_out, n_glue)
  in
  count_color_strings' 0 0 0 f_list

let external_color_flows f_list =
  let n_in, n_out, n_glue = count_color_strings f_list in

```

```

if  $n_{in} \neq n_{out}$  then
  []
else
  let color_strings = ThoList.range 1  $n_{in}$  in
  List.rev_map
    (fun permutation → (color_strings, permutation))
    (Combinatorics.permute color_strings)

```

If there are only adjoints *and* there are no couplings of adjoints to singlets, we can ignore the U(1)-ghosts.

```

let pure_adjoints_f_list =
  List.for_all (fun f → match M.color f with C.AdjSUN _ → true |
    _ → false) f_list

let two_adjoints_couple_to_singlets () =
  let vertices3, vertices4, verticesn = M.vertices () in
  List.exists (fun ((f1, f2, f3), _, _) →
    match M.color f1, M.color f2, M.color f3 with
    | C.AdjSUN _, C.AdjSUN _, C.Singlet
    | C.AdjSUN _, C.Singlet, C.AdjSUN _
    | C.Singlet, C.AdjSUN _, C.AdjSUN _ → true
    | _ → false) vertices3 ∨
  List.exists (fun ((f1, f2, f3, f4), _, _) →
    match M.color f1, M.color f2, M.color f3, M.color f4 with
    | C.AdjSUN _, C.AdjSUN _, C.Singlet, C.Singlet
    | C.AdjSUN _, C.Singlet, C.AdjSUN _, C.Singlet
    | C.Singlet, C.AdjSUN _, C.AdjSUN _, C.Singlet
    | C.AdjSUN _, C.Singlet, C.Singlet, C.AdjSUN _
    | C.Singlet, C.AdjSUN _, C.Singlet, C.AdjSUN _
    | C.Singlet, C.Singlet, C.AdjSUN _, C.AdjSUN _ → true
    | _ → false) vertices4 ∨
  List.exists (fun (flist, _, g) → true) verticesn

let external_ghosts_f_list =
  if pure_adjoints_f_list then
    two_adjoints_couple_to_singlets ()
  else
    true

```

We use *List.hd* and *List.tl* instead of pattern matching, because we consume *ecf\_in* and *ecf\_out* at a different pace.

```

let tail_opt = function
| [] → []
| _ :: tail → tail

let head_req = function
| [] →
  invalid_arg "Colorize.It().colorize_crossed_amplitude1: insufficient flows"
| x :: _ → x

let rec colorize_crossed_amplitude1 ghosts acc f_list (ecf_in, ecf_out) =
  match f_list, ecf_in, ecf_out with

```



```

| [], [], [] → [List.rev acc]
| [], -, - →
  invalid_arg "Colorize.It().colorize_crossed_amplitude1: leftover flows"
| f :: rest, -, - →
  begin match M.color f with
  | C.Singlet →
    colorize_crossed_amplitude1 ghosts
    (White f :: acc)
    rest (ecf_in, ecf_out)
  | C.SUN nc →
    if nc > 0 then
      colorize_crossed_amplitude1 ghosts
      (CF_in (f, head_req ecf_in) :: acc)
      rest (tail_opt ecf_in, ecf_out)
    else if nc < 0 then
      colorize_crossed_amplitude1 ghosts
      (CF_out (f, head_req ecf_out) :: acc)
      rest (ecf_in, tail_opt ecf_out)
    else
      su0 "colorize_flavor"
  | C.AdjSUN _ →
    let ecf_in' = head_req ecf_in
    and ecf_out' = head_req ecf_out in
    if ecf_in' = ecf_out' then begin
      if ghosts then
        colorize_crossed_amplitude1 ghosts
        (CF_aux f :: acc)
        rest (tail_opt ecf_in, tail_opt ecf_out)
      else
        []
    end else
      colorize_crossed_amplitude1 ghosts
      (CF_io (f, ecf_in', ecf_out') :: acc)
      rest (tail_opt ecf_in, tail_opt ecf_out)
  end

let colorize_crossed_amplitude1 ghosts f_list (ecf_in, ecf_out) =
  colorize_crossed_amplitude1 ghosts [] f_list (ecf_in, ecf_out)

let colorize_crossed_amplitude f_list =
  ThoList.rev_flatmap
    (colorize_crossed_amplitude1 (external_ghosts f_list) f_list)
    (external_color_flows f_list)

let cross_uncolored p_in p_out =
  (List.map M.conjugate p_in) @ p_out

let uncross_colored n_in p_lists_colored =
  let p_in_out_colored = List.map (ThoList.splitn n_in) p_lists_colored in
  List.map
    (fun (p_in_colored, p_out_colored) →
      (List.map conjugate p_in_colored, p_out_colored))

```

```

    p_in_out_colorized
let amplitude p_in p_out =
  uncross_colored
  (List.length p_in)
  (colorize_crossed_amplitude (cross_uncolored p_in p_out))

```

The `--` sign in the second component is redundant, but a Whizard convention.

```

let indices = function
| White _ → Color.Flow.of_list [0; 0]
| CF_in (_, c) → Color.Flow.of_list [c; 0]
| CF_out (_, c) → Color.Flow.of_list [0; -c]
| CF_io (_, c1, c2) → Color.Flow.of_list [c1; -c2]
| CF_aux f → Color.Flow.ghost ()

let flow p_in p_out =
  (List.map indices p_in, List.map indices p_out)

end

```

### 11.2.2 Colorizing a Monochrome Gauge Model

```

module Gauge (M : Model.Gauge) =
struct
  let rcs = RCS.rename rcs_file "Colorize.Gauge()"
    [ "Colorizing_Monochrome_Gauge_Models" ]

  module CM = It(M)

  type flavor = CM.flavor
  type flavor_sans_color = CM.flavor_sans_color
  type gauge = CM.gauge
  type constant = CM.constant
  module Ch = CM.Ch
  let charges = CM.charges
  let flavor_sans_color = CM.flavor_sans_color
  let color = CM.color
  let pdg = CM.pdg
  let lorentz = CM.lorentz
  let propagator = CM.propagator
  let width = CM.width
  let conjugate = CM.conjugate
  let conjugate_sans_color = CM.conjugate_sans_color
  let fermion = CM.fermion
  let max_degree = CM.max_degree
  let vertices = CM.vertices
  let fuse2 = CM.fuse2
  let fuse3 = CM.fuse3
  let fuse = CM.fuse
  let flavors = CM.flavors
  let nc = CM.nc

```

---

```

let external_flavors = CM.external_flavors
let goldstone = CM.goldstone
let parameters = CM.parameters
let flavor_of_string = CM.flavor_of_string
let flavor_to_string = CM.flavor_to_string
let flavor_to_TeX = CM.flavor_to_TeX
let flavor_symbol = CM.flavor_symbol
let gauge_symbol = CM.gauge_symbol
let mass_symbol = CM.mass_symbol
let width_symbol = CM.width_symbol
let constant_symbol = CM.constant_symbol
let options = CM.options

let incomplete s =
  failwith ("Colorize.Gauge(). " ^ s ^ " not done yet!")

type matter_field = M.matter_field
type gauge_boson = M.gauge_boson
type other = M.other

type field =
  | Matter of matter_field
  | Gauge of gauge_boson
  | Other of other

let field f =
  incomplete "field"

let matter_field f =
  incomplete "matter_field"

let gauge_boson f =
  incomplete "gauge_boson"

let other f =
  incomplete "other"

let amplitude = CM.amplitude
let flow = CM.flow

end

```

---

# —12—

## PROCESSES

### 12.1 Interface of Process

```

module type T =
  sig
    type flavor
  end

```



Eventually this should become an abstract type:

```

type t = flavor list × flavor list
val incoming : t → flavor list
val outgoing : t → flavor list

```

*parse\_decay* *s* decodes a decay description "*a*<sub>□</sub>->□*b*<sub>□</sub>*c*<sub>□</sub>...", where each word is split into a bag of flavors separated by ':'s.

```

type decay
val parse_decay : string → decay
val expand_decays : decay list → t list

```

*parse\_scattering* *s* decodes a scattering description "*a*<sub>□</sub>*b*<sub>□</sub>->□*c*<sub>□</sub>*d*<sub>□</sub>...", where each word is split into a bag of flavors separated by ':'s.

```

type scattering
val parse_scattering : string → scattering
val expand_scatterings : scattering list → t list

```

*parse\_process* *s* decodes process descriptions

$$\text{"a b c d"} \Rightarrow \text{Any } [a; b; c; d] \quad (12.1a)$$

$$\text{"a -> b c d"} \Rightarrow \text{Decay } (a, [b; c; d]) \quad (12.1b)$$

$$\text{"a b -> c d"} \Rightarrow \text{Scattering } (a, b, [c; d]) \quad (12.1c)$$

where each word is split into a bag of flavors separated by ':'s.

```

type any
type process = Any of any | Decay of decay | Scattering of scattering
val parse_process : string → process

```

*remove\_duplicate\_final\_states partition processes* removes duplicates from *processes*, which differ only by a permutation of final state particles. The permutation must respect the partitioning given by the offset 1 integers in *partition*.

```
val remove_duplicate_final_states : int list list → t list → t list
```

*diff set1 set2* returns the processes in *set1* with the processes in *set2* removed. *set2* does not need to be a subset of *set1*.

```
val diff : t list → t list → t list
```



Not functional yet. Interface subject to change. Should be moved to *Fusion.Multi*, because we will want to cross *colored* matrix elements.

Factor amplitudes that are related by crossing symmetry.

```
val crossing : t list → (flavor list × int list × t) list
```

```
end
```

```
module Make (M : Model.T) : T with type flavor = M.flavor
```

## 12.2 Implementation of *Process*

```
module type T =
```

```
sig
```

```
  type flavor
```

```
  type t = flavor list × flavor list
```

```
  val incoming : t → flavor list
```

```
  val outgoing : t → flavor list
```

```
  type decay
```

```
  val parse_decay : string → decay
```

```
  val expand_decays : decay list → t list
```

```
  type scattering
```

```
  val parse_scattering : string → scattering
```

```
  val expand_scatterings : scattering list → t list
```

```
  type any
```

```
  type process = Any of any | Decay of decay | Scattering of scattering
```

```
  val parse_process : string → process
```

```
  val remove_duplicate_final_states : int list list → t list → t list
```

```
  val diff : t list → t list → t list
```

```
  val crossing : t list → (flavor list × int list × t) list
```

```
end
```

```
module Make (M : Model.T) =
```

```
struct
```

```
  type flavor = M.flavor
```

```
  type t = flavor list × flavor list
```

```
  let incoming (fin, _) = fin
```

```
  let outgoing (_, fout) = fout
```

### 12.2.1 Select Charge Conserving Processes

```
let allowed (fin, fout) =
  M.Ch.is_null (M.Ch.sum (List.map M.charges (List.map M.conjugate fin @ fout)))
```

### 12.2.2 Parsing Process Descriptions

```
type  $\alpha$  bag =  $\alpha$  list

type any = flavor bag list
type decay = flavor bag  $\times$  flavor bag list
type scattering = flavor bag  $\times$  flavor bag  $\times$  flavor bag list

type process =
  | Any of any
  | Decay of decay
  | Scattering of scattering

let unique_flavors f_bags =
  List.for_all (function [f]  $\rightarrow$  true | _  $\rightarrow$  false) f_bags

let unique_final_state = function
  | Any fs  $\rightarrow$  unique_flavors fs
  | Decay (_, fs)  $\rightarrow$  unique_flavors fs
  | Scattering (_, _, fs)  $\rightarrow$  unique_flavors fs

let parse_process process =
  let last = String.length process - 1
  and flavor off len = M.flavor_of_string (String.sub process off len) in

  let add_flavors flavors = function
    | Any l  $\rightarrow$  Any (List.rev flavors :: l)
    | Decay (i, f)  $\rightarrow$  Decay (i, List.rev flavors :: f)
    | Scattering (i1, i2, f)  $\rightarrow$  Scattering (i1, i2, List.rev flavors :: f) in

  let rec scan_list so_far n =
    if n > last then
      so_far
    else
      let n' = succ n in
      match process.[n] with
      | ' ' | '\n'  $\rightarrow$  scan_list so_far n'
      | '-'  $\rightarrow$  scan_gtr so_far n'
      | c  $\rightarrow$  scan_flavors so_far [] n'

  and scan_flavors so_far flavors w n =
    if n > last then
      add_flavors (flavor w (last - w + 1) :: flavors) so_far
    else
      let n' = succ n in
      match process.[n] with
      | ' ' | '\n'  $\rightarrow$ 
        scan_list (add_flavors (flavor w (n - w) :: flavors) so_far) n'
```

```

| ':' → scan_flavors so_far (flavor w (n - w) :: flavors) n' n'
| _ → scan_flavors so_far flavors w n'

and scan_gtr so_far n =
  if n > last then
    invalid_arg "expecting '>'"
  else
    let n' = succ n in
    match process.[n] with
    | '>' →
      begin match so_far with
      | Any [i] → scan_list (Decay (i, [])) n'
      | Any [i2; i1] → scan_list (Scattering (i1, i2, [])) n'
      | Any _ → invalid_arg "only 1 or 2 particles in in>"
      | _ → invalid_arg "too many '->'s"
      end
    | _ → invalid_arg "expecting '>'" in

  match scan_list (Any []) 0 with
  | Any l → Any (List.rev l)
  | Decay (i, f) → Decay (i, List.rev f)
  | Scattering (i1, i2, f) → Scattering (i1, i2, List.rev f)

let parse_decay process =
  match parse_process process with
  | Any (i :: f) →
    prerr_endline "missing '->' in process description, assuming decay.";
    (i, f)
  | Decay (i, f) → (i, f)
  | _ → invalid_arg "expecting decay description: got scattering"

let parse_scattering process =
  match parse_process process with
  | Any (i1 :: i2 :: f) →
    prerr_endline "missing '->' in process description, assuming scattering.";
    (i1, i2, f)
  | Scattering (i1, i2, f) → (i1, i2, f)
  | _ → invalid_arg "expecting scattering description: got decay"

let expand_scatterings scatterings =
  ThoList.flatmap
    (function (fin1, fin2, fout) →
      Product.fold
        (fun flist acc →
          match flist with
          | fin1' :: fin2' :: fout' →
            let fin_fout' = ([fin1'; fin2'], fout') in
            if allowed fin_fout' then
              fin_fout' :: acc
            else
              acc
          | _ → failwith "Omega.expand_scatterings: can't happen")
        (fin1 :: fin2 :: fout) []) scatterings

```

```

let expand_decays decays =
  ThoList.flatmap
    (function (fin, fout) →
      Product.fold
        (fun flist acc →
          match flist with
          | fin' :: fout' →
            let fin_fout' = ([fin'], fout') in
            if allowed fin_fout' then
              fin_fout' :: acc
            else
              acc
          | [] → failwith "Omega.expand_decays:␣can't␣happen")
        (fin :: fout) [] decays

```

### 12.2.3 Remove Duplicate Final States

Test if all final states are the same. Identical to *ThoList.homogeneous*  $\circ$  (*List.map snd*).

```

let rec homogeneous_final_state = function
  | [] | [-] → true
  | (_, fs1) :: ((-, fs2) :: _ as rest) →
    if fs1 ≠ fs2 then
      false
    else
      homogeneous_final_state rest

let by_color f1 f2 =
  let c = Color.compare (M.color f1) (M.color f2) in
  if c ≠ 0 then
    c
  else
    compare f1 f2

module Pre_Bundle =
struct
  type elt = t
  type base = elt

  let compare_elt (fin1, fout1) (fin2, fout2) =
    let c = ThoList.compare ~cmp : by_color fin1 fin2 in
    if c ≠ 0 then
      c
    else
      ThoList.compare ~cmp : by_color fout1 fout2

  let compare_base b1 b2 = compare_elt b2 b1
end

module Process_Bundle = Bundle.Dyn (Pre_Bundle)

let to_string (fin, fout) =

```



```

String.concat "□" (List.map M.flavor_to_string fin)
^ "□->□" ^ String.concat "□" (List.map M.flavor_to_string fout)

let fiber_to_string (base, fiber) =
  (to_string base) ^ "□->□" ^
  (String.concat ",□" (List.map to_string fiber)) ^ "]"

let bundle_to_strings list =
  List.map fiber_to_string list

```

Subtract  $n + 1$  from each element in *index\_set* and drop all negative numbers from the result.

```

let shift_left_pred' n index_set =
  List.fold_right
    (fun i acc → let i' = i - n - 1 in if i' < 0 then acc else i' :: acc)
    index_set []

```

Convert 1-based indices for initial and final state to 0-based indices for the final state only. (NB: *ThoList.partitioned\_sort* expects 0-based indices.)

```

let shift_left_pred fin index_sets =
  let n = match fin with [-] → 1 | [-;-] → 2 | _ → 0 in
  List.fold_right
    (fun iset acc →
      match shift_left_pred' n iset with
      | [] → acc
      | iset' → iset' :: acc)
    index_sets []

```

```

module FSet = Set.Make (struct type t = flavor let compare = compare end)

```

Take a list of final states and return a list of sets of flavors appearing in each slot.

```

let flavors = function
| [] → []
| fs :: fs_list →
  List.fold_right (List.map2 FSet.add) fs_list (List.map FSet.singleton fs)

let flavor_sums flavor_sets =
  let _, result =
    List.fold_left
      (fun (n, acc) flavors →
        if FSet.cardinal flavors = 1 then
          (succ n, acc)
        else
          (succ n, (n, flavors) :: acc))
      (0, []) flavor_sets in
  List.rev result

let overlapping s1 s2 =
  ¬ (FSet.is_empty (FSet.inter s1 s2))

let rec merge_overlapping (n, flavors) = function
| [] → [(n, flavors)]

```

```

| (n_list, flavor_set) :: rest →
  if overlapping_flavors flavor_set then
    (n :: n_list, FSet.union flavors flavor_set) :: rest
  else
    (n_list, flavor_set) :: merge_overlapping (n, flavors) rest
let overlapping_flavor_sums flavor_sums =
  List.rev_map
    (fun (n_list, flavor_set) → (n_list, FSet.elements flavor_set))
    (List.fold_right merge_overlapping flavor_sums [])
module ISet = Set.Make (struct type t = int let compare = compare end)
let integer_range n1 n2 =
  let rec integer_range' acc n' =
    if n' < n1 then
      acc
    else
      integer_range' (ISet.add n' acc) (pred n') in
  integer_range' ISet.empty n2
let coarsest_partition = function
| [] → invalid_arg "coarsest_partition: empty process list"
| ((_, fs) :: _) as proc_list →
  let fs_list = List.map snd proc_list in
  let overlaps =
    List.map fst (overlapping_flavor_sums (flavor_sums (flavors fs_list))) in
  let singletons =
    ISet.elements
      (List.fold_right ISet.remove
        (List.concat overlaps) (integer_range 0 (pred (List.length fs)))) in
  List.map (fun n → [n]) singletons @ overlaps
module IPowSet =
  PowSet.Make (struct type t = int let compare = compare let to_string = string_of_int end)
let merge_partitions p_list =
  IPowSet.to_lists (IPowSet.basis (IPowSet.union (List.map IPowSet.of_lists p_list)))
let remove_duplicate_final_states cascade_partition = function
| [] → []
| [process] → [process]
| list →
  if homogeneous_final_state list then
    list
  else
    let partition = coarsest_partition list in
    let pi (fin, fout) =
      let partition' =
        merge_partitions [partition; shift_left_pred fin cascade_partition] in
      (fin, ThoList.partitioned_sort by_color partition' fout) in
    Process_Bundle.base (Process_Bundle.of_list pi list)
type t' = t

```

```

module PSet = Set.Make (struct type t = t' let compare = compare end)

let set list =
  List.fold_right PSet.add list PSet.empty

let diff list1 list2 =
  PSet.elements (PSet.diff (set list1) (set list2))

```



Not functional yet.

```

module Crossing_Projection =
  struct
    type elt = t
    type base = flavor list × int list × t

    let compare_elt (fin1, fout1) (fin2, fout2) =
      let c = ThoList.compare ~cmp : by_color fin1 fin2 in
      if c ≠ 0 then
        c
      else
        ThoList.compare ~cmp : by_color fout1 fout2

    let compare_base (f1, -, -) (f2, -, -) =
      ThoList.compare ~cmp : by_color f1 f2

    let pi (fin, fout as process) =
      let flist, indices =
        ThoList.ariadne_sort ~cmp : by_color (List.map M.conjugate fin @ fout) in
      (flist, indices, process)
  end

module Crossing_Bundle = Bundle.Make (Crossing_Projection)

let crossing processes =
  List.map
    (fun (fin, fout as process) →
      (List.map M.conjugate fin @ fout, [], process))
  processes
end

```

---

# —13—

## HARDCODED MODELS

### 13.1 Interface of Modeltools

#### 13.1.1 Compilation

```
module type Flavor =
sig
  type f
  type c
  val compare : f → f → int
  val conjugate : f → f
end

module type Fusions =
sig
  type t
  type f
  type c
  val fuse2 : t → f → f → (f × c Coupling.t) list
  val fuse3 : t → f → f → f → (f × c Coupling.t) list
  val fuse : t → f list → (f × c Coupling.t) list
  val of_vertices :
    (((f × f × f) × c Coupling.vertex3 × c) list
     × ((f × f × f × f) × c Coupling.vertex4 × c) list
     × (f list × c Coupling.vertexn × c) list) → t
end

module Fusions : functor (F : Flavor) →
  Fusions with type f = F.f and type c = F.c
```

#### 13.1.2 Mutable Models

```
module Mutable : functor (FGC : sig type f and g and c end) →
  Model.Mutable with type flavor = FGC.f and type gauge = FGC.g
  and type constant = FGC.c
```

## 13.2 Implementation of *Modeltools*

```
let rcs_file = RCS.parse "Modeltools" ["Lagrangians"]
{ RCS.revision = "$Revision: 5864$";
  RCS.date = "$Date: 2014-06-02 15:12:47 +0200 (Mon, 02 Jun 2014)$";
  RCS.author = "$Author: ohl$";
  RCS.source
    = "$URL: svn+ssh://jr-reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/s"
```

### 13.2.1 Compilation

Flavors and coupling constants: flavors can be tested for equality and charge conjugation is defined.

```
module type Flavor =
sig
  type f
  type c
  val compare : f → f → int
  val conjugate : f → f
end
```

Compiling fusions from a list of vertices:

```
module type Fusions =
sig
  type t
  type f
  type c
  val fuse2 : t → f → f → (f × c Coupling.t) list
  val fuse3 : t → f → f → f → (f × c Coupling.t) list
  val fuse : t → f list → (f × c Coupling.t) list
  val of_vertices :
    (((f × f × f) × c Coupling.vertex3 × c) list
     × ((f × f × f × f) × c Coupling.vertex4 × c) list
     × (f list × c Coupling.vertexn × c) list) → t
end
```

```
module Fusions (F : Flavor) : Fusions with type f = F.f and type c = F.c =
struct
```

```
  type f = F.f
  type c = F.c

  module F2 =
    struct
      type t = f × f
      let hash = Hashtbl.hash
      let compare (f1, f2) (f1', f2') =
        let c1 = F.compare f1 f1' in
        if c1 ≠ 0 then
          c1
```

```

      else
        F.compare f2 f2'
      let equal f f' = compare f f' = 0
    end
  module F3 =
    struct
      type t = f × f × f
      let hash = Hashtbl.hash
      let compare (f1, f2, f3) (f1', f2', f3') =
        let c1 = F.compare f1 f1' in
        if c1 ≠ 0 then
          c1
        else
          let c2 = F.compare f2 f2' in
          if c2 ≠ 0 then
            c2
          else
            F.compare f3 f3'
        let equal f f' = compare f f' = 0
      end
    module Fn =
      struct
        type t = f list
        let hash = Hashtbl.hash
        let compare f f' = ThoList.compare ~cmp : F.compare f f'
        let equal f f' = compare f f' = 0
      end
    module H2 = Hashtbl.Make (F2)
    module H3 = Hashtbl.Make (F3)
    module Fn = Hashtbl.Make (Fn)
  type t =
    { v3 : (f × c Coupling.t) list H2.t;
      v4 : (f × c Coupling.t) list H3.t;
      vn : (f × c Coupling.t) list Fn.t }
  let fuse2 table f1 f2 =
    try
      H2.find table.v3 (f1, f2)
    with
    | Not_found → []
  let fuse3 table f1 f2 f3 =
    try
      H3.find table.v4 (f1, f2, f3)
    with
    | Not_found → []
  let fusen table f =
    try
      Fn.find table.vn f

```

```

with
| Not_found → []

let fuse table = function
| [] | [-] → invalid_arg "Fusions().fuse"
| [f1; f2] → fuse2 table f1 f2
| [f1; f2; f3] → fuse3 table f1 f2 f3
| f → fusen table f

```

Note that a pair or a triplet can appear more than once (e.g.  $e^+e^- \rightarrow \gamma$  and  $e^+e^- \rightarrow Z$ ). Therefore don't replace the entry, but augment it instead.

```

let add_fusion2 table f1 f2 fusions =
  H2.add table.v3 (f1, f2) (fusions :: fuse2 table f1 f2)

let add_fusion3 table f1 f2 f3 fusions =
  H3.add table.v4 (f1, f2, f3) (fusions :: fuse3 table f1 f2 f3)

let add_fusionn table f fusions =
  Hn.add table.vn f (fusions :: fusen table f)

```



Do we need to take into account the charge conjugation of the coupling constants here?

If some flavors are identical, we must not introduce the same vertex more than once:

```

open Coupling

let permute3 (f1, f2, f3) =
  [ (f1, f2), F.conjugate f3, F12;
    (f2, f1), F.conjugate f3, F21;
    (f2, f3), F.conjugate f1, F23;
    (f3, f2), F.conjugate f1, F32;
    (f3, f1), F.conjugate f2, F31;
    (f1, f3), F.conjugate f2, F13 ]

```

Here we add identical permutations of pairs only once:

```

module F2' = Set.Make (F2)

let add_permute3 table v c set ((f1, f2 as f12), f, p) =
  if F2'.mem f12 set then
    set
  else begin
    add_fusion2 table f1 f2 (f, V3 (v, p, c));
    F2'.add f12 set
  end

let add_vertex3 table (f123, v, c) =
  ignore (List.fold_left (fun set f → add_permute3 table v c set f)
    F2'.empty (permute3 f123))

```



Handling all the cases explicitly is OK for cubic vertices, but starts to become questionable already for quartic couplings. The advantage remains that we can check completeness in *Targets*.

```

let permute4 (f1, f2, f3, f4) =
  [ (f1, f2, f3), F.conjugate f4, F123;
    (f2, f3, f1), F.conjugate f4, F231;
    (f3, f1, f2), F.conjugate f4, F312;
    (f2, f1, f3), F.conjugate f4, F213;
    (f3, f2, f1), F.conjugate f4, F321;
    (f1, f3, f2), F.conjugate f4, F132;
    (f1, f2, f4), F.conjugate f3, F124;
    (f2, f4, f1), F.conjugate f3, F241;
    (f4, f1, f2), F.conjugate f3, F412;
    (f2, f1, f4), F.conjugate f3, F214;
    (f4, f2, f1), F.conjugate f3, F421;
    (f1, f4, f2), F.conjugate f3, F142;
    (f1, f3, f4), F.conjugate f2, F134;
    (f3, f4, f1), F.conjugate f2, F341;
    (f4, f1, f3), F.conjugate f2, F413;
    (f3, f1, f4), F.conjugate f2, F314;
    (f4, f3, f1), F.conjugate f2, F431;
    (f1, f4, f3), F.conjugate f2, F143;
    (f2, f3, f4), F.conjugate f1, F234;
    (f3, f4, f2), F.conjugate f1, F342;
    (f4, f2, f3), F.conjugate f1, F423;
    (f3, f2, f4), F.conjugate f1, F324;
    (f4, f3, f2), F.conjugate f1, F432;
    (f2, f4, f3), F.conjugate f1, F243 ]

```

Add identical permutations of triplets only once:

```

module F3' = Set.Make (F3)

let add_permute4 table v c set ((f1, f2, f3 as f123), f, p) =
  if F3'.mem f123 set then
    set
  else begin
    add_fusion3 table f1 f2 f3 (f, V4 (v, p, c));
    F3'.add f123 set
  end

let add_vertex4 table (f1234, v, c) =
  ignore (List.fold_left (fun set f → add_permute4 table v c set f)
    F3'.empty (permute4 f1234))

let of_vertices (vlist3, vlist4, vlistn) =
  match vlistn with
  | [] →
    let table =
      { v3 = H2.create 37; v4 = H3.create 37; vn = Hn.create 37 } in
    List.iter (add_vertex3 table) vlist3;
    List.iter (add_vertex4 table) vlist4;
    table
  | _ → failwith "Models.Fusions.of_vertices:␣incomplete"
end

```



13.2.2 *Mutable Models*

```

module Mutable (FGC : sig type f and g and c end) =
  struct
    type flavor = FGC.f
    type gauge = FGC.g
    type constant = FGC.c

    let options = Options.empty

    module Ch = Charges.Null
    let charges _ = ()

    exception Uninitialized of string
    let unitialized name =
      raise (Uninitialized name)

```

Note that *lookup* works, by the magic of currying, for any arity. But we need to supply one argument to delay evaluation.

Also note that the references are *not* shared among results of functor applications. Simple module renaming causes sharing.

```

  let declare template =
    let reference = ref template in
    let update fct = reference := fct
    and lookup arg = !reference arg in
    (update, lookup)

  let set_color, color =
    declare (fun f → unitialized "color")
  let set_pdg, pdg =
    declare (fun f → unitialized "pdg")
  let set_lorentz, lorentz =
    declare (fun f → unitialized "lorentz")
  let set_propagator, propagator =
    declare (fun f → unitialized "propagator")
  let set_width, width =
    declare (fun f → unitialized "width")
  let set_goldstone, goldstone =
    declare (fun f → unitialized "goldstone")
  let set_conjugate, conjugate =
    declare (fun f → unitialized "conjugate")
  let set_fermion, fermion =
    declare (fun f → unitialized "fermion")
  let set_max_degree, max_degree =
    declare (fun () → unitialized "max_degree")
  let set_vertices, vertices =
    declare (fun () → unitialized "vertices")
  let set_fuse2, fuse2 =
    declare (fun f1 f2 → unitialized "fuse2")
  let set_fuse3, fuse3 =
    declare (fun f1 f2 f3 → unitialized "fuse3")
  let set_fuse, fuse =

```

```

    declare (fun f → uninitialized "fuse")
let set_flavors, flavors =
    declare (fun () → [])
let set_external_flavors, external_flavors =
    declare (fun () → [("unitialized", [])])
let set_parameters, parameters =
    declare (fun f → uninitialized "parameters")
let set_flavor_of_string, flavor_of_string =
    declare (fun f → uninitialized "flavor_of_string")
let set_flavor_to_string, flavor_to_string =
    declare (fun f → uninitialized "flavor_to_string")
let set_flavor_to_TeX, flavor_to_TeX =
    declare (fun f → uninitialized "flavor_to_TeX")
let set_flavor_symbol, flavor_symbol =
    declare (fun f → uninitialized "flavor_symbol")
let set_gauge_symbol, gauge_symbol =
    declare (fun f → uninitialized "gauge_symbol")
let set_mass_symbol, mass_symbol =
    declare (fun f → uninitialized "mass_symbol")
let set_width_symbol, width_symbol =
    declare (fun f → uninitialized "width_symbol")
let set_constant_symbol, constant_symbol =
    declare (fun f → uninitialized "constant_symbol")

let setup ~color ~pdg ~lorentz ~propagator ~width ~goldstone
    ~conjugate ~fermion ~max_degree ~vertices
    ~fuse : (fuse2, fuse3, fusen)
    ~flavors ~parameters ~flavor_of_string ~flavor_to_string
    ~flavor_to_TeX ~flavor_symbol
    ~gauge_symbol ~mass_symbol ~width_symbol ~constant_symbol =
set_color color;
set_pdg pdg;
set_lorentz lorentz;
set_propagator propagator;
set_width width;
set_goldstone goldstone;
set_conjugate conjugate;
set_fermion fermion;
set_max_degree (fun () → max_degree);
set_vertices vertices;
set_fuse2 fuse2;
set_fuse3 fuse3;
set_fuse fusen;
set_external_flavors (fun f → flavors);
let flavors = ThoList.flatmap snd flavors in
set_flavors (fun f → flavors);
set_parameters parameters;
set_flavor_of_string flavor_of_string;
set_flavor_to_string flavor_to_string;
set_flavor_to_TeX flavor_to_TeX;

```

```

    set_flavor_symbol flavor_symbol;
    set_gauge_symbol gauge_symbol;
    set_mass_symbol mass_symbol;
    set_width_symbol width_symbol;
    set_constant_symbol constant_symbol

let rcs = RCS.rename rcs_file "Models.Mutable" ["Mutable_Model"]
end

```

### 13.3 Interface of *Modellib-SM*

#### 13.3.1 Hardcoded Models

```

module Phi3 : Model.T with module Ch = Charges.Null
module Phi4 : Model.T with module Ch = Charges.Null
module QED : Model.T with module Ch = Charges.ZZ
module QCD : Model.T with module Ch = Charges.ZZ

module type SM_flags =
sig
  val higgs_triangle : bool (*  $H\gamma\gamma$ ,  $Hg\gamma$  and  $Hgg$ couplings*)
  val higgs_hmm : bool
  val triple_anom : bool
  val quartic_anom : bool
  val higgs_anom : bool
  val k_matrix : bool
  val ckm_present : bool
  val top_anom : bool
  val top_anom_4f : bool
  val tt_threshold : bool
end

module SM_no_anomalous : SM_flags
module SM_anomalous : SM_flags
module SM_k_matrix : SM_flags
module SM_no_anomalous_ckm : SM_flags
module SM_anomalous_ckm : SM_flags
module SM_Higgs : SM_flags
module SM_anomalous_top : SM_flags
module SM_tt_threshold : SM_flags

module SM : functor (F : SM_flags) → Model.Gauge with module Ch = Charges.QQ
module SM_Rxi : Model.T with module Ch = Charges.QQ
module Groves : functor (M : Model.Gauge) → Model.Gauge with module Ch = M.Ch
module SM_clones : Model.Gauge with module Ch = Charges.QQ

```

### 13.4 Implementation of *Modellib-SM*

```

let rcs_file = RCS.parse "Modellib-SM" ["Lagrangians"]

```

```
{ RCS.revision = "$Revision: 6275$";
  RCS.date = "$Date: 2014-11-17 18:02:10 +0100 (Mon, 17 Nov 2014)$";
  RCS.author = "$Author: jr-reuter$";
  RCS.source
    = "$URL: svn+ssh://jr-reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/sr
```

### 13.4.1 $\phi^3$

```
module Phi3 =
struct
  let rcs = RCS.rename rcs_file "Modellib.Phi3"
    ["phi**3_with_a_single_flavor"]

  open Coupling

  let options = Options.empty

  type flavor = Phi
  let external_flavors () = [ "", [Phi] ]
  let flavors () = ThoList.flatmap snd (external_flavors ())

  type gauge = unit
  type constant = G

  type orders = unit
  let orders = function
    | _ → ()

  let lorentz _ = Scalar
  let color _ = Color.Singlet
  let propagator _ = Prop.Scalar
  let width _ = Timelike
  let goldstone _ = None
  let conjugate f = f
  let fermion _ = 0

  module Ch = Charges.Null
  let charges _ = ()

  module F = Modeltools.Fusions (struct
    type f = flavor
    type c = constant
    let compare = compare
    let conjugate = conjugate
  end)

  let vertices () =
    [(Phi, Phi, Phi), Scalar_Scalar_Scalar 1, G], [], []

  let table = F.of_vertices (vertices ())
  let fuse2 = F.fuse2 table
  let fuse3 = F.fuse3 table
  let fuse = F.fuse table
  let max_degree () = 3
```

```

let parameters () = { input = [G, 1.0]; derived = []; derived_arrays = [] }
let flavor_of_string = function
| "p" → Phi
| _ → invalid_arg "Modellib.Phi3.flavor_of_string"
let flavor_to_string Phi = "phi"
let flavor_to_TeX Phi = "\\phi"
let flavor_symbol Phi = "phi"
let gauge_symbol () =
  failwith "Modellib.Phi3.gauge_symbol: internal error"
let pdg _ = 1
let mass_symbol _ = "m"
let width_symbol _ = "w"
let constant_symbol G = "g"
end

```

$$13.4.2 \quad \lambda_3 \phi^3 + \lambda_4 \phi^4$$

```

module Phi4 =
struct
  let rcs = RCS.rename rcs_file "Modellib.Phi4"
    ["phi**4" with a single flavor"]
  open Coupling
  let options = Options.empty
  type flavor = Phi
  let external_flavors () = [ "", [Phi] ]
  let flavors () = ThoList.flatmap snd (external_flavors ())
  type gauge = unit
  type constant = G3 | G4
  type orders = unit
  let orders = function
  | _ → ()
  let lorentz _ = Scalar
  let color _ = Color.Singlet
  let propagator _ = Prop.Scalar
  let width _ = Timelike
  let goldstone _ = None
  let conjugate f = f
  let fermion _ = 0
  module Ch = Charges.Null
  let charges _ = ()
  module F = Modeltools.Fusions (struct
    type f = flavor
    type c = constant

```

```

    let compare = compare
    let conjugate = conjugate
end)

let vertices () =
  [(Phi, Phi, Phi), Scalar_Scalar_Scalar 1, G3],
  [(Phi, Phi, Phi, Phi), Scalar4 1, G4], []

let fuse2 _ = failwith "Modellib.Phi4.fuse2"
let fuse3 _ = failwith "Modellib.Phi4.fuse3"
let fuse = function
  | [] | [-] → invalid_arg "Modellib.Phi4.fuse"
  | [-; -] → [Phi, V3 (Scalar_Scalar_Scalar 1, F23, G3)]
  | [-; -; -] → [Phi, V4 (Scalar4 1, F234, G4)]
  | _ → []
let max_degree () = 4
let parameters () =
  { input = [G3, 1.0; G4, 1.0]; derived = []; derived_arrays = [] }

let flavor_of_string = function
  | "p" → Phi
  | _ → invalid_arg "Modellib.Phi4.flavor_of_string"

let flavor_to_string Phi = "phi"
let flavor_to_TeX Phi = "\\phi"
let flavor_symbol Phi = "phi"

let gauge_symbol () =
  failwith "Modellib.Phi4.gauge_symbol: internal error"

let pdg _ = 1
let mass_symbol _ = "m"
let width_symbol _ = "w"
let constant_symbol = function
  | G3 → "g3"
  | G4 → "g4"

end

```

### 13.4.3 Quantum Electro Dynamics

```

module QED =
struct
  let rcs = RCS.rename rcs_file "Modellib.QED"
    ["QED_with_two_leptonic_flavors"]

  open Coupling

  let options = Options.empty

  type flavor =
    | Electron | Positron
    | Muon | AntiMuon
    | Tau | AntiTau

```

```

    | Photon
let external_flavors () =
  [ "Leptons", [Electron; Positron; Muon; AntiMuon; Tau; AntiTau];
    "Gauge_Bosons", [Photon] ]
let flavors () = ThoList.flatmap snd (external_flavors ())

type gauge = unit
type constant = Q

type orders = unit
let orders = function
  | _ → ()

let lorentz = function
  | Electron | Muon | Tau → Spinor
  | Positron | AntiMuon | AntiTau → ConjSpinor
  | Photon → Vector

let color _ = Color.Singlet

let propagator = function
  | Electron | Muon | Tau → Prop_Spinor
  | Positron | AntiMuon | AntiTau → Prop_ConjSpinor
  | Photon → Prop_Feynman

let width _ = Timelike

let goldstone _ =
  None

let conjugate = function
  | Electron → Positron | Positron → Electron
  | Muon → AntiMuon | AntiMuon → Muon
  | Tau → AntiTau | AntiTau → Tau
  | Photon → Photon

let fermion = function
  | Electron | Muon | Tau → 1
  | Positron | AntiMuon | AntiTau → -1
  | Photon → 0

```

Taking generation numbers makes electric charge redundant.

```

module Ch = Charges.ZZ
let charges = function
  | Electron → [1; 0; 0]
  | Muon → [0; 1; 0]
  | Tau → [0; 0; 1]
  | Positron → [-1; 0; 0]
  | AntiMuon → [0; -1; 0]
  | AntiTau → [0; 0; -1]
  | Photon → [0; 0; 0]

module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant

```

```

    let compare = compare
    let conjugate = conjugate
end)

let vertices () =
  [(Positron, Photon, Electron), FBF (1, Psibar, V, Psi), Q;
   (AntiMuon, Photon, Muon), FBF (1, Psibar, V, Psi), Q;
   (AntiTau, Photon, Tau), FBF (1, Psibar, V, Psi), Q], [], []

let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 3

let parameters () = { input = [Q, 1.0]; derived = []; derived_arrays = [] }

let flavor_of_string = function
| "e-" → Electron | "e+" → Positron
| "m-" → Muon | "m+" → AntiMuon
| "t-" → Tau | "t+" → AntiTau
| "A" → Photon
| _ → invalid_arg "Modellib.QED.flavor_of_string"

let flavor_to_string = function
| Electron → "e-" | Positron → "e+"
| Muon → "m-" | AntiMuon → "m+"
| Tau → "t-" | AntiTau → "t+"
| Photon → "A"

let flavor_to_TeX = function
| Electron → "e^-" | Positron → "e^+"
| Muon → "\\mu^-" | AntiMuon → "\\mu^+"
| Tau → "\\tau^-" | AntiTau → "\\tau^+"
| Photon → "\\gamma"

let flavor_symbol = function
| Electron → "ele" | Positron → "pos"
| Muon → "muo" | AntiMuon → "amu"
| Tau → "tau" | AntiTau → "ata"
| Photon → "gam"

let gauge_symbol () =
  failwith "Modellib.QED.gauge_symbol: internal error"

let pdg = function
| Electron → 11 | Positron → -11
| Muon → 13 | AntiMuon → -13
| Tau → 15 | AntiTau → -15
| Photon → 22

let mass_symbol f =
  "mass(" ^ string_of_int (abs (pdg f)) ^ ")"

let width_symbol f =
  "width(" ^ string_of_int (abs (pdg f)) ^ ")"

```



```

    let constant_symbol = function
    | Q → "qllep"
end

```

#### 13.4.4 Quantum Chromo Dynamics

```

module QCD =
struct
  let rcs = RCS.rename rcs_file "Modellib.QCD"
    ["QCD"]

  open Coupling

  let options = Options.empty

  type flavor =
    | U | Ubar | D | Dbar
    | C | Cbar | S | Sbar
    | T | Tbar | B | Bbar
    | Gl

  let external_flavors () =
    ["Quarks", [U; D; C; S; T; B; Ubar; Dbar; Cbar; Sbar; Tbar; Bbar];
     "Gauge_Bosons", [Gl]]

  let flavors () = ThoList.flatmap snd (external_flavors ())

  type gauge = unit
  type constant = Gs | G2 | I_Gs

  type orders = unit
  let orders = function
    | _ → ()

  let lorentz = function
    | U | D | C | S | T | B → Spinor
    | Ubar | Dbar | Cbar | Sbar | Tbar | Bbar → ConjSpinor
    | Gl → Vector

  let color = function
    | U | D | C | S | T | B → Color.SUN 3
    | Ubar | Dbar | Cbar | Sbar | Tbar | Bbar → Color.SUN (-3)
    | Gl → Color.AdjSUN 3

  let propagator = function
    | U | D | C | S | T | B → Prop_Spinor
    | Ubar | Dbar | Cbar | Sbar | Tbar | Bbar → Prop_ConjSpinor
    | Gl → Prop_Feynman

  let width _ = Timelike

  let goldstone _ =
    None

  let conjugate = function
    | U → Ubar

```

```

|  $D \rightarrow Dbar$ 
|  $C \rightarrow Cbar$ 
|  $S \rightarrow Sbar$ 
|  $T \rightarrow Tbar$ 
|  $B \rightarrow Bbar$ 
|  $Ubar \rightarrow U$ 
|  $Dbar \rightarrow D$ 
|  $Cbar \rightarrow C$ 
|  $Sbar \rightarrow S$ 
|  $Tbar \rightarrow T$ 
|  $Bbar \rightarrow B$ 
|  $Gl \rightarrow Gl$ 

let fermion = function
|  $U \mid D \mid C \mid S \mid T \mid B \rightarrow 1$ 
|  $Ubar \mid Dbar \mid Cbar \mid Sbar \mid Tbar \mid Bbar \rightarrow -1$ 
|  $Gl \rightarrow 0$ 

module Ch = Charges.ZZ
let charges = function
|  $D \rightarrow [1; 0; 0; 0; 0; 0]$ 
|  $U \rightarrow [0; 1; 0; 0; 0; 0]$ 
|  $S \rightarrow [0; 0; 1; 0; 0; 0]$ 
|  $C \rightarrow [0; 0; 0; 1; 0; 0]$ 
|  $B \rightarrow [0; 0; 0; 0; 1; 0]$ 
|  $T \rightarrow [0; 0; 0; 0; 0; 1]$ 
|  $Dbar \rightarrow [-1; 0; 0; 0; 0; 0]$ 
|  $Ubar \rightarrow [0; -1; 0; 0; 0; 0]$ 
|  $Sbar \rightarrow [0; 0; -1; 0; 0; 0]$ 
|  $Cbar \rightarrow [0; 0; 0; -1; 0; 0]$ 
|  $Bbar \rightarrow [0; 0; 0; 0; -1; 0]$ 
|  $Tbar \rightarrow [0; 0; 0; 0; 0; -1]$ 
|  $Gl \rightarrow [0; 0; 0; 0; 0; 0]$ 

module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)

```

This is compatible with CD+.

```

let color_current =
[ ((Dbar, Gl, D), FBF ((-1), Psibar, V, Psi), Gs);
  ((Ubar, Gl, U), FBF ((-1), Psibar, V, Psi), Gs);
  ((Cbar, Gl, C), FBF ((-1), Psibar, V, Psi), Gs);
  ((Sbar, Gl, S), FBF ((-1), Psibar, V, Psi), Gs);
  ((Tbar, Gl, T), FBF ((-1), Psibar, V, Psi), Gs);
  ((Bbar, Gl, B), FBF ((-1), Psibar, V, Psi), Gs)]

let three_gluon =
[ ((Gl, Gl, Gl), Gauge_Gauge_Gauge 1, I_Gs)]

```

---

```

let gauge4 = Vector4 [(2, C_13_42); (-1, C_12_34); (-1, C_14_23)]
let four_gluon =
  [ ((Gl, Gl, Gl, Gl), gauge4, G2)]
let vertices3 =
  (color_current @ three_gluon)
let vertices4 = four_gluon
let vertices () =
  (vertices3, vertices4, [])
let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 4
let parameters () = { input = [Gs, 1.0]; derived = []; derived_arrays = [] }
let flavor_of_string = function
| "u" → U
| "d" → D
| "c" → C
| "s" → S
| "t" → T
| "b" → B
| "ubar" → Ubar
| "dbar" → Dbar
| "cbar" → Cbar
| "sbar" → Sbar
| "tbar" → Tbar
| "bbar" → Bbar
| "gl" → Gl
| _ → invalid_arg "Modellib.QCD.flavor_of_string"
let flavor_to_string = function
| U → "u"
| Ubar → "ubar"
| D → "d"
| Dbar → "dbar"
| C → "c"
| Cbar → "cbar"
| S → "s"
| Sbar → "sbar"
| T → "t"
| Tbar → "tbar"
| B → "b"
| Bbar → "bbar"
| Gl → "gl"
let flavor_to_TeX = function
| U → "u"
| Ubar → "\\bar{u}"

```

```

|  $D \rightarrow "d"$ 
|  $Dbar \rightarrow "\\bar{d}"$ 
|  $C \rightarrow "c"$ 
|  $Cbar \rightarrow "\\bar{c}"$ 
|  $S \rightarrow "s"$ 
|  $Sbar \rightarrow "\\bar{s}"$ 
|  $T \rightarrow "t"$ 
|  $Tbar \rightarrow "\\bar{t}"$ 
|  $B \rightarrow "b"$ 
|  $Bbar \rightarrow "\\bar{b}"$ 
|  $G_l \rightarrow "g"$ 

let flavor_symbol = function
|  $U \rightarrow "u"$ 
|  $Ubar \rightarrow "ubar"$ 
|  $D \rightarrow "d"$ 
|  $Dbar \rightarrow "dbar"$ 
|  $C \rightarrow "c"$ 
|  $Cbar \rightarrow "cbar"$ 
|  $S \rightarrow "s"$ 
|  $Sbar \rightarrow "sbar"$ 
|  $T \rightarrow "t"$ 
|  $Tbar \rightarrow "tbar"$ 
|  $B \rightarrow "b"$ 
|  $Bbar \rightarrow "bbar"$ 
|  $G_l \rightarrow "gl"$ 

let gauge_symbol () =
  failwith "Modellib.QCD.gauge_symbol:_internal_error"

let pdg = function
|  $D \rightarrow 1$  |  $Dbar \rightarrow -1$ 
|  $U \rightarrow 2$  |  $Ubar \rightarrow -2$ 
|  $S \rightarrow 3$  |  $Sbar \rightarrow -3$ 
|  $C \rightarrow 4$  |  $Cbar \rightarrow -4$ 
|  $B \rightarrow 5$  |  $Bbar \rightarrow -5$ 
|  $T \rightarrow 6$  |  $Tbar \rightarrow -6$ 
|  $G_l \rightarrow 21$ 

let mass_symbol f =
  "mass(" ^ string_of_int (abs (pdg f)) ^ ")"

let width_symbol f =
  "width(" ^ string_of_int (abs (pdg f)) ^ ")"

let constant_symbol = function
|  $I_Gs \rightarrow "(0,1)*gs"$ 
|  $G_s \rightarrow "gs"$ 
|  $G_2 \rightarrow "gs**2"$ 

end

```

### 13.4.5 Complete Minimal Standard Model (Unitarity Gauge)

```

module type SM_flags =
  sig
    val higgs_triangle : bool (*  $H\gamma\gamma$ ,  $Hg\gamma$  and  $Hgg$  couplings *)
    val higgs_hmm : bool
    val triple_anom : bool
    val quartic_anom : bool
    val higgs_anom : bool
    val k_matrix : bool
    val ckm_present : bool
    val top_anom : bool
    val top_anom_4f : bool
    val tt_threshold : bool
  end

module SM_no_anomalous : SM_flags =
  struct
    let higgs_triangle = false
    let higgs_hmm = false
    let triple_anom = false
    let quartic_anom = false
    let higgs_anom = false
    let k_matrix = false
    let ckm_present = false
    let top_anom = false
    let top_anom_4f = false
    let tt_threshold = false
  end

module SM_no_anomalous_ckm : SM_flags =
  struct
    let higgs_triangle = false
    let higgs_hmm = false
    let triple_anom = false
    let quartic_anom = false
    let higgs_anom = false
    let k_matrix = false
    let ckm_present = true
    let top_anom = false
    let top_anom_4f = false
    let tt_threshold = false
  end

module SM_anomalous : SM_flags =
  struct
    let higgs_triangle = false
    let higgs_hmm = false
    let triple_anom = true
    let quartic_anom = true
    let higgs_anom = true
  end

```

```

    let k_matrix = false
    let ckm_present = false
    let top_anom = false
    let top_anom_4f = false
    let tt_threshold = false
end

module SM_anomalous_ckm : SM_flags =
struct
    let higgs_triangle = false
    let higgs_hmm = false
    let triple_anom = true
    let quartic_anom = true
    let higgs_anom = true
    let k_matrix = false
    let ckm_present = true
    let top_anom = false
    let top_anom_4f = false
    let tt_threshold = false
end

module SM_k_matrix : SM_flags =
struct
    let higgs_triangle = false
    let higgs_hmm = false
    let triple_anom = false
    let quartic_anom = true
    let higgs_anom = false
    let k_matrix = true
    let ckm_present = false
    let top_anom = false
    let top_anom_4f = false
    let tt_threshold = false
end

module SM_Higgs : SM_flags =
struct
    let higgs_triangle = true
    let higgs_hmm = true
    let triple_anom = false
    let quartic_anom = false
    let higgs_anom = false
    let k_matrix = false
    let ckm_present = false
    let top_anom = false
    let top_anom_4f = false
    let tt_threshold = false
end

module SM_anomalous_top : SM_flags =
struct
    let higgs_triangle = false

```

```

    let higgs_hmm = false
    let triple_anom = false
    let quartic_anom = false
    let higgs_anom = false
    let k_matrix = false
    let ckm_present = false
    let top_anom = true
    let top_anom_4f = true
    let tt_threshold = false
end

module SM_tt_threshold : SM_flags =
  struct
    let higgs_triangle = false
    let higgs_hmm = false
    let triple_anom = false
    let quartic_anom = false
    let higgs_anom = false
    let k_matrix = false
    let ckm_present = false
    let top_anom = false
    let top_anom_4f = false
    let tt_threshold = true
  end

```

### 13.4.6 Complete Minimal Standard Model (including some extensions)

```

module SM (Flags : SM_flags) =
  struct
    let rcs = RCS.rename rcs_file "Modellib.SM"
    [ "minimal_electroweak_standard_model_in_unitarity_gauge" ]

    open Coupling

    let default_width = ref Timelike
    let use_fudged_width = ref false

    let options = Options.create
    [ "constant_width", Arg.Unit (fun () → default_width := Constant),
      "use_constant_width_(also_in_t-channel)",
      "fudged_width", Arg.Set use_fudged_width,
      "use_fudge_factor_for_charge_particle_width",
      "custom_width", Arg.String (fun f → default_width := Custom f),
      "use_custom_width",
      "cancel_widths", Arg.Unit (fun () → default_width := Vanishing),
      "use_vanishing_width" ]

    type f_aux_top = TTGG | TBWA | TBWZ | TTWW | BBWW |
      QGUG | QBUB | QW | DL | DR |
      QUQD1L | QUQD1R | QUQD8L | QUQD8R
  end

```

```

type matter_field = L of int | N of int | U of int | D of int
type gauge_boson = Ga | Wp | Wm | Z | Gl
type other = Phip | Phim | Phi0 | H
              | Aux_top of int×int×int×bool×f_aux_top type flavor = M of matter_field |
G of gauge_boson | O of other

let matter_field f = M f
let gauge_boson f = G f
let other f = O f

type field =
  | Matter of matter_field
  | Gauge of gauge_boson
  | Other of other

let field = function
  | M f → Matter f
  | G f → Gauge f
  | O f → Other f

type gauge = unit

let gauge_symbol () =
  failwith "Modellib.SM.gauge_symbol: internal error"

let family n = List.map matter_field [ L n; N n; U n; D n ]

let rec aux_top_flavors (f, l, co, ch) = List.append
  ( List.map other [ Aux_top(l, co, ch/2, true, f); Aux_top(l, co, ch/2, false, f) ] )
  ( if ch > 1 then List.append
    ( List.map other [ Aux_top(l, co, -ch/2, true, f); Aux_top(l, co, -ch/2, false, f) ] )
    ( aux_top_flavors (f, l, co, (ch - 2)) )
    else [] )

let external_flavors () =
  [ "1st_Generation", ThoList.flatmap family [1; -1];
    "2nd_Generation", ThoList.flatmap family [2; -2];
    "3rd_Generation", ThoList.flatmap family [3; -3];
    "Gauge_Bosons", List.map gauge_boson [Ga; Z; Wp; Wm; Gl];
    "Higgs", List.map other [H];
    "Goldstone_Bosons", List.map other [Phip; Phim; Phi0] ]

let flavors () = List.append
  ( ThoList.flatmap snd (external_flavors ()) )
  ( ThoList.flatmap aux_top_flavors
    [ (TTGG, 2, 1, 1); (TBWA, 2, 0, 2); (TBWZ, 2, 0, 2); (TTWW, 2, 0, 1); (BBWW, 2, 0, 1);
      (QGUG, 1, 1, 1); (QBUB, 1, 0, 1); (QW, 1, 0, 3); (DL, 0, 0, 3); (DR, 0, 0, 3);
      (QUQD1L, 0, 0, 3); (QUQD1R, 0, 0, 3); (QUQD8L, 0, 1, 3); (QUQD8R, 0, 1, 3) ] )

let spinor n =
  if n ≥ 0 then
    Spinor
  else
    ConjSpinor

```



```

let lorentz_aux = function
| 2 → Tensor_1
| 1 → Vector
| 0 → Scalar
| _ → invalid_arg ("SM.lorentz_aux: wrong value")

let lorentz = function
| M f →
  begin match f with
  | L n → spinor n | N n → spinor n
  | U n → spinor n | D n → spinor n
  end
| G f →
  begin match f with
  | Ga | Gl → Vector
  | Wp | Wm | Z → Massive_Vector
  end
| O f →
  begin match f with
  | Aux_top (l, -, -, -, -) → lorentz_aux l
  | _ → Scalar
  end

let color = function
| M (U n) → Color.SUN (if n > 0 then 3 else -3)
| M (D n) → Color.SUN (if n > 0 then 3 else -3)
| G Gl → Color.AdjSUN 3
| O (Aux_top (_, co, -, -, -)) → if co ≡ 0 then Color.Singlet else Color.AdjSUN 3
| _ → Color.Singlet

let prop_spinor n =
  if n ≥ 0 then
    Prop_Spinor
  else
    Prop_ConjSpinor

let prop_aux = function
| 2 → Aux_Tensor_1
| 1 → Aux_Vector
| 0 → Aux_Scalar
| _ → invalid_arg ("SM.prop_aux: wrong value")

let propagator = function
| M f →
  begin match f with
  | L n → prop_spinor n | N n → prop_spinor n
  | U n → prop_spinor n | D n → prop_spinor n
  end
| G f →
  begin match f with
  | Ga | Gl → Prop_Feynman
  | Wp | Wm | Z → Prop_Unitarity
  end

```

```

|  $O f \rightarrow$ 
  begin match  $f$  with
  |  $Phip$  |  $Phim$  |  $Phi0 \rightarrow Only\_Insertion$ 
  |  $H \rightarrow Prop\_Scalar$ 
  |  $Aux\_top (l, -, -, -, -) \rightarrow prop\_aux l$ 
  end

```

Optionally, ask for the fudge factor treatment for the widths of charged particles.  
Currently, this only applies to  $W^\pm$  and top.

```

let width  $f =$ 
  if !use_fudged_width then
    match  $f$  with
    |  $G Wp$  |  $G Wm$  |  $M (U 3)$  |  $M (U (-3)) \rightarrow Fudged$ 
    |  $- \rightarrow !default\_width$ 
  else
    !default_width
let goldstone = function
|  $G f \rightarrow$ 
  begin match  $f$  with
  |  $Wp \rightarrow Some (O Phip, Coupling.Const 1)$ 
  |  $Wm \rightarrow Some (O Phim, Coupling.Const 1)$ 
  |  $Z \rightarrow Some (O Phi0, Coupling.Const 1)$ 
  |  $- \rightarrow None$ 
  end
|  $- \rightarrow None$ 
let conjugate = function
|  $M f \rightarrow$ 
   $M$  (begin match  $f$  with
  |  $L n \rightarrow L (-n)$  |  $N n \rightarrow N (-n)$ 
  |  $U n \rightarrow U (-n)$  |  $D n \rightarrow D (-n)$ 
  end)
|  $G f \rightarrow$ 
   $G$  (begin match  $f$  with
  |  $Gl \rightarrow Gl$  |  $Ga \rightarrow Ga$  |  $Z \rightarrow Z$ 
  |  $Wp \rightarrow Wm$  |  $Wm \rightarrow Wp$ 
  end)
|  $O f \rightarrow$ 
   $O$  (begin match  $f$  with
  |  $Phip \rightarrow Phim$  |  $Phim \rightarrow Phip$  |  $Phi0 \rightarrow Phi0$ 
  |  $H \rightarrow H$ 
  |  $Aux\_top (l, co, ch, n, f) \rightarrow Aux\_top (l, co, (-ch), (\neg n), f)$ 
  end)
let fermion = function
|  $M f \rightarrow$ 
  begin match  $f$  with
  |  $L n \rightarrow$  if  $n > 0$  then 1 else -1
  |  $N n \rightarrow$  if  $n > 0$  then 1 else -1
  |  $U n \rightarrow$  if  $n > 0$  then 1 else -1
  |  $D n \rightarrow$  if  $n > 0$  then 1 else -1

```

```

      end
    |  $G f \rightarrow$ 
      begin match  $f$  with
      |  $Gl$  |  $Ga$  |  $Z$  |  $Wp$  |  $Wm \rightarrow 0$ 
      end
    |  $O_- \rightarrow 0$ 

```

Electrical charge, lepton number, baryon number. We could avoid the rationals altogether by multiplying the first and last by 3 ...

```

module  $Ch = Charges.QQ$ 
let ( // ) = Algebra.Small_Rational.make

let generation' = function
| 1  $\rightarrow$  [ 1//1; 0//1; 0//1]
| 2  $\rightarrow$  [ 0//1; 1//1; 0//1]
| 3  $\rightarrow$  [ 0//1; 0//1; 1//1]
| -1  $\rightarrow$  [-1//1; 0//1; 0//1]
| -2  $\rightarrow$  [ 0//1; -1//1; 0//1]
| -3  $\rightarrow$  [ 0//1; 0//1; -1//1]
|  $n \rightarrow invalid\_arg ("SM.generation':\_{}" ^ string\_of\_int n)$ 

let generation  $f =$ 
  if  $Flags.ckm\_present$  then
    []
  else
    match  $f$  with
    |  $M (L n$  |  $N n$  |  $U n$  |  $D n) \rightarrow generation' n$ 
    |  $G_-$  |  $O_- \rightarrow [0//1; 0//1; 0//1]$ 

let charge = function
|  $M f \rightarrow$ 
  begin match  $f$  with
  |  $L n \rightarrow$  if  $n > 0$  then -1//1 else 1//1
  |  $N n \rightarrow 0//1$ 
  |  $U n \rightarrow$  if  $n > 0$  then 2//3 else -2//3
  |  $D n \rightarrow$  if  $n > 0$  then -1//3 else 1//3
  end
|  $G f \rightarrow$ 
  begin match  $f$  with
  |  $Gl$  |  $Ga$  |  $Z \rightarrow 0//1$ 
  |  $Wp \rightarrow 1//1$ 
  |  $Wm \rightarrow -1//1$ 
  end
|  $O f \rightarrow$ 
  begin match  $f$  with
  |  $H$  |  $Phi0 \rightarrow 0//1$ 
  |  $Phip \rightarrow 1//1$ 
  |  $Phim \rightarrow -1//1$ 
  |  $Aux\_top (-, -, ch, -, -) \rightarrow ch//1$ 
  end

let lepton = function

```

```

| M f →
  begin match f with
  | L n | N n → if n > 0 then 1//1 else -1//1
  | U _ | D _ → 0//1
  end
| G _ | O _ → 0//1
let baryon = function
| M f →
  begin match f with
  | L _ | N _ → 0//1
  | U n | D n → if n > 0 then 1//1 else -1//1
  end
| G _ | O _ → 0//1
let charges f =
[ charge f; lepton f; baryon f ] @ generation f
type constant =
| Unit | Half | Pi | Alpha_QED | Sin2thw
| Sinthw | Costhw | E | G_weak | I_G_weak | Vev
| Q_lepton | Q_up | Q_down | G_CC | G_CCQ of int×int
| G_NC_neutrino | G_NC_lepton | G_NC_up | G_NC_down
| G_TVA_ttA | G_TVA_bbA
| G_VLR_ttZ | G_TVA_ttZ | G_TVA_bbZ
| VA_ILC_ttA | VA_ILC_ttZ
| G_VLR_btW | G_VLR_tbW
| G_TLR_btW | G_TRL_tbW
| G_TLR_btWZ | G_TRL_tbWZ
| G_TLR_btWA | G_TRL_tbWA
| G_TVA_ttWW | G_TVA_bbWW
| G_TVA_ttG | G_TVA_ttGG
| G_SP_ttH
| G_VLR_qGuG | G_VLR_qBuB
| G_VLR_qBuB_u | G_VLR_qBuB_d | G_VLR_qBuB_e | G_VL_qBuB_n
| G_VL_qW | G_VL_qW_u | G_VL_qW_d
| G_SL_DttR | G_SR_DttR | G_SL_DttL | G_SLR_DbtR |
G_SL_DbtL
| C_quqd1R_bt | C_quqd1R_tb | C_quqd1L_bt | C_quqd1L_tb
| C_quqd8R_bt | C_quqd8R_tb | C_quqd8L_bt | C_quqd8L_tb
| I_Q_W | I_G_ZWW
| G_WWWW | G_ZZWW | G_AZWW | G_AAWW
| I_G1_AWW | I_G1_ZWW
| I_G1_plus_kappa_plus_G4_AWW
| I_G1_plus_kappa_plus_G4_ZWW
| I_G1_plus_kappa_minus_G4_AWW
| I_G1_plus_kappa_minus_G4_ZWW
| I_G1_minus_kappa_plus_G4_AWW
| I_G1_minus_kappa_plus_G4_ZWW
| I_G1_minus_kappa_minus_G4_AWW
| I_G1_minus_kappa_minus_G4_ZWW
| I_lambda_AWW | I_lambda_ZWW

```

```

| G5_AWW | G5_ZWW
| I_kappa5_AWW | I_kappa5_ZWW
| I_lambda5_AWW | I_lambda5_ZWW
| Alpha_WWWW0 | Alpha_ZZWW1 | Alpha_WWWW2
| Alpha_ZZWW0 | Alpha_ZZZZ
| D_Alpha_ZZWW0_S | D_Alpha_ZZWW0_T | D_Alpha_ZZWW1_S
| D_Alpha_ZZWW1_T | D_Alpha_ZZWW1_U | D_Alpha_WWWW0_S
| D_Alpha_WWWW0_T | D_Alpha_WWWW0_U | D_Alpha_WWWW2_S
| D_Alpha_WWWW2_T | D_Alpha_ZZZZ_S | D_Alpha_ZZZZ_T
| G_HWW | G_HHWW | G_HZZ | G_HHZZ
| G_Htt | G_Hbb | G_Hcc | G_Hmm | G_Htautau | G_H3 |
G_H4
| G_HGaZ | G_HGaGa | G_Hgg
| G_HGaZ_anom | G_HGaGa_anom | G_HZZ_anom | G_HWW_anom
| G_HGaZ_u | G_HZZ_u | G_HWW_u
| Gs | I_Gs | G2
| Mass of flavor | Width of flavor
| K_Matrix_Coeff of int | K_Matrix_Pole of int

```

Two integer counters for the QCD and EW order of the couplings.

```

type orders = int × int
let orders = function
| Q_lepton | Q_up | Q_down | G_NC_lepton | G_NC_neutrino
| G_NC_up | G_NC_down | G_CC | G_CCQ_ | G_Htt | G_H3
| G_Hbb | G_Hcc | G_Htautau | G_Hmm | I_Q_W
| I_G_ZWW | I_G1_AWW | I_G1_ZWW | I_G_weak
| G_HWW | G_HZZ | G_HWW_u | G_HZZ_u | G_HGaZ_u
| G_HWW_anom | G_HZZ_anom | G_HGaZ | G_HGaGa |
G_HGaZ_anom
| G_HGaGa_anom | Half | Unit
| I_G1_plus_kappa_plus_G4_AWW
| I_G1_plus_kappa_plus_G4_ZWW
| I_G1_minus_kappa_plus_G4_AWW
| I_G1_minus_kappa_plus_G4_ZWW
| I_G1_plus_kappa_minus_G4_AWW
| I_G1_plus_kappa_minus_G4_ZWW
| I_G1_minus_kappa_minus_G4_AWW
| I_G1_minus_kappa_minus_G4_ZWW | I_kappa5_AWW
| I_kappa5_ZWW | G5_AWW | G5_ZWW
| I_lambda_AWW | I_lambda_ZWW | I_lambda5_AWW
| I_lambda5_ZWW | G_TVA_ttA | G_TVA_bbA
| G_VLR_ttZ | G_TVA_ttZ | G_TVA_bbZ
| VA_ILC_ttA | VA_ILC_ttZ
| G_VLR_btW | G_VLR_tbW | G_TLR_btW | G_TRL_tbW
| G_TLR_btWA | G_TRL_tbWA | G_TLR_btWZ | G_TRL_tbWZ
| G_VLR_qBuB | G_VLR_qBuB_u | G_VLR_qBuB_d
| G_VLR_qBuB_e | G_VL_qBuB_n | G_VL_qW | G_VL_qW_u |
G_VL_qW_d
| G_SL_DttR | G_SR_DttR | G_SL_DttL | G_SLR_DbtR |
G_SL_DbtL

```

```

| G_TVA_ttWW | G_TVA_bbWW | G_SP_ttH → (0,1)
| G_HHWW | G_HHZZ | G_H4
| G_WWWW | G_ZZWW | G_AZWW | G_AAWW
| Alpha_WWWW0 | Alpha_WWWW2 | Alpha_ZZWW0
| Alpha_ZZWW1 | Alpha_ZZZZ
| D_Alpha_WWWW0_S | D_Alpha_WWWW0_T | D_Alpha_WWWW0_U
| D_Alpha_WWWW2_S | D_Alpha_WWWW2_T | D_Alpha_ZZWW0_S
| D_Alpha_ZZWW0_T | D_Alpha_ZZWW1_S | D_Alpha_ZZWW1_T
| D_Alpha_ZZWW1_U | D_Alpha_ZZZZ_S | D_Alpha_ZZZZ_T →
(0,2)
| Gs | I_Gs | G_TVA_ttG | G_TVA_ttGG | G_VLR_qGuG
| C_quqd1R_bt | C_quqd1R_tb | C_quqd1L_bt | C_quqd1L_tb
| C_quqd8R_bt | C_quqd8R_tb | C_quqd8L_bt | C_quqd8L_tb →
(1,0)
| G2 | G_Hgg → (2,0)
(* These constants are not used, hence initialized to zero. *)
| Sin2thw | Sin2thw | Costhw | Pi
| Alpha_QED | G_weak | K_Matrix_Coeff _
| K_Matrix_Pole _ | Mass _ | Width _ | Vev | E → (0,0)

```



The current abstract syntax for parameter dependencies is admittedly tedious. Later, there will be a parser for a convenient concrete syntax as a part of a concrete syntax for models. But as these examples show, it should include simple functions.

$$\alpha_{\text{QED}} = \frac{1}{137.0359895} \quad (13.1a)$$

$$\sin^2 \theta_w = 0.23124 \quad (13.1b)$$

```

let input_parameters =
[ Alpha_QED, 1. /. 137.0359895;
  Sin2thw, 0.23124;
  Mass (G Z), 91.187;
  Mass (M (N 1)), 0.0; Mass (M (L 1)), 0.51099907 · 10-3;
  Mass (M (N 2)), 0.0; Mass (M (L 2)), 0.105658389;
  Mass (M (N 3)), 0.0; Mass (M (L 3)), 1.77705;
  Mass (M (U 1)), 5.0 · 10-3; Mass (M (D 1)), 3.0 · 10-3;
  Mass (M (U 2)), 1.2; Mass (M (D 2)), 0.1;
  Mass (M (U 3)), 174.0; Mass (M (D 3)), 4.2 ]

```

$$e = \sqrt{4\pi\alpha} \quad (13.2a)$$

$$\sin \theta_w = \sqrt{\sin^2 \theta_w} \quad (13.2b)$$

$$\cos \theta_w = \sqrt{1 - \sin^2 \theta_w} \quad (13.2c)$$

$$g = \frac{e}{\sin \theta_w} \quad (13.2d)$$

$$m_W = \cos \theta_w m_Z \quad (13.2e)$$

$$v = \frac{2m_W}{g} \quad (13.2f)$$

$$g_{CC} = -\frac{g}{2\sqrt{2}} = -\frac{e}{2\sqrt{2} \sin \theta_w} \quad (13.2g)$$

$$Q_{\text{lepton}} = -q_{\text{lepton}} e = e \quad (13.2h)$$

$$Q_{\text{up}} = -q_{\text{up}} e = -\frac{2}{3} e \quad (13.2i)$$

$$Q_{\text{down}} = -q_{\text{down}} e = \frac{1}{3} e \quad (13.2j)$$

$$ig_W e = ig_{\gamma WW} = ie \quad (13.2k)$$

$$ig_{ZWW} = ig \cos \theta_w \quad (13.2l)$$

$$ig_{WWW} = ig \quad (13.2m)$$



... to be continued ... The quartic couplings can't be correct, because the dimensions are wrong!

$$g_{HWW} = gm_W = 2 \frac{m_W^2}{v} \quad (13.3a)$$

$$g_{HHWW} = 2 \frac{m_W^2}{v^2} = \frac{g^2}{2} \quad (13.3b)$$

$$g_{HZZ} = \frac{g}{\cos \theta_w} m_Z \quad (13.3c)$$

$$g_{HHZZ} = 2 \frac{m_Z^2}{v^2} = \frac{g^2}{2 \cos \theta_w} \quad (13.3d)$$

$$g_{Htt} = \lambda_t \quad (13.3e)$$

$$g_{Hbb} = \lambda_b = \frac{m_b}{m_t} \lambda_t \quad (13.3f)$$

$$g_{H^3} = -\frac{3g}{2} \frac{m_H^2}{m_W} = -3 \frac{m_H^2}{v} g_{H^4} = -\frac{3g^2}{4} \frac{m_W^2}{v^2} = -3 \frac{m_H^2}{v^2} \quad (13.3g)$$

let *derived\_parameters* =

```
[ Real E, Sqrt (Prod [Const 4; Atom Pi; Atom Alpha-QED]);
  Real Sinthw, Sqrt (Atom Sin2thw);
  Real Costhw, Sqrt (Diff (Const 1, Atom Sin2thw));
  Real G_weak, Quot (Atom E, Atom Sinthw);
  Real (Mass (G Wp)), Prod [Atom Costhw; Atom (Mass (G Z))];
  Real Vev, Quot (Prod [Const 2; Atom (Mass (G Wp))], Atom G_weak);
  Real Q_lepton, Atom E;
  Real Q_up, Prod [Quot (Const (-2), Const 3); Atom E];
  Real Q_down, Prod [Quot (Const 1, Const 3); Atom E];
  Real G_CC, Neg (Quot (Atom G_weak, Prod [Const 2; Sqrt (Const 2)]));
  Complex I-Q-W, Prod [I; Atom E];
  Complex I-G_weak, Prod [I; Atom G_weak];
  Complex I-G-ZWW, Prod [I; Atom G_weak; Atom Costhw] ]
```

$$-\frac{g}{2 \cos \theta_w} \quad (13.4)$$

```
let g_over_2_csth =
  Quot (Neg (Atom G_weak), Prod [Const 2; Atom Costhw])
```

$$-\frac{g}{2 \cos \theta_w} g_V = -\frac{g}{2 \cos \theta_w} (T_3 - 2q \sin^2 \theta_w) \quad (13.5a)$$

$$-\frac{g}{2 \cos \theta_w} g_A = -\frac{g}{2 \cos \theta_w} T_3 \quad (13.5b)$$

```
let nc_coupling c t3 q =
  (Real_Array c,
   [Prod [g_over_2_csth; Diff (t3, Prod [Const 2; q; Atom Sin2thw])];
    Prod [g_over_2_csth; t3]])
```

```
let half = Quot (Const 1, Const 2)
```

```
let derived_parameter_arrays =
  [ nc_coupling G_NC_neutrino half (Const 0);
    nc_coupling G_NC_lepton (Neg half) (Const (-1));
    nc_coupling G_NC_up half (Quot (Const 2, Const 3));
    nc_coupling G_NC_down (Neg half) (Quot (Const (-1), Const 3)) ]
```

```
let parameters () =
  { input = input_parameters;
    derived = derived_parameters;
    derived_arrays = derived_parameter_arrays }
```

```
module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)
```

$$\mathcal{L}_{\text{EM}} = -e \sum_i q_i \bar{\psi}_i \not{A} \psi_i \quad (13.6)$$

```
let mgm ((m1, g, m2), fbf, c) = ((M m1, G g, M m2), fbf, c)
let mom ((m1, o, m2), fbf, c) = ((M m1, O o, M m2), fbf, c)
```

```
let electromagnetic_currents n =
  List.map mgm
  [ ((L (-n), Ga, L n), FBF (1, Psibar, V, Psi), Q_lepton);
    ((U (-n), Ga, U n), FBF (1, Psibar, V, Psi), Q_up);
    ((D (-n), Ga, D n), FBF (1, Psibar, V, Psi), Q_down) ]
```

```
let color_currents n =
  List.map mgm
  [ ((U (-n), Gl, U n), FBF ((-1), Psibar, V, Psi), Gs);
    ((D (-n), Gl, D n), FBF ((-1), Psibar, V, Psi), Gs) ]
```

$$\mathcal{L}_{\text{NC}} = -\frac{g}{2 \cos \theta_W} \sum_i \bar{\psi}_i \not{Z} (g_V^i - g_A^i \gamma_5) \psi_i \quad (13.7)$$



```

let neutral_currents n =
  List.map mgm
    [ ((L (-n), Z, L n), FBF (1, Psibar, VA, Psi), G_NC_lepton);
      ((N (-n), Z, N n), FBF (1, Psibar, VA, Psi), G_NC_neutrino);
      ((U (-n), Z, U n), FBF (1, Psibar, VA, Psi), G_NC_up);
      ((D (-n), Z, D n), FBF (1, Psibar, VA, Psi), G_NC_down) ]


$$\mathcal{L}_{\text{CC}} = -\frac{g}{2\sqrt{2}} \sum_i \bar{\psi}_i (T^+ W^+ + T^- W^-) (1 - \gamma_5) \psi_i \quad (13.8)$$


let charged_currents' n =
  List.map mgm
    [ ((L (-n), Wm, N n), FBF (1, Psibar, VL, Psi), G_CC);
      ((N (-n), Wp, L n), FBF (1, Psibar, VL, Psi), G_CC) ]

let charged_currents'' n =
  List.map mgm
    [ ((D (-n), Wm, U n), FBF (1, Psibar, VL, Psi), G_CC);
      ((U (-n), Wp, D n), FBF (1, Psibar, VL, Psi), G_CC) ]

let charged_currents_triv =
  ThoList.flatmap charged_currents' [1; 2; 3] @
  ThoList.flatmap charged_currents'' [1; 2; 3]

let charged_currents_ckm =
  let charged_currents_2 n1 n2 =
    List.map mgm
      [ ((D (-n1), Wm, U n2), FBF (1, Psibar, VL, Psi), G_CCQ (n2, n1));
        ((U (-n1), Wp, D n2), FBF (1, Psibar, VL, Psi), G_CCQ (n1, n2)) ] in
    ThoList.flatmap charged_currents' [1; 2; 3] @
    List.flatten (Product.list2 charged_currents_2 [1; 2; 3] [1; 2; 3])

let yukawa =
  [ ((M (U (-3)), O H, M (U 3)), FBF (1, Psibar, S, Psi), G_Htt);
    ((M (D (-3)), O H, M (D 3)), FBF (1, Psibar, S, Psi), G_Hbb);
    ((M (U (-2)), O H, M (U 2)), FBF (1, Psibar, S, Psi), G_Hcc);
    ((M (L (-3)), O H, M (L 3)), FBF (1, Psibar, S, Psi), G_Htautau) ] @
  if Flags.higgs_hmm then
    [ ((M (L (-2)), O H, M (L 2)), FBF (1, Psibar, S, Psi), G_Hmm) ]
  else
    []

```

$$\mathcal{L}_{\text{TGC}} = -e\partial_\mu A_\nu W_+^\mu W_-^\nu + \dots - e \cot \theta_w \partial_\mu Z_\nu W_+^\mu W_-^\nu + \dots \quad (13.9)$$

```
let tgc ((g1, g2, g3), t, c) = ((G g1, G g2, G g3), t, c)
```

```

let standard_triple_gauge =
  List.map tgc
    [ ((Ga, Wm, Wp), Gauge_Gauge_Gauge 1, I_Q_W);
      ((Z, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_ZWW);
      ((Gl, Gl, Gl), Gauge_Gauge_Gauge 1, I_Gs) ]

```

$$\begin{aligned}\mathcal{L}_{\text{TGC}}(g_1, \kappa) &= g_1 \mathcal{L}_T(V, W^+, W^-) \\ &+ \frac{\kappa + g_1}{2} \left( \mathcal{L}_T(W^-, V, W^+) - \mathcal{L}_T(W^+, V, W^-) \right) \\ &+ \frac{\kappa - g_1}{2} \left( \mathcal{L}_L(W^-, V, W^+) - \mathcal{L}_T(W^+, V, W^-) \right) \quad (13.10)\end{aligned}$$



The whole thing in the LEP2 workshop notation:

$$\begin{aligned}& i\mathcal{L}_{\text{TGC},V}/g_{WWV} = \\ & g_1^V V^\mu (W_{\mu\nu}^- W^{+,\nu} - W_{\mu\nu}^+ W^{-,\nu}) + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{m_W^2} V_{\mu\nu} W_{\rho\mu}^- W^{+,\nu\rho} \\ & + ig_5^V \epsilon_{\mu\nu\rho\sigma} ((\partial^\rho W^{-,\mu}) W^{+,\nu} - W^{-,\mu} (\partial^\rho W^{+,\nu})) V^\sigma \\ & + ig_4^V W_\mu^- W_\nu^+ (\partial^\mu V^\nu + \partial^\nu V^\mu) - \frac{\tilde{\kappa}_V}{2} W_\mu^- W_\nu^+ \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_V}{2m_W^2} W_{\rho\mu}^- W^{+,\mu}_\nu \epsilon^{\nu\rho\alpha\beta} V_{\alpha\beta} \quad (13.11)\end{aligned}$$

using the conventions of Itzykson and Zuber with  $\epsilon^{0123} = +1$ .



This is equivalent to the notation of Hagiwara et al. [?], if we remember that they have opposite signs for  $g_{WWV}$ :

$$\begin{aligned}\mathcal{L}_{WWV}/(-g_{WWV}) &= \\ & ig_1^V (W_{\mu\nu}^\dagger W^\mu - W_\mu^\dagger W_\nu^\mu) V^\nu + i\kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} + i\frac{\lambda_V}{m_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu V^{\nu\lambda} \\ & - g_4^V W_\mu^\dagger W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) + g_5^V \epsilon^{\mu\nu\lambda\sigma} \left( W_\mu^\dagger \overset{\leftrightarrow}{\partial}_\lambda W_\nu \right) V_\sigma \\ & + i\tilde{\kappa}_V W_\mu^\dagger W_\nu \tilde{V}^{\mu\nu} + i\frac{\tilde{\lambda}_V}{m_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu \tilde{V}^{\nu\lambda} \quad (13.12)\end{aligned}$$

Here  $V^\mu$  stands for either the photon or the  $Z$  field,  $W^\mu$  is the  $W^-$  field,  $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$ ,  $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$ , and  $\tilde{V}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\lambda\sigma} V^{\lambda\sigma}$ .

let *anomalous\_triple\_gauge* =

```
List.map tgc
[ ((Ga, Wm, Wp), Dim4_Vector_Vector_Vector_T (-1),
  I_G1_AWW);
  ((Z, Wm, Wp), Dim4_Vector_Vector_Vector_T (-1),
  I_G1_ZWW);
  ((Wm, Ga, Wp), Dim4_Vector_Vector_Vector_T 1,
  I_G1_plus_kappa_minus_G4_AWW);
  ((Wm, Z, Wp), Dim4_Vector_Vector_Vector_T 1,
  I_G1_plus_kappa_minus_G4_ZWW);
  ((Wp, Ga, Wm), Dim4_Vector_Vector_Vector_T (-1),
  I_G1_plus_kappa_plus_G4_AWW);
  ((Wp, Z, Wm), Dim4_Vector_Vector_Vector_T (-1),
  I_G1_plus_kappa_plus_G4_ZWW);
  ((Wm, Ga, Wp), Dim4_Vector_Vector_Vector_L (-1),
```

```

    I-G1-minus-kappa-plus-G4-AWW);
    ((Wm, Z, Wp), Dim4-Vector-Vector-Vector-L (-1),
    I-G1-minus-kappa-plus-G4-ZWW);
    ((Wp, Ga, Wm), Dim4-Vector-Vector-Vector-L 1,
    I-G1-minus-kappa-minus-G4-AWW);
    ((Wp, Z, Wm), Dim4-Vector-Vector-Vector-L 1,
    I-G1-minus-kappa-minus-G4-ZWW);
    ((Ga, Wm, Wp), Dim4-Vector-Vector-Vector-L5 (-1),
    I-kappa5-AWW);
    ((Z, Wm, Wp), Dim4-Vector-Vector-Vector-L5 (-1),
    I-kappa5-ZWW);
    ((Ga, Wm, Wp), Dim4-Vector-Vector-Vector-T5 (-1),
    G5-AWW);
    ((Z, Wm, Wp), Dim4-Vector-Vector-Vector-T5 (-1),
    G5-ZWW);
    ((Ga, Wp, Wm), Dim6-Gauge-Gauge-Gauge (-1),
    I-lambda-AWW);
    ((Z, Wp, Wm), Dim6-Gauge-Gauge-Gauge (-1),
    I-lambda-ZWW);
    ((Ga, Wp, Wm), Dim6-Gauge-Gauge-Gauge-5 (-1),
    I-lambda5-AWW);
    ((Z, Wp, Wm), Dim6-Gauge-Gauge-Gauge-5 (-1),
    I-lambda5-ZWW) ]

let triple-gauge =
  if Flags.triple-anom then
    anomalous-triple-gauge
  else
    standard-triple-gauge

```

$$\mathcal{L}_{\text{QGC}} = -g^2 W_{+,\mu} W_{-,\nu} W_+^\mu W_-^\nu + \dots \quad (13.13)$$

Actually, quartic gauge couplings are a little bit more straightforward using auxiliary fields. Here we have to impose the antisymmetry manually:

$$\begin{aligned}
 & (W_1^{+,\mu} W_2^{-,\nu} - W_1^{+,\nu} W_2^{-,\mu}) (W_{3,\mu}^+ W_{4,\nu}^- - W_{3,\nu}^+ W_{4,\mu}^-) \\
 & = 2(W_1^+ W_3^+) (W_2^- W_4^-) - 2(W_1^+ W_4^-) (W_2^- W_3^+) \quad (13.14a)
 \end{aligned}$$

also ( $V$  can be  $A$  or  $Z$ )

$$\begin{aligned}
 & (W_1^{+,\mu} V_2^\nu - W_1^{+,\nu} V_2^\mu) (W_{3,\mu}^- V_{4,\nu} - W_{3,\nu}^- V_{4,\mu}) \\
 & = 2(W_1^+ W_3^-) (V_2 V_4) - 2(W_1^+ V_4) (V_2 W_3^-) \quad (13.14b)
 \end{aligned}$$

$$W^{+,\mu} W^{-,\nu} W_\mu^+ W_\nu^- \quad (13.15a)$$

```

let qgc ((g1, g2, g3, g4), t, c) = ((G g1, G g2, G g3, G g4), t, c)
let gauge4 = Vector4 [(2, C-13-42); (-1, C-12-34); (-1, C-14-23)]

```

```

let minus_gauge4 = Vector4 [(-2, C_13_42); (1, C_12_34); (1, C_14_23)]
let standard_quartic_gauge =
  List.map qgc
    [ (Wm, Wp, Wm, Wp), gauge4, G_WWWW;
      (Wm, Z, Wp, Z), minus_gauge4, G_ZZWW;
      (Wm, Z, Wp, Ga), minus_gauge4, G_AZWW;
      (Wm, Ga, Wp, Ga), minus_gauge4, G_AAWW;
      (Gl, Gl, Gl, Gl), gauge4, G2 ]

```

$$\mathcal{L}_4 = \alpha_4 \left( \frac{g^4}{2} ((W_\mu^+ W^{-,\mu})^2 + W_\mu^+ W^{+,\mu} W_\mu^- W^{-,\mu}) \right. \\ \left. + \frac{g^4}{\cos^2 \theta_w} W_\mu^+ Z^\mu W_\nu^- Z^\nu + \frac{g^4}{4 \cos^4 \theta_w} (Z_\mu Z^\mu)^2 \right) \quad (13.16a)$$

$$\mathcal{L}_5 = \alpha_5 \left( g^4 (W_\mu^+ W^{-,\mu})^2 + \frac{g^4}{\cos^2 \theta_w} W_\mu^+ W^{-,\mu} Z_\nu Z^\nu + \frac{g^4}{4 \cos^4 \theta_w} (Z_\mu Z^\mu)^2 \right) \quad (13.16b)$$

or

$$\mathcal{L}_4 + \mathcal{L}_5 = (\alpha_4 + 2\alpha_5) g^4 \frac{1}{2} (W_\mu^+ W^{-,\mu})^2 \\ + 2\alpha_4 g^4 \frac{1}{4} W_\mu^+ W^{+,\mu} W_\mu^- W^{-,\mu} + \alpha_4 \frac{g^4}{\cos^2 \theta_w} W_\mu^+ Z^\mu W_\nu^- Z^\nu \\ + 2\alpha_5 \frac{g^4}{\cos^2 \theta_w} \frac{1}{2} W_\mu^+ W^{-,\mu} Z_\nu Z^\nu + (2\alpha_4 + 2\alpha_5) \frac{g^4}{\cos^4 \theta_w} \frac{1}{8} (Z_\mu Z^\mu)^2 \quad (13.17)$$

and therefore

$$\alpha_{(WW)_0} = (\alpha_4 + 2\alpha_5) g^4 \quad (13.18a)$$

$$\alpha_{(WW)_2} = 2\alpha_4 g^4 \quad (13.18b)$$

$$\alpha_{(WZ)_0} = 2\alpha_5 \frac{g^4}{\cos^2 \theta_w} \quad (13.18c)$$

$$\alpha_{(WZ)_1} = \alpha_4 \frac{g^4}{\cos^2 \theta_w} \quad (13.18d)$$

$$\alpha_{ZZ} = (2\alpha_4 + 2\alpha_5) \frac{g^4}{\cos^4 \theta_w} \quad (13.18e)$$

```

let anomalous_quartic_gauge =
  if Flags.quartic_anom then
    List.map qgc
      [ ((Wm, Wm, Wp, Wp),
          Vector4 [(1, C_13_42); (1, C_14_23)], Alpha_WWWW0);
        ((Wm, Wm, Wp, Wp),
          Vector4 [1, C_12_34], Alpha_WWWW2);
        ((Wm, Wp, Z, Z),
          Vector4 [1, C_12_34], Alpha_ZZWW0);
        ((Wm, Wp, Z, Z),

```

```

Vector4 [(1, C_13_42); (1, C_14_23)], Alpha_ZZWW1);
((Z, Z, Z, Z),
Vector4 [(1, C_12_34); (1, C_13_42); (1, C_14_23)], Alpha_ZZZZ) ]
else
[]

```

In any diagonal channel  $\chi$ , the scattering amplitude  $a_\chi(s)$  is unitary iff<sup>1</sup>

$$\text{Im} \left( \frac{1}{a_\chi(s)} \right) = -1 \quad (13.20)$$

For a real perturbative scattering amplitude  $r_\chi(s)$  this can be enforced easily– and arbitrarily–by

$$\frac{1}{a_\chi(s)} = \frac{1}{r_\chi(s)} - i \quad (13.21)$$

```

let k_matrix_quartic_gauge =
  if Flags.k_matrix then
    List.map qgc
      [ ((Wm, Wp, Wm, Wp), Vector4_K_Matrix_jr (0,
        [(1, C_12_34)]), D_Alpha_WWWW0_S);
        ((Wm, Wp, Wm, Wp), Vector4_K_Matrix_jr (0,
        [(1, C_14_23)]), D_Alpha_WWWW0_T);
        ((Wm, Wp, Wm, Wp), Vector4_K_Matrix_jr (0,
        [(1, C_13_42)]), D_Alpha_WWWW0_U);
        ((Wp, Wm, Wp, Wm), Vector4_K_Matrix_jr (0,
        [(1, C_12_34)]), D_Alpha_WWWW0_S);
        ((Wp, Wm, Wp, Wm), Vector4_K_Matrix_jr (0,
        [(1, C_14_23)]), D_Alpha_WWWW0_T);
        ((Wp, Wm, Wp, Wm), Vector4_K_Matrix_jr (0,
        [(1, C_13_42)]), D_Alpha_WWWW0_U);
        ((Wm, Wm, Wp, Wp), Vector4_K_Matrix_jr (0,
        [(1, C_12_34)]), D_Alpha_WWWW2_S);
        ((Wm, Wm, Wp, Wp), Vector4_K_Matrix_jr (0,
        [(1, C_13_42); (1, C_14_23)]), D_Alpha_WWWW2_T);
        ((Wm, Wp, Z, Z), Vector4_K_Matrix_jr (0,
        [(1, C_12_34)]), D_Alpha_ZZWW0_S);
        ((Wm, Wp, Z, Z), Vector4_K_Matrix_jr (0,
        [(1, C_13_42); (1, C_14_23)]), D_Alpha_ZZWW0_T);
        ((Wm, Z, Wp, Z), Vector4_K_Matrix_jr (0,
        [(1, C_12_34)]), D_Alpha_ZZWW1_S);
        ((Wm, Z, Wp, Z), Vector4_K_Matrix_jr (0,
        [(1, C_13_42)]), D_Alpha_ZZWW1_T);
        ((Wm, Z, Wp, Z), Vector4_K_Matrix_jr (0,
        [(1, C_14_23)]), D_Alpha_ZZWW1_U);
        ((Wp, Z, Z, Wm), Vector4_K_Matrix_jr (1,

```

---

<sup>1</sup>Trivial proof:

$$-1 = \text{Im} \left( \frac{1}{a_\chi(s)} \right) = \frac{\text{Im}(a_\chi^*(s))}{|a_\chi(s)|^2} = -\frac{\text{Im}(a_\chi(s))}{|a_\chi(s)|^2} \quad (13.19)$$

i. e.  $\text{Im}(a_\chi(s)) = |a_\chi(s)|^2$ .

```

        [(1, C-12-34)], D-Alpha-ZZWW1-S);
    ((Wp, Z, Z, Wm), Vector4-K-Matrix-jr (1,
        [(1, C-13-42)], D-Alpha-ZZWW1-U);
    ((Wp, Z, Z, Wm), Vector4-K-Matrix-jr (1,
        [(1, C-14-23)], D-Alpha-ZZWW1-T);
    ((Z, Wp, Wm, Z), Vector4-K-Matrix-jr (2,
        [(1, C-12-34)], D-Alpha-ZZWW1-S);
    ((Z, Wp, Wm, Z), Vector4-K-Matrix-jr (2,
        [(1, C-13-42)], D-Alpha-ZZWW1-U);
    ((Z, Wp, Wm, Z), Vector4-K-Matrix-jr (2,
        [(1, C-14-23)], D-Alpha-ZZWW1-T);
    ((Z, Z, Z, Z), Vector4-K-Matrix-jr (0,
        [(1, C-12-34)], D-Alpha-ZZZZ-S);
    ((Z, Z, Z, Z), Vector4-K-Matrix-jr (0,
        [(1, C-13-42); (1, C-14-23)], D-Alpha-ZZZZ-T);
    ((Z, Z, Z, Z), Vector4-K-Matrix-jr (3,
        [(1, C-14-23)], D-Alpha-ZZZZ-S);
    ((Z, Z, Z, Z), Vector4-K-Matrix-jr (3,
        [(1, C-13-42); (1, C-12-34)], D-Alpha-ZZZZ-T)]
else
    []
let quartic-gauge =
    standard-quartic-gauge @ anomalous-quartic-gauge @ k-matrix-quartic-gauge
let standard-gauge-higgs =
    [ ((O H, G Wp, G Wm), Scalar-Vector-Vector 1, G-HWW);
      ((O H, G Z, G Z), Scalar-Vector-Vector 1, G-HZZ) ]
let standard-gauge-higgs4 =
    [ (O H, O H, G Wp, G Wm), Scalar2-Vector2 1, G-HHWW;
      (O H, O H, G Z, G Z), Scalar2-Vector2 1, G-HHZZ ]
let standard-higgs =
    [ (O H, O H, O H), Scalar-Scalar-Scalar 1, G-H3 ]
let standard-higgs4 =
    [ (O H, O H, O H, O H), Scalar4 1, G-H4 ]

```

WK's couplings (apparently, he still intends to divide by  $\Lambda_{\text{EWSB}}^2 = 16\pi^2 v_F^2$ ):

$$\mathcal{L}_4^\tau = \left[ (\partial_\mu H)(\partial^\mu H) + \frac{g^2 v_F^2}{4} V_\mu V^\mu \right]^2 \quad (13.22a)$$

$$\mathcal{L}_5^\tau = \left[ (\partial_\mu H)(\partial_\nu H) + \frac{g^2 v_F^2}{4} V_\mu V_\nu \right]^2 \quad (13.22b)$$

with

$$V_\mu V_\nu = \frac{1}{2} (W_\mu^+ W_\nu^- + W_\nu^+ W_\mu^-) + \frac{1}{2 \cos^2 \theta_w} Z_\mu Z_\nu \quad (13.23)$$

(note the symmetrization!), i. e.

$$\mathcal{L}_4 = \alpha_4 \frac{g^4 v_F^4}{16} (V_\mu V_\nu)^2 \quad (13.24a)$$

$$\mathcal{L}_5 = \alpha_5 \frac{g^4 v_F^4}{16} (V_\mu V^\mu)^2 \quad (13.24b)$$

Breaking thinks up

$$\mathcal{L}_4^{\tau, H^4} = [(\partial_\mu H)(\partial^\mu H)]^2 \quad (13.25a)$$

$$\mathcal{L}_5^{\tau, H^4} = [(\partial_\mu H)(\partial^\mu H)]^2 \quad (13.25b)$$

and

$$\mathcal{L}_4^{\tau, H^2 V^2} = \frac{g^2 v_F^2}{2} (\partial_\mu H)(\partial^\mu H) V_\mu V^\mu \quad (13.26a)$$

$$\mathcal{L}_5^{\tau, H^2 V^2} = \frac{g^2 v_F^2}{2} (\partial_\mu H)(\partial_\nu H) V_\mu V_\nu \quad (13.26b)$$

i. e.

$$\mathcal{L}_4^{\tau, H^2 V^2} = \frac{g^2 v_F^2}{2} \left[ (\partial_\mu H)(\partial^\mu H) W_\nu^+ W^{-, \nu} + \frac{1}{2 \cos^2 \theta_w} (\partial_\mu H)(\partial^\mu H) Z_\nu Z^\nu \right] \quad (13.27a)$$

$$\mathcal{L}_5^{\tau, H^2 V^2} = \frac{g^2 v_F^2}{2} \left[ (W^{+, \mu} \partial_\mu H)(W^{-, \nu} \partial_\nu H) + \frac{1}{2 \cos^2 \theta_w} (Z^\mu \partial_\mu H)(Z^\nu \partial_\nu H) \right] \quad (13.27b)$$

$$\begin{aligned} \tau_8^4 \mathcal{L}_4^{\tau, H^2 V^2} + \tau_8^5 \mathcal{L}_5^{\tau, H^2 V^2} = & \\ & - \frac{g^2 v_F^2}{2} \left[ 2\tau_8^4 \frac{1}{2} (i\partial_\mu H)(i\partial^\mu H) W_\nu^+ W^{-, \nu} + \tau_8^5 (W^{+, \mu} i\partial_\mu H)(W^{-, \nu} i\partial_\nu H) \right. \\ & \left. + \frac{2\tau_8^4}{\cos^2 \theta_w} \frac{1}{4} (i\partial_\mu H)(i\partial^\mu H) Z_\nu Z^\nu + \frac{\tau_8^5}{\cos^2 \theta_w} \frac{1}{2} (Z^\mu i\partial_\mu H)(Z^\nu i\partial_\nu H) \right] \end{aligned} \quad (13.28)$$

where the two powers of  $i$  make the sign conveniently negative, i. e.

$$\alpha_{(\partial H)^2 W^2}^2 = \tau_8^4 g^2 v_F^2 \quad (13.29a)$$

$$\alpha_{(\partial HW)^2}^2 = \frac{\tau_8^5 g^2 v_F^2}{2} \quad (13.29b)$$

$$\alpha_{(\partial H)^2 Z^2}^2 = \frac{\tau_8^4 g^2 v_F^2}{\cos^2 \theta_w} \quad (13.29c)$$

$$\alpha_{(\partial HZ)^2}^2 = \frac{\tau_8^5 g^2 v_F^2}{2 \cos^2 \theta_w} \quad (13.29d)$$

let *anomalous\_gauge\_higgs* =

```
[ (O H, G Ga, G Ga), Dim5_Scalar_Gauge2 1, G_HGaGa_anom;
  (O H, G Ga, G Z), Dim5_Scalar_Gauge2 1, G_HGaZ_anom;
  (O H, G Z, G Z), Dim5_Scalar_Gauge2 1, G_HZZ_anom;
  (O H, G Wp, G Wm), Dim5_Scalar_Gauge2 1, G_HWW_anom;
  (O H, G Ga, G Z), Dim5_Scalar_Vector_Vector_TU 1, G_HGaZ_u;
  (O H, G Z, G Z), Dim5_Scalar_Vector_Vector_U 1, G_HZZ_u;
```

```

      (O H, G Wp, G Wm), Dim5_Scalar_Vector_Vector_U 1, G_HWW_u
    ]
  let anomalous_gauge_higgs4 =
    []
  let anomalous_higgs =
    []
  let higgs_triangle_vertices =
    if Flags.higgs_triangle then
      [ (O H, G Ga, G Ga), Dim5_Scalar_Gauge2 1, G_HGaGa;
        (O H, G Ga, G Z), Dim5_Scalar_Gauge2 1, G_HGaZ;
        (O H, G Gl, G Gl), Dim5_Scalar_Gauge2 1, G_Hgg ]
    else
      []
  let anomalous_higgs4 =
    []
  let gauge_higgs =
    if Flags.higgs_anom then
      standard_gauge_higgs @ anomalous_gauge_higgs
    else
      standard_gauge_higgs
  let gauge_higgs4 =
    if Flags.higgs_anom then
      standard_gauge_higgs4 @ anomalous_gauge_higgs4
    else
      standard_gauge_higgs4
  let higgs =
    if Flags.higgs_anom then
      standard_higgs @ anomalous_higgs
    else
      standard_higgs
  let higgs4 =
    if Flags.higgs_anom then
      standard_higgs4 @ anomalous_higgs4
    else
      standard_higgs4
  let goldstone_vertices =
    [ ((O Phi0, G Wm, G Wp), Scalar_Vector_Vector 1, I_G_ZWW);
      ((O Phip, G Ga, G Wm), Scalar_Vector_Vector 1, I_Q_W);
      ((O Phip, G Z, G Wm), Scalar_Vector_Vector 1, I_G_ZWW);
      ((O Phim, G Wp, G Ga), Scalar_Vector_Vector 1, I_Q_W);
      ((O Phim, G Wp, G Z), Scalar_Vector_Vector 1, I_G_ZWW) ]

```

Anomalous trilinear interactions  $f_i f_j V$  and  $ttH$ :

$$\Delta\mathcal{L}_{tt\gamma} = -e\frac{v}{\Lambda^2}\bar{t}i\sigma^{\mu\nu}k_\nu(d_V(k^2) + id_A(k^2)\gamma_5)tA_\mu \quad (13.30)$$



```

let anomalous_ttA =
  if Flags.top_anom then
    [ ((M (U (-3)), G Ga, M (U 3)), FBF (1, Psibar, TVAM, Psi), G_TVA_ttA) ]
  else
    []
let tt_threshold_ttA =
  if Flags.tt_threshold then
    [ ((M (U (-3)), G Ga, M (U 3)), FBF (1, Psibar, VAM, Psi), VA_ILC_ttA) ]
  else
    []

```

$$\Delta\mathcal{L}_{bb\gamma} = -e \frac{v}{\Lambda^2} \bar{b} i \sigma^{\mu\nu} k_\nu (d_V(k^2) + i d_A(k^2) \gamma_5) b A_\mu \quad (13.31)$$

```

let anomalous_bbA =
  if Flags.top_anom then
    [ ((M (D (-3)), G Ga, M (D 3)), FBF (1, Psibar, TVAM, Psi), G_TVA_bbA) ]
  else
    []

```

$$\Delta\mathcal{L}_{tg} = -g_s \frac{v}{\Lambda^2} \bar{t} \lambda^a i \sigma^{\mu\nu} k_\nu (d_V(k^2) + i d_A(k^2) \gamma_5) t G_\mu^a \quad (13.32)$$

```

let anomalous_ttG =
  if Flags.top_anom then
    [ ((M (U (-3)), G Gl, M (U 3)), FBF (1, Psibar, TVAM, Psi), G_TVA_ttG) ]
  else
    []

```

$$\Delta\mathcal{L}_{ttZ} = -\frac{g}{2c_W} \frac{v^2}{\Lambda^2} \left[ \bar{t} \not{Z} (X_L(k^2) P_L + X_R(k^2) P_R) t + \bar{t} \frac{i \sigma^{\mu\nu} k_\nu}{m_Z} (d_V(k^2) + i d_A(k^2) \gamma_5) t Z_\mu \right] \quad (13.33)$$

```

let anomalous_ttZ =
  if Flags.top_anom then
    [ ((M (U (-3)), G Z, M (U 3)), FBF (1, Psibar, VLRM, Psi), G_VLR_ttZ);
      ((M (U (-3)), G Z, M (U 3)), FBF (1, Psibar, TVAM, Psi), G_TVA_ttZ) ]
  else
    []
let tt_threshold_ttZ =
  if Flags.tt_threshold then
    [ ((M (U (-3)), G Z, M (U 3)), FBF (1, Psibar, VAM, Psi), VA_ILC_ttZ) ]
  else
    []

```

$$\Delta\mathcal{L}_{bbZ} = -\frac{g}{2c_W} \frac{v^2}{\Lambda^2} \bar{b} \frac{i \sigma^{\mu\nu} k_\nu}{m_Z} (d_V(k^2) + i d_A(k^2) \gamma_5) b Z_\mu \quad (13.34)$$

```

let anomalous_bbZ =

```

```

if Flags.top_anom then
  [ ((M (D (-3)), G Z, M (D 3)), FBF (1, Psibar, TVAM, Psi), G-TVAbbZ) ]
else
  []

```

$$\Delta\mathcal{L}_{tbW} = -\frac{g}{\sqrt{2}}\frac{v^2}{\Lambda^2} \left[ \bar{b}W^-(V_L(k^2)P_L + V_R(k^2)P_R)t + \bar{b}\frac{i\sigma^{\mu\nu}k_\nu}{m_W}(g_L(k^2)P_L + g_R(k^2)P_R)tW_\mu^- \right] + \text{H.c.} \quad (13.35)$$

```

let anomalous_tbW =
  if Flags.top_anom then
    [ ((M (D (-3)), G Wm, M (U 3)), FBF (1, Psibar, VLRM, Psi), G-VLRbtW);
      ((M (U (-3)), G Wp, M (D 3)), FBF (1, Psibar, VLRM, Psi), G-VLRtbW);
      ((M (D (-3)), G Wm, M (U 3)), FBF (1, Psibar, TLRM, Psi), G-TLRbtW);
      ((M (U (-3)), G Wp, M (D 3)), FBF (1, Psibar, TRLM, Psi), G-TRLtbW) ]
  else
    []

```

$$\Delta\mathcal{L}_{ttH} = -\frac{1}{\sqrt{2}}\bar{t}(Y_V(k^2) + iY_A(k^2)\gamma_5)tH \quad (13.36)$$

```

let anomalous_ttH =
  if Flags.top_anom then
    [ ((M (U (-3)), O H, M (U 3)), FBF (1, Psibar, SPM, Psi), G-SPttH) ]
  else
    []

```

quartic fermion-gauge interactions  $f_i f_j V_1 V_2$  emerging from gauge-invariant effective operators:

$$\Delta\mathcal{L}_{ttgg} = -\frac{g_s^2}{2}f_{abc}\frac{v}{\Lambda^2}\bar{t}\lambda^a\sigma^{\mu\nu}(d_V(k^2) + id_A(k^2)\gamma_5)tG_\mu^b G_\nu^c \quad (13.37)$$

```

let anomalous_ttGG =
  if Flags.top_anom then
    [ ((M (U (-3)), O (Aux_top (2, 1, 0, true, TTGG)), M (U 3)), FBF (1, Psibar, TVA, Psi), G-TVATtGG);
      ((O (Aux_top (2, 1, 0, false, TTGG)), G Gl, G Gl), Aux-Gauge-Gauge 1, I-Gs) ]
  else
    []

```

$$\Delta\mathcal{L}_{tbWA} = -i\sin\theta_w\frac{g^2}{2\sqrt{2}}\frac{v^2}{\Lambda^2} \left[ \bar{b}\frac{\sigma^{\mu\nu}}{m_W}(g_L(k^2)P_L + g_R(k^2)P_R)tA_\mu W_\nu^- \right] + \text{H.c.} \quad (13.38)$$

```

let anomalous_tbWA =
  if Flags.top_anom then
    [ ((M (D (-3)), O (Aux_top (2, 0, -1, true, TBWA)), M (U 3)), FBF (1, Psibar, TLR, Psi), G-TLtbWA);
      ((O (Aux_top (2, 0, 1, false, TBWA)), G Ga, G Wm), Aux-Gauge-Gauge 1, I-G-weak);
      ((M (U (-3)), O (Aux_top (2, 0, 1, true, TBWA)), M (D 3)), FBF (1, Psibar, TRL, Psi), G-TRlbWA) ]

```

```

      ((O (Aux_top (2, 0, -1, false, TBWA)), G Wp, G Ga), Aux_Gauge_Gauge 1, I_G_weak) ]
else
  []

```

$$\Delta\mathcal{L}_{tbWZ} = -i \cos \theta_w \frac{g^2}{2\sqrt{2}} \frac{v^2}{\Lambda^2} \left[ \bar{b} \frac{\sigma^{\mu\nu}}{m_W} (g_L(k^2)P_L + g_R(k^2)P_R) t Z_\mu W_\nu^- \right] + \text{H.c.} \quad (13.39)$$

```

let anomalous_tbWZ =
  if Flags.top_anom then
    [ ((M (D (-3)), O (Aux_top (2, 0, -1, true, TBWZ)), M (U 3)), FBF (1, Psibar, TLR, Psi), G_TL
      ((O (Aux_top (2, 0, 1, false, TBWZ)), G Z, G Wm), Aux_Gauge_Gauge 1, I_G_weak);
      ((M (U (-3)), O (Aux_top (2, 0, 1, true, TBWZ)), M (D 3)), FBF (1, Psibar, TRL, Psi), G_TRL
      ((O (Aux_top (2, 0, -1, false, TBWZ)), G Wp, G Z), Aux_Gauge_Gauge 1, I_G_weak) ]
  else
    []

```

$$\Delta\mathcal{L}_{ttWW} = -i \frac{g^2}{2} \frac{v^2}{\Lambda^2} \bar{t} \frac{\sigma^{\mu\nu}}{m_W} (d_V(k^2) + i d_A(k^2) \gamma_5) t W_\mu^- W_\nu^+ \quad (13.40)$$

```

let anomalous_ttWW =
  if Flags.top_anom then
    [ ((M (U (-3)), O (Aux_top (2, 0, 0, true, TTWW)), M (U 3)), FBF (1, Psibar, TVA, Psi), G_TVA
      ((O (Aux_top (2, 0, 0, false, TTWW)), G Wm, G Wp), Aux_Gauge_Gauge 1, I_G_weak) ]
  else
    []

```

$$\Delta\mathcal{L}_{bbWW} = -i \frac{g^2}{2} \frac{v^2}{\Lambda^2} \bar{b} \frac{\sigma^{\mu\nu}}{m_W} (d_V(k^2) + i d_A(k^2) \gamma_5) b W_\mu^- W_\nu^+ \quad (13.41)$$

```

let anomalous_bbWW =
  if Flags.top_anom then
    [ ((M (D (-3)), O (Aux_top (2, 0, 0, true, BBWW)), M (D 3)), FBF (1, Psibar, TVA, Psi), G_TVA
      ((O (Aux_top (2, 0, 0, false, BBWW)), G Wm, G Wp), Aux_Gauge_Gauge 1, I_G_weak) ]
  else
    []

```

4-fermion contact terms emerging from operator rewriting:

```

let anomalous_top_qGuG_tt =
  [ ((M (U (-3)), O (Aux_top (1, 1, 0, true, QGUG)), M (U 3)), FBF (1, Psibar, VLR, Psi), G_VLR_q
let anomalous_top_qGuG_ff n =
  List.map mom
    [ ((U (-n), Aux_top (1, 1, 0, false, QGUG), U n), FBF (1, Psibar, V, Psi), Unit);
      ((D (-n), Aux_top (1, 1, 0, false, QGUG), D n), FBF (1, Psibar, V, Psi), Unit) ]
let anomalous_top_qGuG =
  if Flags.top_anom_4f then
    anomalous_top_qGuG_tt @ ThoList.flatmap anomalous_top_qGuG_ff [1; 2; 3]
  else

```

```

[]

let anomalous_top_qBuB_tt =
  [ ((M (U (-3)), O (Aux_top (1,0,0,true,QBUB)), M (U 3)), FBF (1, Psibar, VLR, Psi), G_VLR_q
let anomalous_top_qBuB_ff n =
  List.map mom
    [ ((U (-n), Aux_top (1,0,0,false,QBUB), U n), FBF (1, Psibar, VLR, Psi), G_VLR_qBuB_u);
      ((D (-n), Aux_top (1,0,0,false,QBUB), D n), FBF (1, Psibar, VLR, Psi), G_VLR_qBuB_d);
      ((L (-n), Aux_top (1,0,0,false,QBUB), L n), FBF (1, Psibar, VLR, Psi), G_VLR_qBuB_e);
      ((N (-n), Aux_top (1,0,0,false,QBUB), N n), FBF (1, Psibar, VL, Psi), G_VL_qBuB_n) ]

let anomalous_top_qBuB =
  if Flags.top_anom_4f then
    anomalous_top_qBuB_tt @ ThoList.flatmap anomalous_top_qBuB_ff [1;2;3]
  else
    []

let anomalous_top_qW_tq =
  [ ((M (U (-3)), O (Aux_top (1,0,0,true,QW)), M (U 3)), FBF (1, Psibar, VL, Psi), G_VL_qW);
    ((M (D (-3)), O (Aux_top (1,0,-1,true,QW)), M (U 3)), FBF (1, Psibar, VL, Psi), G_VL_qW);
    ((M (U (-3)), O (Aux_top (1,0,1,true,QW)), M (D 3)), FBF (1, Psibar, VL, Psi), G_VL_qW) ]

let anomalous_top_qW_ff n =
  List.map mom
    [ ((U (-n), Aux_top (1,0,0,false,QW), U n), FBF (1, Psibar, VL, Psi), G_VL_qW_u);
      ((D (-n), Aux_top (1,0,0,false,QW), D n), FBF (1, Psibar, VL, Psi), G_VL_qW_d);
      ((N (-n), Aux_top (1,0,0,false,QW), N n), FBF (1, Psibar, VL, Psi), G_VL_qW_u);
      ((L (-n), Aux_top (1,0,0,false,QW), L n), FBF (1, Psibar, VL, Psi), G_VL_qW_d);
      ((D (-n), Aux_top (1,0,-1,false,QW), U n), FBF (1, Psibar, VL, Psi), Half);
      ((U (-n), Aux_top (1,0,1,false,QW), D n), FBF (1, Psibar, VL, Psi), Half);
      ((L (-n), Aux_top (1,0,-1,false,QW), N n), FBF (1, Psibar, VL, Psi), Half);
      ((N (-n), Aux_top (1,0,1,false,QW), L n), FBF (1, Psibar, VL, Psi), Half) ]

let anomalous_top_qW =
  if Flags.top_anom_4f then
    anomalous_top_qW_tq @ ThoList.flatmap anomalous_top_qW_ff [1;2;3]
  else
    []

let anomalous_top_DuDd =
  if Flags.top_anom_4f then
    [ ((M (U (-3)), O (Aux_top (0,0,0,true,DR)), M (U 3)), FBF (1, Psibar, SR, Psi), Half);
      ((M (U (-3)), O (Aux_top (0,0,0,false,DR)), M (U 3)), FBF (1, Psibar, SL, Psi), G_SL_DttR);
      ((M (D (-3)), O (Aux_top (0,0,0,false,DR)), M (D 3)), FBF (1, Psibar, SR, Psi), G_SR_DttR);
      ((M (U (-3)), O (Aux_top (0,0,0,true,DL)), M (U 3)), FBF (1, Psibar, SL, Psi), Half);
      ((M (D (-3)), O (Aux_top (0,0,0,false,DL)), M (D 3)), FBF (1, Psibar, SL, Psi), G_SL_DttL);
      ((M (D (-3)), O (Aux_top (0,0,-1,true,DR)), M (U 3)), FBF (1, Psibar, SR, Psi), Half);
      ((M (U (-3)), O (Aux_top (0,0,1,false,DR)), M (D 3)), FBF (1, Psibar, SLR, Psi), G_SLR_D);
      ((M (D (-3)), O (Aux_top (0,0,-1,true,DL)), M (U 3)), FBF (1, Psibar, SL, Psi), Half);
      ((M (U (-3)), O (Aux_top (0,0,1,false,DL)), M (D 3)), FBF (1, Psibar, SL, Psi), G_SL_DbtL)
  else
    []

```

```

let anomalous_top_quqd1_tq =
  [ ((M (D (-3)), O (Aux_top (0, 0, -1, true, QUQD1R)), M (U 3)), FBF (1, Psibar, SR, Psi), C_quqd1),
    ((M (U (-3)), O (Aux_top (0, 0, 1, true, QUQD1R)), M (D 3)), FBF (1, Psibar, SL, Psi), C_quqd1),
    ((M (D (-3)), O (Aux_top (0, 0, -1, true, QUQD1L)), M (U 3)), FBF (1, Psibar, SL, Psi), C_quqd1),
    ((M (U (-3)), O (Aux_top (0, 0, 1, true, QUQD1L)), M (D 3)), FBF (1, Psibar, SR, Psi), C_quqd1) ]

let anomalous_top_quqd1_ff n =
  List.map mom
    [ ((U (-n), Aux_top (0, 0, 1, false, QUQD1R), D n), FBF (1, Psibar, SR, Psi), Half);
      ((D (-n), Aux_top (0, 0, -1, false, QUQD1R), U n), FBF (1, Psibar, SL, Psi), Half);
      ((U (-n), Aux_top (0, 0, 1, false, QUQD1L), D n), FBF (1, Psibar, SL, Psi), Half);
      ((D (-n), Aux_top (0, 0, -1, false, QUQD1L), U n), FBF (1, Psibar, SR, Psi), Half) ]

let anomalous_top_quqd1 =
  if Flags.top_anom_4f then
    anomalous_top_quqd1_tq @ ThoList.flatmap anomalous_top_quqd1_ff [1; 2; 3]
  else
    []

let anomalous_top_quqd8_tq =
  [ ((M (D (-3)), O (Aux_top (0, 1, -1, true, QUQD8R)), M (U 3)), FBF (1, Psibar, SR, Psi), C_quqd8),
    ((M (U (-3)), O (Aux_top (0, 1, 1, true, QUQD8R)), M (D 3)), FBF (1, Psibar, SL, Psi), C_quqd8),
    ((M (D (-3)), O (Aux_top (0, 1, -1, true, QUQD8L)), M (U 3)), FBF (1, Psibar, SL, Psi), C_quqd8),
    ((M (U (-3)), O (Aux_top (0, 1, 1, true, QUQD8L)), M (D 3)), FBF (1, Psibar, SR, Psi), C_quqd8) ]

let anomalous_top_quqd8_ff n =
  List.map mom
    [ ((U (-n), Aux_top (0, 1, 1, false, QUQD8R), D n), FBF (1, Psibar, SR, Psi), Half);
      ((D (-n), Aux_top (0, 1, -1, false, QUQD8R), U n), FBF (1, Psibar, SL, Psi), Half);
      ((U (-n), Aux_top (0, 1, 1, false, QUQD8L), D n), FBF (1, Psibar, SL, Psi), Half);
      ((D (-n), Aux_top (0, 1, -1, false, QUQD8L), U n), FBF (1, Psibar, SR, Psi), Half) ]

let anomalous_top_quqd8 =
  if Flags.top_anom_4f then
    anomalous_top_quqd8_tq @ ThoList.flatmap anomalous_top_quqd8_ff [1; 2; 3]
  else
    []

let vertices3 =
  (ThoList.flatmap electromagnetic_currents [1; 2; 3] @
   ThoList.flatmap color_currents [1; 2; 3] @
   ThoList.flatmap neutral_currents [1; 2; 3] @
   (if Flags.ckm_present then
      charged_currents_ckm
    else
      charged_currents_triv) @
   yukawa @ triple_gauge @
   gauge_higgs @ higgs @ higgs_triangle_vertices
  @ goldstone_vertices @
  tt_threshold_ttA @ tt_threshold_ttZ @
  anomalous_ttA @ anomalous_bbA @
  anomalous_ttZ @ anomalous_bbZ @
  anomalous_tbW @ anomalous_tbWA @ anomalous_tbWZ @

```

```

anomalous_ttWW @ anomalous_bbWW @
anomalous_ttG @ anomalous_ttGG @
anomalous_ttH @
anomalous_top_qGuG @ anomalous_top_qBuB @
anomalous_top_qW @ anomalous_top_DuDd @
anomalous_top_quqd1 @ anomalous_top_quqd8)

let vertices4 =
  quartic_gauge @ gauge_higgs4 @ higgs4

let vertices () = (vertices3, vertices4, [])

```

For efficiency, make sure that *F.of\_vertices vertices* is evaluated only once.

```

let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 4

let flavor_of_string = function
| "e-" → M (L 1) | "e+" → M (L (-1))
| "mu-" → M (L 2) | "mu+" → M (L (-2))
| "tau-" → M (L 3) | "tau+" → M (L (-3))
| "nue" → M (N 1) | "nuebar" → M (N (-1))
| "numu" → M (N 2) | "numubar" → M (N (-2))
| "nutau" → M (N 3) | "nutaubar" → M (N (-3))
| "u" → M (U 1) | "ubar" → M (U (-1))
| "c" → M (U 2) | "cbar" → M (U (-2))
| "t" → M (U 3) | "tbar" → M (U (-3))
| "d" → M (D 1) | "dbar" → M (D (-1))
| "s" → M (D 2) | "sbar" → M (D (-2))
| "b" → M (D 3) | "bbar" → M (D (-3))
| "g" | "gl" → G Gl
| "A" → G Ga | "Z" | "ZO" → G Z
| "W+" → G Wp | "W-" → G Wm
| "H" → O H
| "Aux_t_ttGG0" → O (Aux_top (2, 1, 0, true, TTGG)) | "Aux_ttGG0" →
O (Aux_top (2, 1, 0, false, TTGG))
| "Aux_t_tbWA+" → O (Aux_top (2, 0, 1, true, TBWA)) | "Aux_tbWA+" →
O (Aux_top (2, 0, 1, false, TBWA))
| "Aux_t_tbWA-" → O (Aux_top (2, 0, -1, true, TBWA)) | "Aux_tbWA-" →
O (Aux_top (2, 0, -1, false, TBWA))
| "Aux_t_tbWZ+" → O (Aux_top (2, 0, 1, true, TBWZ)) | "Aux_tbWZ+" →
O (Aux_top (2, 0, 1, false, TBWZ))
| "Aux_t_tbWZ-" → O (Aux_top (2, 0, -1, true, TBWZ)) | "Aux_tbWZ-" →
O (Aux_top (2, 0, -1, false, TBWZ))
| "Aux_t_ttWW0" → O (Aux_top (2, 0, 0, true, TTWW)) | "Aux_ttWW0" →
O (Aux_top (2, 0, 0, false, TTWW))
| "Aux_t_bbWW0" → O (Aux_top (2, 0, 0, true, BBWW)) | "Aux_bbWW0" →
O (Aux_top (2, 0, 0, false, BBWW))
| "Aux_t_qGuG0" → O (Aux_top (1, 1, 0, true, QGUG)) | "Aux_qGuG0" →
O (Aux_top (1, 1, 0, false, QGUG))

```

```

    | "Aux_t_qBuB0" → O (Aux_top (1, 0, 0, true, QBUB)) | "Aux_qBuB0" →
O (Aux_top (1, 0, 0, false, QBUB))
    | "Aux_t_qW0" → O (Aux_top (1, 0, 0, true, QW)) | "Aux_qW0" →
O (Aux_top (1, 0, 0, false, QW))
    | "Aux_t_qW+" → O (Aux_top (1, 0, 1, true, QW)) | "Aux_qW+" →
O (Aux_top (1, 0, 1, false, QW))
    | "Aux_t_qW-" → O (Aux_top (1, 0, -1, true, QW)) | "Aux_qW-" →
O (Aux_top (1, 0, -1, false, QW))
    | "Aux_t_dL0" → O (Aux_top (0, 0, 0, true, DL)) | "Aux_dL0" →
O (Aux_top (0, 0, 0, false, DL))
    | "Aux_t_dL+" → O (Aux_top (0, 0, 1, true, DL)) | "Aux_dL+" →
O (Aux_top (0, 0, 1, false, DL))
    | "Aux_t_dL-" → O (Aux_top (0, 0, -1, true, DL)) | "Aux_dL-" →
O (Aux_top (0, 0, -1, false, DL))
    | "Aux_t_dR0" → O (Aux_top (0, 0, 0, true, DR)) | "Aux_dR0" →
O (Aux_top (0, 0, 0, false, DR))
    | "Aux_t_dR+" → O (Aux_top (0, 0, 1, true, DR)) | "Aux_dR+" →
O (Aux_top (0, 0, 1, false, DR))
    | "Aux_t_dR-" → O (Aux_top (0, 0, -1, true, DR)) | "Aux_dR-" →
O (Aux_top (0, 0, -1, false, DR))
    | "Aux_t_quqd1L+" → O (Aux_top (0, 0, 1, true, QUQD1L)) | "Aux_quqd1L+" →
O (Aux_top (0, 0, 1, false, QUQD1L))
    | "Aux_t_quqd1L-" → O (Aux_top (0, 0, -1, true, QUQD1L)) | "Aux_quqd1L-" →
O (Aux_top (0, 0, -1, false, QUQD1L))
    | "Aux_t_quqd1R+" → O (Aux_top (0, 0, 1, true, QUQD1R)) | "Aux_quqd1R+" →
O (Aux_top (0, 0, 1, false, QUQD1R))
    | "Aux_t_quqd1R-" → O (Aux_top (0, 0, -1, true, QUQD1R)) | "Aux_quqd1R-" →
O (Aux_top (0, 0, -1, false, QUQD1R))
    | "Aux_t_quqd8L+" → O (Aux_top (0, 1, 1, true, QUQD8L)) | "Aux_quqd8L+" →
O (Aux_top (0, 1, 1, false, QUQD8L))
    | "Aux_t_quqd8L-" → O (Aux_top (0, 1, -1, true, QUQD8L)) | "Aux_quqd8L-" →
O (Aux_top (0, 1, -1, false, QUQD8L))
    | "Aux_t_quqd8R+" → O (Aux_top (0, 1, 1, true, QUQD8R)) | "Aux_quqd8R+" →
O (Aux_top (0, 1, 1, false, QUQD8R))
    | "Aux_t_quqd8R-" → O (Aux_top (0, 1, -1, true, QUQD8R)) | "Aux_quqd8R-" →
O (Aux_top (0, 1, -1, false, QUQD8R))
    | _ → invalid_arg "Modellib.SM.flavor_of_string"

let flavor_to_string = function
| M f →
  begin match f with
  | L 1 → "e-" | L (-1) → "e+"
  | L 2 → "mu-" | L (-2) → "mu+"
  | L 3 → "tau-" | L (-3) → "tau+"
  | L _ → invalid_arg
  "Modellib.SM.flavor_to_string:␣invalid␣lepton"
  | N 1 → "nue" | N (-1) → "nuebar"
  | N 2 → "numu" | N (-2) → "numubar"
  | N 3 → "nutau" | N (-3) → "nutaubar"
  | N _ → invalid_arg

```

```

        "Modellib.SM.flavor_to_string:_invalid_neutrino"
    |  $U\ 1 \rightarrow "u" \mid U\ (-1) \rightarrow "ubar"$ 
    |  $U\ 2 \rightarrow "c" \mid U\ (-2) \rightarrow "cbar"$ 
    |  $U\ 3 \rightarrow "t" \mid U\ (-3) \rightarrow "tbar"$ 
    |  $U\ _ \rightarrow invalid\_arg$ 
        "Modellib.SM.flavor_to_string:_invalid_up_type_quark"
    |  $D\ 1 \rightarrow "d" \mid D\ (-1) \rightarrow "dbar"$ 
    |  $D\ 2 \rightarrow "s" \mid D\ (-2) \rightarrow "sbar"$ 
    |  $D\ 3 \rightarrow "b" \mid D\ (-3) \rightarrow "bbar"$ 
    |  $D\ _ \rightarrow invalid\_arg$ 
        "Modellib.SM.flavor_to_string:_invalid_down_type_quark"
    end
|  $G\ f \rightarrow$ 
    begin match  $f$  with
    |  $G_l \rightarrow "gl"$ 
    |  $G_a \rightarrow "A" \mid Z \rightarrow "Z"$ 
    |  $W_p \rightarrow "W+" \mid W_m \rightarrow "W-"$ 
    end
|  $O\ f \rightarrow$ 
    begin match  $f$  with
    |  $\Phi_{ip} \rightarrow "phi+" \mid \Phi_{im} \rightarrow "phi-" \mid \Phi_{i0} \rightarrow "phi0"$ 
    |  $H \rightarrow "H"$ 
    |  $Aux\_top\ (_,_,ch,n,v) \rightarrow "Aux\_ " ^ (if\ n\ then\ "t\_ " else\ "") ^ ($ 
        begin match  $v$  with
        |  $TTGG \rightarrow "ttGG" \mid TBWA \rightarrow "tbWA" \mid TBWZ \rightarrow$ 
            "tbWZ"
        |  $TTWW \rightarrow "ttWW" \mid BBWW \rightarrow "bbWW"$ 
        |  $QGUG \rightarrow "qGuG" \mid QBUB \rightarrow "qBuB"$ 
        |  $QW \rightarrow "qW" \mid DL \rightarrow "dL" \mid DR \rightarrow "dR"$ 
        |  $QUQD1L \rightarrow "quqd1L" \mid QUQD1R \rightarrow "quqd1R"$ 
        |  $QUQD8L \rightarrow "quqd8L" \mid QUQD8R \rightarrow "quqd8R"$ 
        end) ^ (if\  $ch > 0$  then\ "+" else\ if\  $ch < 0$  then\ "-" else\ "0")
    end
let flavor_to_TeX = function
|  $M\ f \rightarrow$ 
    begin match  $f$  with
    |  $L\ 1 \rightarrow "e^- " \mid L\ (-1) \rightarrow "e^+ "$ 
    |  $L\ 2 \rightarrow "\\mu^- " \mid L\ (-2) \rightarrow "\\mu^+ "$ 
    |  $L\ 3 \rightarrow "\\tau^- " \mid L\ (-3) \rightarrow "\\tau^+ "$ 
    |  $L\ _ \rightarrow invalid\_arg$ 
        "Modellib.SM.flavor_to_TeX:_invalid_lepton"
    |  $N\ 1 \rightarrow "\\nu\_e" \mid N\ (-1) \rightarrow "\\bar{\nu}\_e"$ 
    |  $N\ 2 \rightarrow "\\nu\_\\mu" \mid N\ (-2) \rightarrow "\\bar{\nu}\_\\mu"$ 
    |  $N\ 3 \rightarrow "\\nu\_\\tau" \mid N\ (-3) \rightarrow "\\bar{\nu}\_\\tau"$ 
    |  $N\ _ \rightarrow invalid\_arg$ 
        "Modellib.SM.flavor_to_TeX:_invalid_neutrino"
    |  $U\ 1 \rightarrow "u" \mid U\ (-1) \rightarrow "\\bar{u}"$ 
    |  $U\ 2 \rightarrow "c" \mid U\ (-2) \rightarrow "\\bar{c}"$ 
    |  $U\ 3 \rightarrow "t" \mid U\ (-3) \rightarrow "\\bar{t}"$ 

```



```

|  $U_- \rightarrow \text{invalid\_arg}$ 
  "Modellib.SM.flavor_to_TeX:invalid_up_type_quark"
|  $D\ 1 \rightarrow "d" \mid D\ (-1) \rightarrow "\\bar{d}"$ 
|  $D\ 2 \rightarrow "s" \mid D\ (-2) \rightarrow "\\bar{s}"$ 
|  $D\ 3 \rightarrow "b" \mid D\ (-3) \rightarrow "\\bar{b}"$ 
|  $D_- \rightarrow \text{invalid\_arg}$ 
  "Modellib.SM.flavor_to_TeX:invalid_down_type_quark"
end
|  $G\ f \rightarrow$ 
  begin match  $f$  with
  |  $G_l \rightarrow "g"$ 
  |  $G_a \rightarrow "\\gamma" \mid Z \rightarrow "Z"$ 
  |  $W_p \rightarrow "W^+" \mid W_m \rightarrow "W^-"$ 
  end
|  $O\ f \rightarrow$ 
  begin match  $f$  with
  |  $Phip \rightarrow "\\phi^+" \mid Phim \rightarrow "\\phi^-"$  |  $Phi0 \rightarrow$ 
    "\\phi^0"
  |  $H \rightarrow "H"$ 
  |  $Aux\_top(-, -, ch, n, v) \rightarrow "\\textnormal{Aux\_}^{\wedge}(\text{if } n \text{ then } "t\_ " \text{ else } "")^{\wedge}(\text{begin match } v \text{ with}$ 
    |  $TTGG \rightarrow "ttGG" \mid TBWA \rightarrow "tbWA" \mid TBWZ \rightarrow$ 
      "tbWZ"
    |  $TTWW \rightarrow "ttWW" \mid BBWW \rightarrow "bbWW"$ 
    |  $QGUG \rightarrow "qGuG" \mid QBUB \rightarrow "qBuB"$ 
    |  $QW \rightarrow "qW" \mid DL \rightarrow "dL" \mid DR \rightarrow "dR"$ 
    |  $QUQD1L \rightarrow "quqd1L" \mid QUQD1R \rightarrow "quqd1R"$ 
    |  $QUQD8L \rightarrow "quqd8L" \mid QUQD8R \rightarrow "quqd8R"$ 
    end) ^ (if  $ch > 0$  then "^+" else if  $ch < 0$  then "^-" else "^0") ^ "}"
  end
let flavor_symbol = function
|  $M\ f \rightarrow$ 
  begin match  $f$  with
  |  $L\ n$  when  $n > 0 \rightarrow "l" ^ \text{string\_of\_int } n$ 
  |  $L\ n \rightarrow "l" ^ \text{string\_of\_int } (\text{abs } n) ^ "b"$ 
  |  $N\ n$  when  $n > 0 \rightarrow "n" ^ \text{string\_of\_int } n$ 
  |  $N\ n \rightarrow "n" ^ \text{string\_of\_int } (\text{abs } n) ^ "b"$ 
  |  $U\ n$  when  $n > 0 \rightarrow "u" ^ \text{string\_of\_int } n$ 
  |  $U\ n \rightarrow "u" ^ \text{string\_of\_int } (\text{abs } n) ^ "b"$ 
  |  $D\ n$  when  $n > 0 \rightarrow "d" ^ \text{string\_of\_int } n$ 
  |  $D\ n \rightarrow "d" ^ \text{string\_of\_int } (\text{abs } n) ^ "b"$ 
  end
|  $G\ f \rightarrow$ 
  begin match  $f$  with
  |  $G_l \rightarrow "gl"$ 
  |  $G_a \rightarrow "a" \mid Z \rightarrow "z"$ 
  |  $W_p \rightarrow "wp" \mid W_m \rightarrow "wm"$ 
  end
|  $O\ f \rightarrow$ 

```

```

begin match f with
| Phip → "pp" | Phim → "pm" | Phi0 → "p0"
| H → "h"
| Aux_top (–, –, ch, n, v) → "aux_" ^ (if n then "t_" else "") ^ (
  begin match v with
    | TTGG → "ttgg" | TBWA → "tbwa" | TBWZ →
"tbwz"
    | TTWW → "ttww" | BBWW → "bbww"
    | QGUG → "qgug" | QBUB → "qbub"
    | QW → "qw" | DL → "dl" | DR → "dr"
    | QUQD1L → "quqd1l" | QUQD1R → "quqd1r"
    | QUQD8L → "quqd8l" | QUQD8R → "quqd8r"
  end) ^ "_" ^ (if ch > 0 then "p" else if ch < 0 then "m" else "0")
end

let pdg = function
| M f →
  begin match f with
  | L n when n > 0 → 9 + 2 × n
  | L n → – 9 + 2 × n
  | N n when n > 0 → 10 + 2 × n
  | N n → – 10 + 2 × n
  | U n when n > 0 → 2 × n
  | U n → 2 × n
  | D n when n > 0 → – 1 + 2 × n
  | D n → 1 + 2 × n
  end
| G f →
  begin match f with
  | Gl → 21
  | Ga → 22 | Z → 23
  | Wp → 24 | Wm → (–24)
  end
| O f →
  begin match f with
  | Phip | Phim → 27 | Phi0 → 26
  | H → 25
  | Aux_top (–, –, ch, t, f) → let n =
    begin match f with
    | QW → 0
    | QUQD1R → 1 | QUQD1L → 2
    | QUQD8R → 3 | QUQD8L → 4
    | – → 5
    end
    in (602 + 3 × n – ch) × (if t then (1) else (–1))
  end
end

let mass_symbol f =
  if ( Flags.tt_threshold ∧ (abs (pdg f)) ≡ 6 ) then
    "ttv_mtpole(p12*p12)"
  else

```

```

"mass(" ^ string_of_int (abs (pdg f)) ^ ")")
let width_symbol f =
  "width(" ^ string_of_int (abs (pdg f)) ^ ")")
let constant_symbol = function
| Unit → "unit" | Half → "half" | Pi → "PI"
| Alpha-QED → "alpha" | E → "e" | G-weak → "g" | Vev →
"vev"
| I-G-weak → "ig"
| Sin2thw → "sin2thw" | Sinthw → "sinthw" | Costhw →
"costhw"
| Q-lepton → "qllep" | Q-up → "qup" | Q-down → "qdown"
| G-NC-lepton → "gnclep" | G-NC-neutrino → "gncneu"
| G-NC-up → "gncup" | G-NC-down → "gncdown"
| G-TVA-ttA → "gtva-tta" | G-TVA-bbA → "gtva-bba"
| G-VLR-ttZ → "gvlr-ttz" | G-TVA-ttZ → "gtva-ttz" |
G-TVA-bbZ → "gtva-bbz"
| VA-ILC-ttA → "va-ilc-tta" | VA-ILC-ttZ → "va-ilc-ttz"
| G-VLR-btW → "gvlr-btw" | G-VLR-tbW → "gvlr-tbw"
| G-TLR-btW → "gtlr-btw" | G-TRL-tbW → "gtrl-tbw"
| G-TLR-btWA → "gtlr-btwa" | G-TRL-tbWA → "gtrl-tbwa"
| G-TLR-btWZ → "gtlr-btwz" | G-TRL-tbWZ → "gtrl-tbwz"
| G-TVA-ttWW → "gtva-ttww" | G-TVA-bbWW → "gtva-bbww"
| G-TVA-ttG → "gtva-ttg" | G-TVA-ttGG → "gtva-ttgg"
| G-SP-ttH → "gsp-tth"
| G-VLR-qGuG → "gvlr-qgug"
| G-VLR-qBuB → "gvlr-qbub"
| G-VLR-qBuB-u → "gvlr-qbub-u" | G-VLR-qBuB-d → "gvlr-qbub-d"
| G-VLR-qBuB-e → "gvlr-qbub-e" | G-VL-qBuB-n → "gvl-qbub-n"
| G-VL-qW → "gvl-qw"
| G-VL-qW-u → "gvl-qw-u" | G-VL-qW-d → "gvl-qw-d"
| G-SL-DttR → "gsl-dttr" | G-SR-DttR → "gsr-dttr" |
G-SL-DttL → "gsl-dttl"
| G-SLR-DbtR → "gslr-dbtr" | G-SL-DbtL → "gsl-dbtl"
| C-quqd1R-bt → "c-quqd1.1" | C-quqd1R-tb → "conjg(c-quqd1.1)"
| C-quqd1L-bt → "conjg(c-quqd1.2)" | C-quqd1L-tb → "c-quqd1.2"
| C-quqd8R-bt → "c-quqd8.1" | C-quqd8R-tb → "conjg(c-quqd8.1)"
| C-quqd8L-bt → "conjg(c-quqd8.2)" | C-quqd8L-tb → "c-quqd8.2"
| G-CC → "gcc"
| G-CCQ (n1, n2) → "gccq" ^ string_of_int n1 ^ string_of_int n2
| I-Q-W → "iqw" | I-G-ZWW → "igzww"
| G-WWWW → "gw4" | G-ZZWW → "gzzww"
| G-AZWW → "gazww" | G-AAWW → "gaaww"
| I-G1-AWW → "ig1a" | I-G1-ZWW → "ig1z"
| I-G1-plus-kappa-plus-G4-AWW → "ig1pkpg4a"
| I-G1-plus-kappa-plus-G4-ZWW → "ig1pkpg4z"
| I-G1-plus-kappa-minus-G4-AWW → "ig1pkmg4a"
| I-G1-plus-kappa-minus-G4-ZWW → "ig1pkmg4z"
| I-G1-minus-kappa-plus-G4-AWW → "ig1mkpg4a"
| I-G1-minus-kappa-plus-G4-ZWW → "ig1mkpg4z"

```

```

| I_G1_minus_kappa_minus_G4_AWW → "ig1mkmg4a"
| I_G1_minus_kappa_minus_G4_ZWW → "ig1mkmg4z"
| I_lambda_AWW → "ila"
| I_lambda_ZWW → "ilz"
| G5_AWW → "rg5a"
| G5_ZWW → "rg5z"
| I_kappa5_AWW → "ik5a"
| I_kappa5_ZWW → "ik5z"
| I_lambda5_AWW → "il5a" | I_lambda5_ZWW → "il5z"
| Alpha_WWWWW0 → "alww0" | Alpha_WWWWW2 → "alww2"
| Alpha_ZZWW0 → "alzw0" | Alpha_ZZWW1 → "alzw1"
| Alpha_ZZZZ → "alzz"
| D_Alpha_ZZWW0_S → "dalzz0-s(gkm,mkm,"
| D_Alpha_ZZWW0_T → "dalzz0-t(gkm,mkm,"
| D_Alpha_ZZWW1_S → "dalzz1-s(gkm,mkm,"
| D_Alpha_ZZWW1_T → "dalzz1-t(gkm,mkm,"
| D_Alpha_ZZWW1_U → "dalzz1-u(gkm,mkm,"
| D_Alpha_WWWWW0_S → "dalww0-s(gkm,mkm,"
| D_Alpha_WWWWW0_T → "dalww0-t(gkm,mkm,"
| D_Alpha_WWWWW0_U → "dalww0-u(gkm,mkm,"
| D_Alpha_WWWWW2_S → "dalww2-s(gkm,mkm,"
| D_Alpha_WWWWW2_T → "dalww2-t(gkm,mkm,"
| D_Alpha_ZZZZ_S → "dalz4-s(gkm,mkm,"
| D_Alpha_ZZZZ_T → "dalz4-t(gkm,mkm,"
| G_HWW → "ghww" | G_HZZ → "ghzz"
| G_HHWW → "ghhww" | G_HHZZ → "ghhzz"
| G_Htt → "ghtt" | G_Hbb → "ghbb"
| G_Htautau → "ghtautau" | G_Hcc → "ghcc" | G_Hmm →
"ghmm"
| G_HGaZ → "ghgaz" | G_HGaGa → "ghgaga" | G_Hgg →
"ghgg"
| G_HGaGa_anom → "ghgaga-ac" | G_HGaZ_anom → "ghgaz-ac"
| G_HZZ_anom → "ghzz-ac" | G_HWW_anom → "ghww-ac"
| G_HGaZ_u → "ghgaz-u" | G_HZZ_u → "ghzz-u"
| G_HWW_u → "ghww-u"
| G_H3 → "gh3" | G_H4 → "gh4"
| Gs → "gs" | I_Gs → "igs" | G2 → "gs**2"
| Mass f → "mass" ^ flavor_symbol f
| Width f → "width" ^ flavor_symbol f
| K_Matrix_Coeff i → "kc" ^ string_of_int i
| K_Matrix_Pole i → "kp" ^ string_of_int i
end

```

### 13.4.7 Incomplete Standard Model in $R_\xi$ Gauge



At the end of the day, we want a functor mapping from gauge models in unitarity gauge to  $R_\xi$  gauge and vice versa. For this, we will need a more abstract implementation of (spontaneously broken) gauge theories.

```

module SM_Rxi =
  struct
    let rcs = RCS.rename rcs_file "Modellib.SM_Rxi"
    [ "minimal_electroweak_standard_model_in_R-xi_gauge";
      "NB: very incomplete still!, no CKM matrix" ]

    open Coupling

    module SM = SM(SM_no_anomalous)
    let options = SM.options
    type flavor = SM.flavor
    let flavors = SM.flavors
    let external_flavors = SM.external_flavors
    (* Later: type orders = SM.orders *)
    type constant = SM.constant
    (* Later: let orders = SM.orders *)
    let lorentz = SM.lorentz
    let color = SM.color
    let goldstone = SM.goldstone
    let conjugate = SM.conjugate
    let fermion = SM.fermion

```



Check if it makes sense to have separate gauge fixing parameters for each vector boson. There's probably only one independent parameter for each group factor.

```

type gauge =
  | XiA | XiZ | XiW

let gauge_symbol = function
  | XiA → "xia" | XiZ → "xi0" | XiW → "xipm"

```

Change the gauge boson propagators and make the Goldstone bosons propagating.

```

let propagator = function
  | SM.G SM.Ga → Prop_Gauge XiA
  | SM.G SM.Z → Prop_Rxi XiZ
  | SM.G SM.Wp | SM.G SM.Wm → Prop_Rxi XiW
  | SM.O SM.Phip | SM.O SM.Phim | SM.O SM.Phi0 → Prop_Scalar
  | f → SM.propagator f

let width = SM.width

module Ch = Charges.QQ
let charges = SM.charges

module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)

```

```

let vertices = SM.vertices
let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 3

let parameters = SM.parameters
let flavor_of_string = SM.flavor_of_string
let flavor_to_string = SM.flavor_to_string
let flavor_to_TeX = SM.flavor_to_TeX
let flavor_symbol = SM.flavor_symbol
let pdg = SM.pdg
let mass_symbol = SM.mass_symbol
let width_symbol = SM.width_symbol
let constant_symbol = SM.constant_symbol

end

```

#### 13.4.8 Groves

```

module Groves (M : Model.Gauge) : Model.Gauge with module Ch = M.Ch =
struct
  let max_generations = 5
  let rcs = RCS.rename M.rcs
    ("Modellib.Groves(" ^ (RCS.name M.rcs) ^ ")")
    ([ "experimental_Groves_functor";
      Printf.sprintf "for_maximally_%d_flavored_legs"
        (2 × max_generations) ] @
      RCS.description M.rcs)

  let options = M.options

  type matter_field = M.matter_field × int
  type gauge_boson = M.gauge_boson
  type other = M.other
  type field =
    | Matter of matter_field
    | Gauge of gauge_boson
    | Other of other
  type flavor = M of matter_field | G of gauge_boson | O of other
  let matter_field (f, g) = M (f, g)
  let gauge_boson f = G f
  let other f = O f
  let field = function
    | M f → Matter f
    | G f → Gauge f
    | O f → Other f
  let project = function
    | M (f, _) → M.matter_field f
    | G f → M.gauge_boson f

```

```

    |  $O f \rightarrow M.other\ f$ 
let inject  $g\ f =$ 
  match  $M.field\ f$  with
  |  $M.Matter\ f \rightarrow M(f, g)$ 
  |  $M.Gauge\ f \rightarrow G\ f$ 
  |  $M.Other\ f \rightarrow O\ f$ 
type gauge =  $M.gauge$ 
let gauge_symbol =  $M.gauge\_symbol$ 
let color  $f = M.color\ (project\ f)$ 
let pdg  $f = M.pdg\ (project\ f)$ 
let lorentz  $f = M.lorentz\ (project\ f)$ 
let propagator  $f = M.propagator\ (project\ f)$ 
let fermion  $f = M.fermion\ (project\ f)$ 
let width  $f = M.width\ (project\ f)$ 
let mass_symbol  $f = M.mass\_symbol\ (project\ f)$ 
let width_symbol  $f = M.width\_symbol\ (project\ f)$ 
let flavor_symbol  $f = M.flavor\_symbol\ (project\ f)$ 

type constant =  $M.constant$ 
(* Later: type orders =  $M.orders$  *)
let constant_symbol =  $M.constant\_symbol$ 
let max_degree =  $M.max\_degree$ 
let parameters =  $M.parameters$ 
(* Later: let orders =  $M.orders$  *)

let conjugate = function
|  $M(-, g)$  as  $f \rightarrow inject\ g\ (M.conjugate\ (project\ f))$ 
|  $f \rightarrow inject\ 0\ (M.conjugate\ (project\ f))$ 

let read_generation  $s =$ 
  try
    let offset =  $String.index\ s\ '/'$  in
    (int_of_string
      ( $String.sub\ s\ (succ\ offset)\ (String.length\ s - offset - 1)$ ),
       $String.sub\ s\ 0\ offset$ )
  with
  |  $Not\_found \rightarrow (1, s)$ 

let format_generation  $c\ s =$ 
   $s \wedge "/" \wedge string\_of\_int\ c$ 

let flavor_of_string  $s =$ 
  let  $g, s = read\_generation\ s$  in
  inject  $g\ (M.flavor\_of\_string\ s)$ 

let flavor_to_string = function
|  $M(-, g)$  as  $f \rightarrow format\_generation\ g\ (M.flavor\_to\_string\ (project\ f))$ 
|  $f \rightarrow M.flavor\_to\_string\ (project\ f)$ 

let flavor_to_TeX = function
|  $M(-, g)$  as  $f \rightarrow format\_generation\ g\ (M.flavor\_to\_TeX\ (project\ f))$ 
|  $f \rightarrow M.flavor\_to\_TeX\ (project\ f)$ 

let goldstone = function

```

```

| G _ as f →
  begin match M.goldstone (project f) with
  | None → None
  | Some (f, c) → Some (inject 0 f, c)
  end
| M _ | O _ → None

let clone generations flavor =
  match M.field flavor with
  | M.Matter f → List.map (fun g → M (f, g)) generations
  | M.Gauge f → [G f]
  | M.Other f → [O f]

let generations = ThoList.range 1 max_generations

let flavors () =
  ThoList.flatmap (clone generations) (M.flavors ())

let external_flavors () =
  List.map (fun (s, fl) → (s, ThoList.flatmap (clone generations) fl))
    (M.external_flavors ())

module Ch = M.Ch
let charges f = M.charges (project f)

module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)

```

In the following functions, we might replace `_` by `(M.Gauge _ | M.Other _)`, in order to allow the compiler to check completeness. However, this makes the code much less readable.

```

let clone3 ((f1, f2, f3), v, c) =
  match M.field f1, M.field f2, M.field f3 with
  | M.Matter _, M.Matter _, M.Matter _ →
    invalid_arg "Modellib.Groves().vertices:␣three␣matter␣fields!"
  | M.Matter f1', M.Matter f2', _ →
    List.map (fun g → ((M (f1', g), M (f2', g), inject 0 f3), v, c))
      generations
  | M.Matter f1', _, M.Matter f3' →
    List.map (fun g → ((M (f1', g), inject 0 f2, M (f3', g)), v, c))
      generations
  | _, M.Matter f2', M.Matter f3' →
    List.map (fun g → ((inject 0 f1, M (f2', g), M (f3', g)), v, c))
      generations
  | M.Matter _, _, _ | _, M.Matter _, _ | _, _, M.Matter _ →
    invalid_arg "Modellib.Groves().vertices:␣lone␣matter␣field!"
  | _, _, _ →
    [(inject 0 f1, inject 0 f2, inject 0 f3), v, c]

```



```

let clone4 ((f1, f2, f3, f4), v, c) =
  match M.field f1, M.field f2, M.field f3, M.field f4 with
  | M.Matter -, M.Matter -, M.Matter -, M.Matter - →
    invalid_arg "Modellib.Groves().vertices:␣four␣matter␣fields!"
  | M.Matter -, M.Matter -, M.Matter -, -
  | M.Matter -, M.Matter -, -, M.Matter -
  | M.Matter -, -, M.Matter -, M.Matter -
  | -, M.Matter -, M.Matter -, M.Matter - →
    invalid_arg "Modellib.Groves().vertices:␣three␣matter␣fields!"
  | M.Matter f1', M.Matter f2', -, - →
    List.map (fun g →
      ((M (f1', g), M (f2', g), inject 0 f3, inject 0 f4), v, c))
      generations
  | M.Matter f1', -, M.Matter f3', - →
    List.map (fun g →
      ((M (f1', g), inject 0 f2, M (f3', g), inject 0 f4), v, c))
      generations
  | M.Matter f1', -, -, M.Matter f4' →
    List.map (fun g →
      ((M (f1', g), inject 0 f2, inject 0 f3, M (f4', g)), v, c))
      generations
  | -, M.Matter f2', M.Matter f3', - →
    List.map (fun g →
      ((inject 0 f1, M (f2', g), M (f3', g), inject 0 f4), v, c))
      generations
  | -, M.Matter f2', -, M.Matter f4' →
    List.map (fun g →
      ((inject 0 f1, M (f2', g), inject 0 f3, M (f4', g)), v, c))
      generations
  | -, -, M.Matter f3', M.Matter f4' →
    List.map (fun g →
      ((inject 0 f1, inject 0 f2, M (f3', g), M (f4', g)), v, c))
      generations
  | M.Matter -, -, -, - | -, M.Matter -, -, -
  | -, -, M.Matter -, - | -, -, -, M.Matter - →
    invalid_arg "Modellib.Groves().vertices:␣lone␣matter␣field!"
  | -, -, -, - →
    [(inject 0 f1, inject 0 f2, inject 0 f3, inject 0 f4), v, c]

let clonen (fl, v, c) =
  match List.map M.field fl with
  | - → failwith "Modellib.Groves().vertices:␣incomplete"

let vertices () =
  let vertices3, vertices4, verticesn = M.vertices () in
  (ThoList.flatmap clone3 vertices3,
   ThoList.flatmap clone4 vertices4,
   ThoList.flatmap clonen verticesn)

let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table

```

```
let fuse = F.fuse table
```



The following (incomplete) alternative implementations are included for illustrative purposes only:

```
let injectl g fcl =
  List.map (fun (f, c) → (inject g f, c)) fcl

let alt_fuse2 f1 f2 =
  match f1, f2 with
  | M (f1', g1'), M (f2', g2') →
    if g1' = g2' then
      injectl 0 (M.fuse2 (M.matter_field f1') (M.matter_field f2'))
    else
      []
  | M (f1', g'), -, - → injectl g' (M.fuse2 (M.matter_field f1') (project f2))
  | -, M (f2', g') → injectl g' (M.fuse2 (project f1) (M.matter_field f2'))
  | -, - → injectl 0 (M.fuse2 (project f1) (project f2))

let alt_fuse3 f1 f2 f3 =
  match f1, f2, f3 with
  | M (f1', g1'), M (f2', g2'), M (f3', g3') →
    invalid_arg "Modellib.Groves().fuse3:␣three␣matter␣fields!"
  | M (f1', g1'), M (f2', g2'), - →
    if g1' = g2' then
      injectl 0
        (M.fuse3 (M.matter_field f1') (M.matter_field f2') (project f3))
    else
      []
  | M (f1', g1'), -, M (f3', g3') →
    if g1' = g3' then
      injectl 0
        (M.fuse3 (M.matter_field f1') (project f2) (M.matter_field f3'))
    else
      []
  | -, M (f2', g2'), M (f3', g3') →
    if g2' = g3' then
      injectl 0
        (M.fuse3 (project f1) (M.matter_field f2') (M.matter_field f3'))
    else
      []
  | M (f1', g'), -, - →
    injectl g' (M.fuse3 (M.matter_field f1') (project f2) (project f3))
  | -, M (f2', g'), - →
    injectl g' (M.fuse3 (project f1) (M.matter_field f2') (project f3))
  | -, -, M (f3', g') →
    injectl g' (M.fuse3 (project f1) (project f2) (M.matter_field f3'))
  | -, -, - → injectl 0 (M.fuse3 (project f1) (project f2) (project f3))
```

end

### 13.4.9 MSM With Cloned Families

```
module SM_clones = Groves(SM(SM_no_anomalous))
```

## 13.5 Interface of *Modellib\_BSM*

### 13.5.1 More Hardcoded BSM Models

```
module type BSM_flags =
  sig
    val u1_gauged : bool
    val anom_ferm_ass : bool
  end

module type THDM_flags =
  sig
    val ckm_present : bool
  end

module BSM_bsm : BSM_flags
module BSM_ungauged : BSM_flags
module BSM_anom : BSM_flags
module Littlest : functor (F : BSM_flags) → Model.Gauge with mod-
  ule Ch = Charges.QQ
module Littlest_Tpar : functor (F : BSM_flags) → Model.T with mod-
  ule Ch = Charges.QQ
module Simplest : functor (F : BSM_flags) → Model.T with module Ch = Charges.QQ
module Xdim : functor (F : BSM_flags) → Model.Gauge with mod-
  ule Ch = Charges.QQ
module UED : functor (F : BSM_flags) → Model.Gauge with mod-
  ule Ch = Charges.QQ
module GravTest : functor (F : BSM_flags) → Model.Gauge with mod-
  ule Ch = Charges.QQ
module THDM : THDM_flags
module THDM_CKM : THDM_flags
module TwoHiggsDoublet : functor (F : THDM_flags) → Model.Gauge with mod-
  ule Ch = Charges.QQ
module Template : functor (F : BSM_flags) → Model.Gauge with mod-
  ule Ch = Charges.QQ
module HSExt : functor (F : BSM_flags) → Model.Gauge with mod-
  ule Ch = Charges.QQ

module type Threshl_options =
  sig
    val include_ckm : bool
    val include_hf : bool
    val diet : bool
  end

module Threshl_no_ckm : Threshl_options
module Threshl_ckm : Threshl_options
```

```

module Threeshl_no_ckm_no_hf : Threeshl_options
module Threeshl_ckm_no_hf : Threeshl_options
module Threeshl_diet_no_hf : Threeshl_options
module Threeshl_diet : Threeshl_options
module Threeshl : functor (Module_options : Threeshl_options) →
  Model.T with module Ch = Charges.QQ

module type SSC_flags =
  sig
    val higgs_triangle : bool (*  $H\gamma\gamma$ ,  $Hg\gamma$  and  $Hgg$  couplings *)
    val higgs_hmm : bool
    val triple_anom : bool
    val quartic_anom : bool
    val higgs_anom : bool
    val k_matrix : bool
    val ckm_present : bool
    val top_anom : bool
    val top_anom_4f : bool
  end

module SSC_kmatrix : SSC_flags

module SSC : functor (F : SSC_flags) → Model.Gauge with module Ch = Charges.QQ

```

### 13.6 Implementation of *Modellib\_BSM*

```

let rcs_file = RCS.parse "Modellib_BSM" ["BSM_Models"]
{ RCS.revision = "$Revision: 6295$";
  RCS.date = "$Date: 2014-11-21 19:58:53 +0100 (Fri, 21 Nov 2014)$";
  RCS.author = "$Author: bchokoufe$";
  RCS.source
    = "$URL: svn+ssh://jr-reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/s"

```

#### 13.6.1 Littlest Higgs Model

```

module type BSM_flags =
  sig
    val u1_gauged : bool
    val anom_ferm_ass : bool
  end

module BSM_bsm : BSM_flags =
  struct
    let u1_gauged = true
    let anom_ferm_ass = false
  end

module BSM_ungauged : BSM_flags =
  struct
    let u1_gauged = false
  end

```

```

    let anom_ferm_ass = false
  end

module BSM_anom : BSM_flags =
  struct
    let u1_gauged = false
    let anom_ferm_ass = true
  end

module Littlest (Flags : BSM_flags) =
  struct
    let rcs = rcs_file

    open Coupling

    let default_width = ref Timelike
    let use_fudged_width = ref false

    let options = Options.create
      [ "constant_width", Arg.Unit (fun () → default_width := Constant),
        "use_constant_width(also_in_t-channel)";
        "fudged_width", Arg.Set use_fudged_width,
        "use_fudge_factor_for_charge_particle_width";
        "custom_width", Arg.String (fun f → default_width := Custom f),
        "use_custom_width";
        "cancel_widths", Arg.Unit (fun () → default_width := Vanishing),
        "use_vanishing_width" ]

    let gauge_symbol () =
      failwith "Modellib-BSM.Littlest.gauge_symbol: internal error"

    type matter_field = L of int | N of int | U of int | D of int
      | TopH | TopHb
    type gauge_boson = Ga | Wp | Wm | Z | Gl | WHp | WHm
      | ZH | AH
    type other = Phip | Phim | Phi0 | H | Eta | Psi0
      | Psi1 | Psip | Psim | Psipp | Psimm

    type flavor = M of matter_field | G of gauge_boson | O of other

    let matter_field f = M f
    let gauge_boson f = G f
    let other f = O f

    type field =
      | Matter of matter_field
      | Gauge of gauge_boson
      | Other of other

    let field = function
      | M f → Matter f
      | G f → Gauge f
      | O f → Other f

    type gauge = unit

```

```

let gauge_symbol () =
  failwith "Modellib_BSM.Littlest.gauge_symbol: internal error"

let family n = List.map matter_field [ L n; N n; U n; D n ]

```

Since *Phi* already belongs to the EW Goldstone bosons we use *Psi* for the TeV scale complex triplet.

```

let external_flavors () =
  [ "1st_Generation", ThoList.flatmap family [1; -1];
    "2nd_Generation", ThoList.flatmap family [2; -2];
    "3rd_Generation", ThoList.flatmap family [3; -3];
    "Heavy_Quarks", List.map matter_field [TopH; TopHb];
    "HeavyScalars", List.map other
      [Psi0; Psi1; Psip; Psim; Psipp; Psimm];
    "GaugeBosons", List.map gauge_boson
      (if Flags.u1_gauged then
        [Ga; Z; Wp; Wm; Gl; WHp; WHm; ZH; AH]
      else
        [Ga; Z; Wp; Wm; Gl; WHp; WHm; ZH]);
    "Higgs", List.map other
      (if Flags.u1_gauged then [H]
      else [H; Eta]);
    "GoldstoneBosons", List.map other [Phip; Phim; Phi0] ]

let flavors () = ThoList.flatmap snd (external_flavors ())

let spinor n =
  if n ≥ 0 then
    Spinor
  else
    ConjSpinor

let lorentz = function
| M f →
  begin match f with
  | L n → spinor n | N n → spinor n
  | U n → spinor n | D n → spinor n
  | TopH → Spinor | TopHb → ConjSpinor
  end
| G f →
  begin match f with
  | Ga | Gl → Vector
  | Wp | Wm | Z | WHp | WHm | ZH | AH →
Massive_Vector
  end
| O f →
  begin match f with
  | Phip | Phim | Phi0 | H | Eta | Psi0
  | Psi1 | Psip | Psim | Psipp | Psimm → Scalar
  end

let color = function
| M (U n) → Color.SUN (if n > 0 then 3 else -3)

```

```

|  $M (D n) \rightarrow Color.SUN$  (if  $n > 0$  then 3 else -3)
|  $M TopH \rightarrow Color.SUN$  3 |  $M TopHb \rightarrow Color.SUN$  (-3)
|  $G Gl \rightarrow Color.AdjSUN$  3
|  $- \rightarrow Color.Singlet$ 

let prop_spinor  $n =$ 
  if  $n \geq 0$  then
    Prop_Spinor
  else
    Prop_ConjSpinor

let propagator = function
|  $M f \rightarrow$ 
  begin match  $f$  with
  |  $L n \rightarrow prop\_spinor\ n$  |  $N n \rightarrow prop\_spinor\ n$ 
  |  $U n \rightarrow prop\_spinor\ n$  |  $D n \rightarrow prop\_spinor\ n$ 
  |  $TopH \rightarrow Prop\_Spinor$  |  $TopHb \rightarrow Prop\_ConjSpinor$ 
  end
|  $G f \rightarrow$ 
  begin match  $f$  with
  |  $Ga$  |  $Gl \rightarrow Prop\_Feynman$ 
  |  $Wp$  |  $Wm$  |  $Z$  |  $WHp$  |  $WHm$  |  $ZH$  |  $AH \rightarrow$ 
Prop_Unitarity
  end
|  $O f \rightarrow$ 
  begin match  $f$  with
  |  $Phip$  |  $Phim$  |  $Phi0 \rightarrow Only\_Insertion$ 
  |  $H$  |  $Eta$  |  $Psi0$  |  $Psi1$  |  $Psip$  |  $Psim$ 
  |  $Psipp$  |  $Psimm \rightarrow Prop\_Scalar$ 
  end
end

```

Optionally, ask for the fudge factor treatment for the widths of charged particles.  
Currently, this only applies to  $W^\pm$  and top.

```

let width  $f =$ 
  if !use_fudged_width then
    match  $f$  with
    |  $G Wp$  |  $G Wm$  |  $M (U\ 3)$  |  $M (U\ (-3))$ 
    |  $G WHp$  |  $G WHm$  |  $G ZH$  |  $G AH$ 
    |  $M TopH$  |  $M TopHb \rightarrow Fudged$ 
    |  $- \rightarrow !default\_width$ 
  else
    !default_width

let goldstone = function
|  $G f \rightarrow$ 
  begin match  $f$  with
  |  $Wp \rightarrow Some (O\ Phip, Coupling.Const\ 1)$ 
  |  $Wm \rightarrow Some (O\ Phim, Coupling.Const\ 1)$ 
  |  $Z \rightarrow Some (O\ Phi0, Coupling.Const\ 1)$ 
  |  $- \rightarrow None$ 
  end
|  $- \rightarrow None$ 

```

```

let conjugate = function
| M f →
  M (begin match f with
    | L n → L (-n) | N n → N (-n)
    | U n → U (-n) | D n → D (-n)
    | TopH → TopHb | TopHb → TopH
  end)
| G f →
  G (begin match f with
    | Gl → Gl | Ga → Ga | Z → Z
    | Wp → Wm | Wm → Wp | WHm → WHp
    | WHp → WHm | ZH → ZH | AH → AH
  end)
| O f →
  O (begin match f with
    | Psi0 → Psi0 | Psi1 → Psi1 | Psip → Psim
    | Psim → Psip | Psipp → Psimm | Psimm → Psipp
    | Phip → Phim | Phim → Phip | Phi0 → Phi0
    | H → H | Eta → Eta
  end)

let fermion = function
| M f →
  begin match f with
  | L n → if n > 0 then 1 else -1
  | N n → if n > 0 then 1 else -1
  | U n → if n > 0 then 1 else -1
  | D n → if n > 0 then 1 else -1
  | TopH → 1 | TopHb → -1
  end
| G f →
  begin match f with
  | Gl | Ga | Z | Wp | Wm | WHp
  | WHm | AH | ZH → 0
  end
| O f →
  begin match f with
  | Psi0 | Psi1 | Psip | Psim | Psipp | Psimm
  | Phip | Phim | Phi0 | H | Eta → 0
  end

```

This model does NOT have a conserved generation charge even in absence of CKM mixing because of the heavy top admixture.

```

module Ch = Charges.QQ
let ( // ) = Algebra.Small_Rational.make

let charge = function
| M f →
  begin match f with
  | L n → if n > 0 then -1//1 else 1//1
  | N n → 0//1

```



```

|  $U\ n \rightarrow \text{if } n > 0 \text{ then } 2//3 \text{ else } -2//3$ 
|  $D\ n \rightarrow \text{if } n > 0 \text{ then } -1//3 \text{ else } 1//3$ 
|  $TopH \rightarrow 2//3$ 
|  $TopHb \rightarrow -2//3$ 
end
|  $G\ f \rightarrow$ 
  begin match  $f$  with
  |  $Gl$  |  $Ga$  |  $Z$  |  $AH$  |  $ZH \rightarrow 0//1$ 
  |  $Wp$  |  $WHp \rightarrow 1//1$ 
  |  $Wm$  |  $WHm \rightarrow -1//1$ 
  end
|  $O\ f \rightarrow$ 
  begin match  $f$  with
  |  $H$  |  $Phi0$  |  $Eta$  |  $Psi1$  |  $Psi0 \rightarrow 0//1$ 
  |  $Phip$  |  $Psip \rightarrow 1//1$ 
  |  $Phim$  |  $Psim \rightarrow -1//1$ 
  |  $Psipp \rightarrow 2//1$ 
  |  $Psimm \rightarrow -2//1$ 
  end

let lepton = function
|  $M\ f \rightarrow$ 
  begin match  $f$  with
  |  $L\ n$  |  $N\ n \rightarrow \text{if } n > 0 \text{ then } 1//1 \text{ else } -1//1$ 
  |  $U\ -$  |  $D\ -$  |  $- \rightarrow 0//1$ 
  end
|  $G\ -$  |  $O\ - \rightarrow 0//1$ 

let baryon = function
|  $M\ f \rightarrow$ 
  begin match  $f$  with
  |  $L\ -$  |  $N\ - \rightarrow 0//1$ 
  |  $U\ n$  |  $D\ n \rightarrow \text{if } n > 0 \text{ then } 1//1 \text{ else } -1//1$ 
  |  $TopH \rightarrow 1//1$ 
  |  $TopHb \rightarrow -1//1$ 
  end
|  $G\ -$  |  $O\ - \rightarrow 0//1$ 

let charges  $f =$ 
[ charge  $f$ ; lepton  $f$ ; baryon  $f$ ]

type constant =
| Unit | Pi | Alpha_QED | Sin2thw
| Sinthw | Costhw | E | G_weak | Vev | VHeavy
| Supp | Supp2
| Sinpsi | Cospsi | Atpsi | Scs (* Mixing angles of SU(2) *)
| Q_lepton | Q_up | Q_down | Q_Z-up | G_CC | G_CCtop
| G_NC_neutrino | G_NC_lepton | G_NC_up | G_NC_down |
G_NC_heavy
| G_NC_h_neutrino | G_NC_h_lepton | G_NC_h_up | G_NC_h_down
| G_CC_heavy | G_ZHTHT | G_ZTHT | G_AHTHTH |
G_AHTHT | G_AHTT

```

---

```

      | G_CC_WH | G_CC_W
      | I_Q_W | I_G_ZWW | I_G_WWW
      | I_G_AHWW | I_G_ZHWW | I_G_ZHWW | I_G_AHWHWH |
I_G_ZHWHWH
      | I_G_AHWHWH | I_Q_H
      | G_WWWW | G_ZZWW | G_AZWW | G_AAWW
      | G_WH4 | G_WHWHWW | G_WHWWW | G_WH3W
      | G_WWAAH | G_WWAZH | G_WWZZH | G_WWZAH |
G_WWHWAAH
      | G_WWHWAZH | G_WWHWZZH | G_WWHWZAH | G_WWZHAH
      | G_WWHWZHAH | G_WHWZZ | G_WHWAZ | G_WHWAAH |
G_WHWZAH
      | G_WHWZHZH | G_WHWZHAH | G_WHWAZH | G_WHWZZH
      | G_HWW | G_HHWW | G_HZZ | G_HHZZ
      | G_PsiWW | G_PsiWHW | G_PsiZZ | G_PsiZHZH
      | G_PsiZHZ | G_PsiZAH | G_PsiZHAH | G_PsiAAH
      | G_PsiZW | G_PsiZWH | G_PsiAHW | G_PsiAHWH
      | G_PsiZHW | G_PsiZHWH
      | G_PsippWW | G_PsippWHW | G_PsippWHWH
      | G_PsiHW | G_PsiHWH | G_Psi0W | G_Psi0WH
      | G_Psi1W | G_Psi1WH | G_PsiPPW | G_PsiPPWH
      | G_Psi1HAH | G_Psi01AH | G_AHPsip | G_Psi1HZ
      | G_Psi1HZH | G_Psi01Z | G_Psi01ZH | G_ZPsip | G_ZPsipp |
G_ZHPsipp
      | G_HHAA | G_HHWHW | G_HHZHZ | G_HHAHZ | G_HHZHAH
      | G_HPsi0WW | G_HPsi0WHW | G_HPsi0ZZ
      | G_HPsi0ZHZH | G_HPsi0ZHZ | G_HPsi0AAH | G_HPsi0ZAH |
G_HPsi0ZHAH
      | G_HPsipWA | G_HPsipWHA | G_HPsipWZ | G_HPsipWHZ |
G_HPsipWAH
      | G_HPsipWHAH | G_HPsipWZH | G_HPsipWHZH | G_HPsippWW |
G_HPsippWHWH
      | G_HPsippWHW | G_Psi00ZH | G_Psi00AH | G_Psi00ZHAH
      | G_Psi0pWA | G_Psi0pWHA | G_Psi0pWZ | G_Psi0pWHZ |
G_Psi0pWAH
      | G_Psi0pWHAH | G_Psi0pWZH | G_Psi0pWHZH | G_Psi0ppWW |
G_Psi0ppWHWH
      | G_Psi0ppWHW | I_G_Psi0pWA | I_G_Psi0pWHA | I_G_Psi0pWZ |
I_G_Psi0pWHZ
      | I_G_Psi0pWAH | I_G_Psi0pWHAH | I_G_Psi0pWZH | I_G_Psi0pWHZH
      | I_G_Psi0ppWW | I_G_Psi0ppWHWH | I_G_Psi0ppWHW
      | G_PsippZZ | G_PsippZHZH | G_PsippAZ | G_PsippAAH |
G_PsippZAH
      | G_PsippWA | G_PsippWHA | G_PsippWZ | G_PsippWHZ |
G_PsippWAH
      | G_PsippWHAH | G_PsippWZH | G_PsippWHZH
      | G_PsiccZZ | G_PsiccAZ | G_PsiccAAH | G_PsiccZZH |
G_PsiccAZH
      | G_PsiccZAH
      | G_Htt | G_Hbb | G_Hcc | G_Htautau | G_H3 | G_H4

```

```

| G_Hthth | G_Htht | G_Ethth | G_Etht | G_Ett
| G_HHtt | G_HHthth | G_HHtht
| G_Psi0tt | G_Psi0bb | G_Psi0cc | G_Psi0tautau
| G_Psi1tt | G_Psi1bb | G_Psi1cc | G_Psi1tautau
| G_Psipq3 | G_Psipq2 | G_Psipl3 | G_Psi0tth | G_Psi1tth
| G_Psipbth | G_Ebb
| G_HGaGa | G_HGaZ | G_EGaGa | G_EGaZ | G_EGIGl
| Gs | I_Gs | G2
| G_HWHW | G_HWHWH | G_HAHAH | G_HZHZ | G_HZHAH |
G_HAHZ
| Mass of flavor | Width of flavor

```

Two integer counters for the QCD and EW order of the couplings.

```

type orders = int × int

let orders = function
| _ → (0, 0)

let input_parameters =
[]

let derived_parameters =
[]

let g_over_2_costh =
Quot (Neg (Atom G_weak), Prod [Const 2; Atom Costhw])

let nc_coupling c t3 q =
(Real_Array c,
 [Prod [g_over_2_costh; Diff (t3, Prod [Const 2; q; Atom Sin2thw])];
  Prod [g_over_2_costh; t3]])

let half = Quot (Const 1, Const 2)

let derived_parameter_arrays =
[ nc_coupling G_NC_neutrino half (Const 0);
  nc_coupling G_NC_lepton (Neg half) (Const (-1));
  nc_coupling G_NC_up half (Quot (Const 2, Const 3));
  nc_coupling G_NC_down (Neg half) (Quot (Const (-1), Const 3));
  nc_coupling G_NC_h_neutrino half (Const 0);
  nc_coupling G_NC_h_lepton (Neg half) (Const (-1));
  nc_coupling G_NC_h_up half (Quot (Const 2, Const 3));
  nc_coupling G_NC_h_down (Neg half) (Quot (Const (-1), Const 3)) ]

let parameters () =
{ input = input_parameters;
  derived = derived_parameters;
  derived_arrays = derived_parameter_arrays }

module F = Modeltools.Fusions (struct
type f = flavor
type c = constant
let compare = compare
let conjugate = conjugate
end)

```

```

let mgm ((m1, g, m2), fbf, c) = ((M m1, G g, M m2), fbf, c)
let mhm ((m1, h, m2), fbf, c) = ((M m1, O h, M m2), fbf, c)
let tgc ((g1, g2, g3), t, c) = ((G g1, G g2, G g3), t, c)
let qgc ((g1, g2, g3, g4), t, c) = ((G g1, G g2, G g3, G g4), t, c)
let hgg ((h, g1, g2), coup, c) = ((O h, G g1, G g2), coup, c)
let ghg ((g, h1, h2), coup, c) = ((G g, O h1, O h2), coup, c)
let hhgg ((h1, h2, g1, g2), coup, c) = ((O h1, O h2, G g1, G g2), coup, c)

```

```

let electromagnetic_currents n =
  List.map mgm
    [ ((L (-n), Ga, L n), FBF (1, Psibar, V, Psi), Q_lepton);
      ((U (-n), Ga, U n), FBF (1, Psibar, V, Psi), Q_up);
      ((D (-n), Ga, D n), FBF (1, Psibar, V, Psi), Q_down) ]

let neutral_currents n =
  List.map mgm
    [ ((L (-n), Z, L n), FBF (1, Psibar, VA, Psi), G_NC_lepton);
      ((N (-n), Z, N n), FBF (1, Psibar, VA, Psi), G_NC_neutrino);
      ((U (-n), Z, U n), FBF (1, Psibar, VA, Psi), G_NC_up);
      ((D (-n), Z, D n), FBF (1, Psibar, VA, Psi), G_NC_down) ]

```

The sign of this coupling is just the one of the T3, being  $-(1/2)$  for leptons and down quarks, and  $+(1/2)$  for neutrinos and up quarks.

```

let neutral_heavy_currents n =
  List.map mgm
    [ ((L (-n), ZH, L n), FBF ((-1), Psibar, VL, Psi), G_NC_heavy);
      ((N (-n), ZH, N n), FBF (1, Psibar, VL, Psi), G_NC_heavy);
      ((U (-n), ZH, U n), FBF (1, Psibar, VL, Psi), G_NC_heavy);
      ((D (-n), ZH, D n), FBF ((-1), Psibar, VL, Psi), G_NC_heavy) ]
    @
    (if Flags.u1_gauged then
      [ ((L (-n), AH, L n), FBF (1, Psibar, VA, Psi), G_NC_h_lepton);
        ((N (-n), AH, N n), FBF (1, Psibar, VA, Psi), G_NC_h_neutrino);
        ((D (-n), AH, D n), FBF (1, Psibar, VA, Psi), G_NC_h_down) ]
      else
        [])

```

```

let color_currents n =
  List.map mgm
    [ ((D (-n), Gl, D n), FBF ((-1), Psibar, V, Psi), Gs);
      ((U (-n), Gl, U n), FBF ((-1), Psibar, V, Psi), Gs) ]

```

```

let heavy_top_currents =
  List.map mgm
    [ ((TopHb, Ga, TopH), FBF (1, Psibar, V, Psi), Q_up);
      ((TopHb, Z, TopH), FBF (1, Psibar, V, Psi), Q_Z_up);
      ((TopHb, Z, U 3), FBF (1, Psibar, VL, Psi), G_ZTHT);
      ((U (-3), Z, TopH), FBF (1, Psibar, VL, Psi), G_ZTHT);
      ((TopHb, ZH, U 3), FBF (1, Psibar, VL, Psi), G_ZHTHT);
      ((U (-3), ZH, TopH), FBF (1, Psibar, VL, Psi), G_ZHTHT);
      ((U (-3), Wp, D 3), FBF (1, Psibar, VL, Psi), G_CCtop);
      ((D (-3), Wm, U 3), FBF (1, Psibar, VL, Psi), G_CCtop);

```

```

((TopHb, WHp, D 3), FBF (1, Psibar, VL, Psi), G_CC_WH);
((D (-3), WHm, TopH), FBF (1, Psibar, VL, Psi), G_CC_WH);
((TopHb, Wp, D 3), FBF (1, Psibar, VL, Psi), G_CC_W);
((D (-3), Wm, TopH), FBF (1, Psibar, VL, Psi), G_CC_W)]
@
(if Flags.u1_gauged then
[ ((U (-3), AH, U 3), FBF (1, Psibar, VA, Psi), G_AHTT);
  ((TopHb, AH, TopH), FBF (1, Psibar, VA, Psi), G_AHTHTH);
  ((TopHb, AH, U 3), FBF (1, Psibar, VR, Psi), G_AHTHT);
  ((U (-3), AH, TopH), FBF (1, Psibar, VR, Psi), G_AHTHT)]
else
[])

```

$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}} \sum_i \bar{\psi}_i (T^+ W^+ + T^- W^-) (1 - \gamma_5) \psi_i \quad (13.42)$$

```

let charged_currents n =
  List.map mgm
    [ ((L (-n), Wm, N n), FBF (1, Psibar, VL, Psi), G_CC);
      ((N (-n), Wp, L n), FBF (1, Psibar, VL, Psi), G_CC);
      ((D (-n), Wm, U n), FBF (1, Psibar, VL, Psi), G_CC);
      ((U (-n), Wp, D n), FBF (1, Psibar, VL, Psi), G_CC) ]

let charged_heavy_currents n =
  List.map mgm
    [ ((L (-n), WHm, N n), FBF (1, Psibar, VL, Psi), G_CC_heavy);
      ((N (-n), WHp, L n), FBF (1, Psibar, VL, Psi), G_CC_heavy);
      ((D (-n), WHm, U n), FBF (1, Psibar, VL, Psi), G_CC_heavy);
      ((U (-n), WHp, D n), FBF (1, Psibar, VL, Psi), G_CC_heavy)]
  @
  (if Flags.u1_gauged then
    [ ((U (-n), AH, U n), FBF (1, Psibar, VA, Psi), G_NC_h_up)]
    else
    [])

```

We specialize the third generation since there is an additional shift coming from the admixture of the heavy top quark. The universal shift, coming from the mixing in the non-Abelian gauge boson sector is unobservable. (Redefinition of coupling constants by measured ones.

```

let yukawa =
  List.map mhm
    [ ((U (-3), H, U 3), FBF (1, Psibar, S, Psi), G_Htt);
      ((D (-3), H, D 3), FBF (1, Psibar, S, Psi), G_Hbb);
      ((U (-2), H, U 2), FBF (1, Psibar, S, Psi), G_Hcc);
      ((L (-3), H, L 3), FBF (1, Psibar, S, Psi), G_Htautau)]

let yukawa_add' =
  List.map mhm
    [ ((TopHb, H, TopH), FBF (1, Psibar, S, Psi), G_Hthth);
      ((TopHb, H, U 3), FBF (1, Psibar, SLR, Psi), G_Htht);
      ((U (-3), H, TopH), FBF (1, Psibar, SLR, Psi), G_Htht);

```

```

((U (-3), Psi0, U 3), FBF (1, Psibar, S, Psi), G_Psi0tt);
((D (-3), Psi0, D 3), FBF (1, Psibar, S, Psi), G_Psi0bb);
((U (-2), Psi0, U 2), FBF (1, Psibar, S, Psi), G_Psi0cc);
((L (-3), Psi0, L 3), FBF (1, Psibar, S, Psi), G_Psi0tautau);
((U (-3), Psi1, U 3), FBF (1, Psibar, P, Psi), G_Psi1tt);
((D (-3), Psi1, D 3), FBF (1, Psibar, P, Psi), G_Psi1bb);
((U (-2), Psi1, U 2), FBF (1, Psibar, P, Psi), G_Psi1cc);
((L (-3), Psi1, L 3), FBF (1, Psibar, P, Psi), G_Psi1tautau);
((U (-3), Psip, D 3), FBF (1, Psibar, SLR, Psi), G_Psipq3);
((U (-2), Psip, D 2), FBF (1, Psibar, SLR, Psi), G_Psipq2);
((N (-3), Psip, L 3), FBF (1, Psibar, SR, Psi), G_Psipl3);
((D (-3), Psim, U 3), FBF (1, Psibar, SLR, Psi), G_Psipq3);
((D (-2), Psim, U 2), FBF (1, Psibar, SLR, Psi), G_Psipq2);
((L (-3), Psim, N 3), FBF (1, Psibar, SL, Psi), G_Psipl3);
((TopHb, Psi0, U 3), FBF (1, Psibar, SL, Psi), G_Psi0tth);
((U (-3), Psi0, TopH), FBF (1, Psibar, SR, Psi), G_Psi0tth);
((TopHb, Psi1, U 3), FBF (1, Psibar, SL, Psi), G_Psi1tth);
((U (-3), Psi1, TopH), FBF (1, Psibar, SR, Psi), G_Psi1tth);
((TopHb, Psip, D 3), FBF (1, Psibar, SL, Psi), G_Psipbth);
((D (-3), Psim, TopH), FBF (1, Psibar, SR, Psi), G_Psipbth)]

let yukawa_add =
  if Flags.u1_gauged then
    yukawa_add'
  else
    yukawa_add' @
    List.map mhm
    [ ((U (-3), Eta, U 3), FBF (1, Psibar, P, Psi), G_Ett);
      ((TopHb, Eta, U 3), FBF (1, Psibar, SLR, Psi), G_Etht);
      ((D (-3), Eta, D 3), FBF (1, Psibar, P, Psi), G_Ebb);
      ((U (-3), Eta, TopH), FBF (1, Psibar, SLR, Psi), G_Etht)]


$$\mathcal{L}_{\text{TGC}} = -e\partial_\mu A_\nu W_+^\mu W_-^\nu + \dots - e\cot\theta_w\partial_\mu Z_\nu W_+^\mu W_-^\nu + \dots \quad (13.43)$$


let standard_triple_gauge =
  List.map tgc
  [ ((Ga, Wm, Wp), Gauge_Gauge_Gauge 1, I_Q_W);
    ((Z, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_ZWW);
    ((Gl, Gl, Gl), Gauge_Gauge_Gauge 1, I_Gs) ]

let heavy_triple_gauge =
  List.map tgc
  [ ((Ga, WHm, WHp), Gauge_Gauge_Gauge 1, I_Q_W);
    ((Z, WHm, WHp), Gauge_Gauge_Gauge 1, I_G_ZWW);
    ((ZH, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_ZHWW);
    ((Z, WHm, Wp), Gauge_Gauge_Gauge 1, I_G_ZWHW);
    ((Z, Wm, WHp), Gauge_Gauge_Gauge (-1), I_G_ZWHW);
    ((ZH, WHm, Wp), Gauge_Gauge_Gauge 1, I_G_WWW);
    ((ZH, Wm, WHp), Gauge_Gauge_Gauge (-1), I_G_WWW);
    ((ZH, WHm, WHp), Gauge_Gauge_Gauge (-1), I_G_ZHWHWH)]

```

```

@
  (if Flags.u1_gauged then
    [ ((AH, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_AHWW);
      ((AH, WHm, Wp), Gauge_Gauge_Gauge 1, I_G_AHWHW);
      ((AH, Wm, WHp), Gauge_Gauge_Gauge (-1), I_G_AHWHW);
      ((AH, WHm, WHp), Gauge_Gauge_Gauge 1, I_G_AHWHWH)
    ]
  else
    [])
let triple_gauge =
  standard_triple_gauge @ heavy_triple_gauge
let gauge4 = Vector4 [(2, C_13_42); (-1, C_12_34); (-1, C_14_23)]
let minus_gauge4 = Vector4 [(-2, C_13_42); (1, C_12_34); (1, C_14_23)]
let standard_quartic_gauge =
  List.map qgc
    [ (Wm, Wp, Wm, Wp), gauge4, G_WWWW;
      (Wm, Z, Wp, Z), minus_gauge4, G_ZZWW;
      (Wm, Z, Wp, Ga), minus_gauge4, G_AZWW;
      (Wm, Ga, Wp, Ga), minus_gauge4, G_AAWW;
      (Gl, Gl, Gl, Gl), gauge4, G2 ]
let heavy_quartic_gauge =
  List.map qgc
    [ (WHm, Wp, WHm, Wp), gauge4, G_WWWW;
      (Wm, WHp, Wm, WHp), gauge4, G_WWWW;
      (WHm, WHp, WHm, WHp), gauge4, G_WH4;
      (Wm, Wp, WHm, WHp), gauge4, G_WHWHWW;
      (Wm, Wp, Wm, WHp), gauge4, G_WHWWWW;
      (Wm, Wp, WHm, Wp), gauge4, G_WHWWWW;
      (WHm, WHp, Wm, WHp), gauge4, G_WH3W;
      (WHm, WHp, WHm, Wp), gauge4, G_WH3W;
      (WHm, Z, WHp, Z), minus_gauge4, G_ZZWW;
      (WHm, Z, WHp, Ga), minus_gauge4, G_AZWW;
      (WHm, Ga, WHp, ZH), minus_gauge4, G_AAWW;
      (WHm, Z, WHp, ZH), minus_gauge4, G_ZZWW;
      (Wm, ZH, Wp, ZH), minus_gauge4, G_WWWW;
      (Wm, Ga, Wp, ZH), minus_gauge4, G_WWAZH;
      (Wm, Z, Wp, ZH), minus_gauge4, G_WWZZH;
      (WHm, Ga, WHp, ZH), minus_gauge4, G_WHWHAZH;
      (WHm, Z, WHp, ZH), minus_gauge4, G_WHWHZZH;
      (WHm, ZH, WHp, ZH), minus_gauge4, G_WH4;
      (WHm, Z, Wp, Z), minus_gauge4, G_WHWZZ;
      (Wm, Z, WHp, Z), minus_gauge4, G_WHWZZ;
      (WHm, Ga, Wp, Z), minus_gauge4, G_WHWAZ;
      (Wm, Ga, WHp, Z), minus_gauge4, G_WHWAZ;
      (WHm, ZH, Wp, ZH), minus_gauge4, G_WHWZHZH;
      (Wm, ZH, WHp, ZH), minus_gauge4, G_WHWZHZH;
      (WHm, Ga, Wp, ZH), minus_gauge4, G_WHWAZH;
      (Wm, Ga, WHp, ZH), minus_gauge4, G_WHWAZH;
      (WHm, Z, Wp, ZH), minus_gauge4, G_WHWZZH;
      (Wm, Z, WHp, ZH), minus_gauge4, G_WHWZZH ]

```

```

@
  (if Flags.u1_gauged then
    [ (Wm, Ga, Wp, AH), minus_gauge4, G_WWAAH;
      (Wm, Z, Wp, AH), minus_gauge4, G_WWZAH;
      (WHm, Ga, WHp, AH), minus_gauge4, G_WHWHAAH;
      (WHm, Z, WHp, AH), minus_gauge4, G_WHWHZAH;
      (Wm, ZH, Wp, AH), minus_gauge4, G_WWZHAH;
      (WHm, ZH, WHp, AH), minus_gauge4, G_WHWHZHAH;
      (WHm, Ga, Wp, AH), minus_gauge4, G_WHWAAH;
      (Wm, Ga, WHp, AH), minus_gauge4, G_WHWAAH;
      (WHm, Z, Wp, AH), minus_gauge4, G_WHWZAH;
      (Wm, Z, WHp, AH), minus_gauge4, G_WHWZAH;
      (WHm, ZH, Wp, AH), minus_gauge4, G_WHWZHAH;
      (Wm, ZH, WHp, AH), minus_gauge4, G_WHWZHAH]
    else
      [])
let quartic_gauge =
  standard_quartic_gauge @ heavy_quartic_gauge
let standard_gauge_higgs' =
  List.map hgg
    [ ((H, Wp, Wm), Scalar_Vector_Vector 1, G_HWW);
      ((H, Z, Z), Scalar_Vector_Vector 1, G_HZZ) ]
let heavy_gauge_higgs =
  List.map hgg
    [ ((H, Wp, WHm), Scalar_Vector_Vector 1, G_HWHW);
      ((H, WHp, Wm), Scalar_Vector_Vector 1, G_HWHW);
      ((H, WHp, WHm), Scalar_Vector_Vector 1, G_HWHWH);
      ((H, ZH, ZH), Scalar_Vector_Vector 1, G_HWHWH);
      ((H, ZH, Z), Scalar_Vector_Vector 1, G_HZHZ);
      ((H, Wp, Wm), Scalar_Vector_Vector 1, G_HZHAH)]
@
  (if Flags.u1_gauged then
    [ ((H, AH, AH), Scalar_Vector_Vector 1, G_HAHAH);
      ((H, Z, AH), Scalar_Vector_Vector 1, G_HAHZ)]
    else
      [])
let triplet_gauge_higgs =
  List.map hgg
    [ ((Psi0, Wp, Wm), Scalar_Vector_Vector 1, G_PsiWW);
      ((Psi0, WHp, WHm), Scalar_Vector_Vector (-1), G_PsiWW);
      ((Psi0, WHp, Wm), Scalar_Vector_Vector 1, G_PsiWHW);
      ((Psi0, WHm, Wp), Scalar_Vector_Vector 1, G_PsiWHW);
      ((Psi0, Z, Z), Scalar_Vector_Vector 1, G_PsiZZ);
      ((Psi0, ZH, ZH), Scalar_Vector_Vector 1, G_PsiZHZH);
      ((Psi0, ZH, Z), Scalar_Vector_Vector 1, G_PsiZHZ);
      ((Psim, Wp, Z), Scalar_Vector_Vector 1, G_PsiZW);
      ((Psip, Wm, Z), Scalar_Vector_Vector 1, G_PsiZW);
      ((Psim, WHp, Z), Scalar_Vector_Vector 1, G_PsiZWH);

```



```

((Psip, WHm, Z), Scalar_Vector_Vector 1, G_PsiZWH);
((Psim, Wp, ZH), Scalar_Vector_Vector 1, G_PsiZHW);
((Psip, Wm, ZH), Scalar_Vector_Vector 1, G_PsiZHW);
((Psim, WHp, ZH), Scalar_Vector_Vector 1, G_PsiZHHW);
((Psip, WHm, ZH), Scalar_Vector_Vector 1, G_PsiZHHW);
((Psimm, Wp, Wp), Scalar_Vector_Vector 1, G_PsippWW);
((Psipp, Wm, Wm), Scalar_Vector_Vector 1, G_PsippWW);
((Psimm, WHp, Wp), Scalar_Vector_Vector 1, G_PsippWHW);
((Psipp, WHm, Wm), Scalar_Vector_Vector 1, G_PsippWHW);
((Psimm, WHp, WHp), Scalar_Vector_Vector 1, G_PsippWHWH);
((Psipp, WHm, WHm), Scalar_Vector_Vector 1, G_PsippWHWH)]
@
(if Flags.u1_gauged then
  [((Psi0, AH, Z), Scalar_Vector_Vector 1, G_PsiZAH);
   ((Psi0, AH, ZH), Scalar_Vector_Vector 1, G_PsiZHAH);
   ((Psi0, AH, AH), Scalar_Vector_Vector 1, G_PsiAHAH);
   ((Psim, Wp, AH), Scalar_Vector_Vector 1, G_PsiAHW);
   ((Psip, Wm, AH), Scalar_Vector_Vector 1, G_PsiAHW);
   ((Psim, WHp, AH), Scalar_Vector_Vector 1, G_PsiAHWH);
   ((Psip, WHm, AH), Scalar_Vector_Vector 1, G_PsiAHWH)]
else
  [])
let triplet_gauge2_higgs =
List.map gh
  ([((Wp, H, Psim), Vector_Scalar_Scalar 1, G_PsiHW);
    ((Wm, H, Psip), Vector_Scalar_Scalar 1, G_PsiHW);
    ((WHp, H, Psim), Vector_Scalar_Scalar 1, G_PsiHWH);
    ((WHm, H, Psip), Vector_Scalar_Scalar 1, G_PsiHWH);
    ((Wp, Psi0, Psim), Vector_Scalar_Scalar 1, G_Psi0W);
    ((Wm, Psi0, Psip), Vector_Scalar_Scalar 1, G_Psi0W);
    ((WHp, Psi0, Psim), Vector_Scalar_Scalar 1, G_Psi0WH);
    ((WHm, Psi0, Psip), Vector_Scalar_Scalar 1, G_Psi0WH);
    ((Wp, Psi1, Psim), Vector_Scalar_Scalar 1, G_Psi1W);
    ((Wm, Psi1, Psip), Vector_Scalar_Scalar (-1), G_Psi1W);
    ((WHp, Psi1, Psim), Vector_Scalar_Scalar 1, G_Psi1WH);
    ((WHm, Psi1, Psip), Vector_Scalar_Scalar (-1), G_Psi1WH);
    ((Wp, Psip, Psimm), Vector_Scalar_Scalar 1, G_PsiPPW);
    ((Wm, Psim, Psipp), Vector_Scalar_Scalar 1, G_PsiPPW);
    ((WHp, Psip, Psimm), Vector_Scalar_Scalar 1, G_PsiPPWH);
    ((WHm, Psim, Psipp), Vector_Scalar_Scalar 1, G_PsiPPWH);
    ((Ga, Psip, Psim), Vector_Scalar_Scalar 1, Q_lepton);
    ((Ga, Psipp, Psimm), Vector_Scalar_Scalar 2, Q_lepton);
    ((Z, H, Psi1), Vector_Scalar_Scalar 1, G_Psi1HZ);
    ((ZH, H, Psi1), Vector_Scalar_Scalar 1, G_Psi1HZH);
    ((Z, Psi0, Psi1), Vector_Scalar_Scalar 1, G_Psi01Z);
    ((ZH, Psi0, Psi1), Vector_Scalar_Scalar 1, G_Psi01ZH);
    ((Z, Psip, Psim), Vector_Scalar_Scalar 1, G_ZPsip);
    ((Z, Psipp, Psimm), Vector_Scalar_Scalar 2, G_ZPsipp);
    ((ZH, Psipp, Psimm), Vector_Scalar_Scalar 2, G_ZHPsipp)]

```

```

@
  (if Flags.u1_gauged then
    [((AH, H, Psi1), Vector_Scalar_Scalar 1, G_Psi1HAH);
     ((AH, Psi0, Psi1), Vector_Scalar_Scalar 1, G_Psi01AH);
     ((AH, Psip, Psim), Vector_Scalar_Scalar 1, G_AHPsip);
     ((AH, Psipp, Psim), Vector_Scalar_Scalar 2, G_AHPsip)]
  else [])
let standard_gauge_higgs =
  standard_gauge_higgs' @ heavy_gauge_higgs @ triplet_gauge_higgs @
  triplet_gauge2_higgs
let standard_gauge_higgs4 =
  List.map hhgg
  [ (H, H, Wp, Wm), Scalar2_Vector2 1, G_HHWW;
    (H, H, Z, Z), Scalar2_Vector2 1, G_HHZZ ]
let littlest_gauge_higgs4 =
  List.map hhgg
  [ (H, H, WHp, WHm), Scalar2_Vector2 (-1), G_HHWW;
    (H, H, ZH, ZH), Scalar2_Vector2 (-1), G_HHWW;
    (H, H, Wp, WHm), Scalar2_Vector2 1, G_HHWHW;
    (H, H, WHp, Wm), Scalar2_Vector2 1, G_HHWHW;
    (H, H, ZH, Z), Scalar2_Vector2 (-1), G_HHZHZ;
    (H, Psi0, Wp, Wm), Scalar2_Vector2 1, G_HPsi0WW;
    (H, Psi0, WHp, WHm), Scalar2_Vector2 (-1), G_HPsi0WW;
    (H, Psi0, WHp, Wm), Scalar2_Vector2 1, G_HPsi0WHW;
    (H, Psi0, Wp, WHm), Scalar2_Vector2 1, G_HPsi0WHW;
    (H, Psi0, Z, Z), Scalar2_Vector2 1, G_HPsi0ZZ;
    (H, Psi0, ZH, ZH), Scalar2_Vector2 1, G_HPsi0ZHZH;
    (H, Psi0, ZH, Z), Scalar2_Vector2 1, G_HPsi0ZHZ;
    (H, Psim, Wp, Ga), Scalar2_Vector2 1, G_HPsipWA;
    (H, Psip, Wm, Ga), Scalar2_Vector2 1, G_HPsipWA;
    (H, Psim, WHp, Ga), Scalar2_Vector2 1, G_HPsipWHA;
    (H, Psip, WHm, Ga), Scalar2_Vector2 1, G_HPsipWHA;
    (H, Psim, Wp, Z), Scalar2_Vector2 1, G_HPsipWZ;
    (H, Psip, Wm, Z), Scalar2_Vector2 1, G_HPsipWZ;
    (H, Psim, WHp, Z), Scalar2_Vector2 1, G_HPsipWHZ;
    (H, Psip, WHm, Z), Scalar2_Vector2 1, G_HPsipWHZ;
    (H, Psim, Wp, ZH), Scalar2_Vector2 1, G_HPsipWZH;
    (H, Psip, Wm, ZH), Scalar2_Vector2 1, G_HPsipWZH;
    (H, Psim, WHp, ZH), Scalar2_Vector2 1, G_HPsipWZH;
    (H, Psip, WHm, ZH), Scalar2_Vector2 1, G_HPsipWZH;
    (H, Psimm, Wp, Wp), Scalar2_Vector2 1, G_HPsippWW;
    (H, Psipp, Wm, Wm), Scalar2_Vector2 1, G_HPsippWW;
    (H, Psimm, WHp, WHp), Scalar2_Vector2 1, G_HPsippWHWH;
    (H, Psipp, WHm, WHm), Scalar2_Vector2 1, G_HPsippWHWH;
    (H, Psimm, WHp, Wp), Scalar2_Vector2 1, G_HPsippWHW;
    (H, Psipp, WHm, Wm), Scalar2_Vector2 1, G_HPsippWHW;
    (Psi0, Psi0, Wp, Wm), Scalar2_Vector2 2, G_HHWW;
    (Psi0, Psi0, WHp, WHm), Scalar2_Vector2 (-2), G_HHWW;
    (Psi0, Psi0, Z, Z), Scalar2_Vector2 4, G_HHZZ;

```

(*Psi0*, *Psi0*, *ZH*, *ZH*), *Scalar2\_Vector2* 1, *G\_Psi00ZH*;  
 (*Psi0*, *Psi0*, *WHP*, *Wm*), *Scalar2\_Vector2* 2, *G\_HHWHW*;  
 (*Psi0*, *Psi0*, *Wp*, *WHm*), *Scalar2\_Vector2* 2, *G\_HHWHW*;  
 (*Psi0*, *Psi0*, *Z*, *ZH*), *Scalar2\_Vector2* 4, *G\_HHZHZ*;  
 (*Psi0*, *Psim*, *Wp*, *Ga*), *Scalar2\_Vector2* 1, *G\_Psi0pWA*;  
 (*Psi0*, *Psip*, *Wm*, *Ga*), *Scalar2\_Vector2* 1, *G\_Psi0pWA*;  
 (*Psi0*, *Psim*, *WHP*, *Ga*), *Scalar2\_Vector2* 1, *G\_Psi0pWHA*;  
 (*Psi0*, *Psip*, *WHm*, *Ga*), *Scalar2\_Vector2* 1, *G\_Psi0pWHA*;  
 (*Psi0*, *Psim*, *Wp*, *Z*), *Scalar2\_Vector2* 1, *G\_Psi0pWZ*;  
 (*Psi0*, *Psip*, *Wm*, *Z*), *Scalar2\_Vector2* 1, *G\_Psi0pWZ*;  
 (*Psi0*, *Psim*, *WHP*, *Z*), *Scalar2\_Vector2* 1, *G\_Psi0pWHZ*;  
 (*Psi0*, *Psip*, *WHm*, *Z*), *Scalar2\_Vector2* 1, *G\_Psi0pWHZ*;  
 (*Psi0*, *Psim*, *Wp*, *ZH*), *Scalar2\_Vector2* 1, *G\_Psi0pWZH*;  
 (*Psi0*, *Psip*, *Wm*, *ZH*), *Scalar2\_Vector2* 1, *G\_Psi0pWZH*;  
 (*Psi0*, *Psim*, *WHP*, *ZH*), *Scalar2\_Vector2* 1, *G\_Psi0pWHZH*;  
 (*Psi0*, *Psip*, *WHm*, *ZH*), *Scalar2\_Vector2* 1, *G\_Psi0pWHZH*;  
 (*Psi0*, *Psimm*, *Wp*, *Wp*), *Scalar2\_Vector2* 1, *G\_Psi0ppWW*;  
 (*Psi0*, *Psipp*, *Wm*, *Wm*), *Scalar2\_Vector2* 1, *G\_Psi0ppWW*;  
 (*Psi0*, *Psimm*, *WHP*, *WHP*), *Scalar2\_Vector2* 1, *G\_Psi0ppWHWH*;  
 (*Psi0*, *Psipp*, *WHm*, *WHm*), *Scalar2\_Vector2* 1, *G\_Psi0ppWHWH*;  
 (*Psi0*, *Psimm*, *WHP*, *Wp*), *Scalar2\_Vector2* 1, *G\_Psi0ppWHW*;  
 (*Psi0*, *Psipp*, *WHm*, *Wm*), *Scalar2\_Vector2* 1, *G\_Psi0ppWHW*;  
 (*Psi1*, *Psi1*, *Wp*, *Wm*), *Scalar2\_Vector2* 2, *G\_HHWW*;  
 (*Psi1*, *Psi1*, *WHP*, *WHm*), *Scalar2\_Vector2* (-2), *G\_HHWW*;  
 (*Psi1*, *Psi1*, *Z*, *Z*), *Scalar2\_Vector2* 4, *G\_HHZZ*;  
 (*Psi1*, *Psi1*, *ZH*, *ZH*), *Scalar2\_Vector2* 1, *G\_Psi00ZH*;  
 (*Psi1*, *Psi1*, *WHP*, *Wm*), *Scalar2\_Vector2* 2, *G\_HHWHW*;  
 (*Psi1*, *Psi1*, *Wp*, *WHm*), *Scalar2\_Vector2* 2, *G\_HHWHW*;  
 (*Psi1*, *Psi1*, *Z*, *ZH*), *Scalar2\_Vector2* 4, *G\_HHZHZ*;  
 (*Psi1*, *Psim*, *Wp*, *Ga*), *Scalar2\_Vector2* 1, *I\_G\_Psi0pWA*;  
 (*Psi1*, *Psip*, *Wm*, *Ga*), *Scalar2\_Vector2* (-1), *I\_G\_Psi0pWA*;  
 (*Psi1*, *Psim*, *WHP*, *Ga*), *Scalar2\_Vector2* 1, *I\_G\_Psi0pWHA*;  
 (*Psi1*, *Psip*, *WHm*, *Ga*), *Scalar2\_Vector2* (-1), *I\_G\_Psi0pWHA*;  
 (*Psi1*, *Psim*, *Wp*, *Z*), *Scalar2\_Vector2* 1, *I\_G\_Psi0pWZ*;  
 (*Psi1*, *Psip*, *Wm*, *Z*), *Scalar2\_Vector2* (-1), *I\_G\_Psi0pWZ*;  
 (*Psi1*, *Psim*, *WHP*, *Z*), *Scalar2\_Vector2* 1, *I\_G\_Psi0pWHZ*;  
 (*Psi1*, *Psip*, *WHm*, *Z*), *Scalar2\_Vector2* (-1), *I\_G\_Psi0pWHZ*;  
 (*Psi1*, *Psim*, *Wp*, *ZH*), *Scalar2\_Vector2* 1, *I\_G\_Psi0pWZH*;  
 (*Psi1*, *Psip*, *Wm*, *ZH*), *Scalar2\_Vector2* (-1), *I\_G\_Psi0pWZH*;  
 (*Psi1*, *Psim*, *WHP*, *ZH*), *Scalar2\_Vector2* 1, *I\_G\_Psi0pWHZH*;  
 (*Psi1*, *Psip*, *WHm*, *ZH*), *Scalar2\_Vector2* (-1), *I\_G\_Psi0pWHZH*;  
 (*Psi1*, *Psimm*, *Wp*, *Wp*), *Scalar2\_Vector2* 1, *I\_G\_Psi0ppWW*;  
 (*Psi1*, *Psipp*, *Wm*, *Wm*), *Scalar2\_Vector2* (-1), *I\_G\_Psi0ppWW*;  
 (*Psi1*, *Psimm*, *WHP*, *WHP*), *Scalar2\_Vector2* 1, *I\_G\_Psi0ppWHWH*;  
 (*Psi1*, *Psipp*, *WHm*, *WHm*), *Scalar2\_Vector2* (-1), *I\_G\_Psi0ppWHWH*;  
 (*Psi1*, *Psimm*, *WHP*, *Wp*), *Scalar2\_Vector2* 1, *I\_G\_Psi0ppWHW*;  
 (*Psi1*, *Psipp*, *WHm*, *Wm*), *Scalar2\_Vector2* (-1), *I\_G\_Psi0ppWHW*;  
 (*Psip*, *Psim*, *Wp*, *Wm*), *Scalar2\_Vector2* 4, *G\_HHWW*;  
 (*Psip*, *Psim*, *WHP*, *WHm*), *Scalar2\_Vector2* 1, *G\_Psi00ZH*;  
 (*Psip*, *Psim*, *WHP*, *Wm*), *Scalar2\_Vector2* 4, *G\_HHWHW*;

```

(Psip, Psim, Wp, WHm), Scalar2_Vector2 4, G_HHWHW;
(Psip, Psim, Z, Z), Scalar2_Vector2 1, G_PsippZZ;
(Psip, Psim, Ga, Ga), Scalar2_Vector2 2, G_AAWW;
(Psip, Psim, ZH, ZH), Scalar2_Vector2 1, G_PsippZHZH;
(Psip, Psim, Ga, Z), Scalar2_Vector2 4, G_PsippAZ;
(Psip, Psimm, Wp, Ga), Scalar2_Vector2 1, G_PsippWA;
(Psim, Psipp, Wm, Ga), Scalar2_Vector2 1, G_PsippWA;
(Psip, Psimm, WHp, Ga), Scalar2_Vector2 1, G_PsippWHA;
(Psim, Psipp, WHm, Ga), Scalar2_Vector2 1, G_PsippWHA;
(Psip, Psimm, Wp, Z), Scalar2_Vector2 1, G_PsippWZ;
(Psim, Psipp, Wm, Z), Scalar2_Vector2 1, G_PsippWZ;
(Psip, Psimm, WHp, Z), Scalar2_Vector2 1, G_PsippWHZ;
(Psim, Psipp, WHm, Z), Scalar2_Vector2 1, G_PsippWHZ;
(Psip, Psimm, Wp, ZH), Scalar2_Vector2 1, G_PsippWZH;
(Psim, Psipp, Wm, ZH), Scalar2_Vector2 1, G_PsippWZH;
(Psip, Psimm, WHp, ZH), Scalar2_Vector2 1, G_PsippWHZH;
(Psim, Psipp, WHm, ZH), Scalar2_Vector2 1, G_PsippWHZH;
(Psipp, Psimm, Wp, Wm), Scalar2_Vector2 2, G_HHWW;
(Psipp, Psimm, WHp, WHm), Scalar2_Vector2 (-2), G_HHWW;
(Psipp, Psimm, WHp, Wm), Scalar2_Vector2 2, G_HHWHW;
(Psipp, Psimm, Wp, WHm), Scalar2_Vector2 2, G_HHWHW;
(Psipp, Psimm, Z, Z), Scalar2_Vector2 1, G_PsiccZZ;
(Psipp, Psimm, Ga, Ga), Scalar2_Vector2 8, G_AAWW;
(Psipp, Psimm, ZH, ZH), Scalar2_Vector2 1, G_Psi00ZH;
(Psipp, Psimm, Ga, Z), Scalar2_Vector2 1, G_PsiccAZ;
(Psipp, Psimm, Z, ZH), Scalar2_Vector2 4, G_PsiccZZH;
(Psipp, Psimm, Ga, ZH), Scalar2_Vector2 4, G_PsiccAZH]

```

@

(if *Flags.u1\_gauged* then

```

[(H, H, AH, AH), Scalar2_Vector2 1, G_HHAA;
 (H, H, AH, Z), Scalar2_Vector2 (-1), G_HHAHZ;
 (H, H, ZH, AH), Scalar2_Vector2 (-1), G_HHZHAH;
 (H, Psi0, AH, AH), Scalar2_Vector2 1, G_HPsi0AAH;
 (H, Psi0, Z, AH), Scalar2_Vector2 1, G_HPsi0ZAH;
 (H, Psi0, ZH, AH), Scalar2_Vector2 1, G_HPsi0ZHAH;
 (H, Psim, Wp, AH), Scalar2_Vector2 1, G_HPsipWAH;
 (H, Psip, Wm, AH), Scalar2_Vector2 1, G_HPsipWAH;
 (H, Psim, WHp, AH), Scalar2_Vector2 1, G_HPsipWHAH;
 (H, Psip, WHm, AH), Scalar2_Vector2 1, G_HPsipWHAH;
 (Psi0, Psi0, AH, AH), Scalar2_Vector2 1, G_Psi00AAH;
 (Psi0, Psi0, Z, AH), Scalar2_Vector2 4, G_HHAHZ;
 (Psi0, Psi0, AH, ZH), Scalar2_Vector2 1, G_Psi00ZHAH;
 (Psi0, Psim, Wp, AH), Scalar2_Vector2 1, G_Psi0pWAH;
 (Psi0, Psip, Wm, AH), Scalar2_Vector2 1, G_Psi0pWAH;
 (Psi0, Psim, WHp, AH), Scalar2_Vector2 1, G_Psi0pWHAH;
 (Psi0, Psip, WHm, AH), Scalar2_Vector2 1, G_Psi0pWHAH;
 (Psi1, Psi1, AH, AH), Scalar2_Vector2 1, G_Psi00AAH;
 (Psi1, Psi1, Z, AH), Scalar2_Vector2 4, G_HHAHZ;
 (Psi1, Psi1, AH, ZH), Scalar2_Vector2 1, G_Psi00ZHAH;
 (Psi1, Psim, Wp, AH), Scalar2_Vector2 1, I_G_Psi0pWAH;

```

```

(Psi1, Psip, Wm, AH), Scalar2_Vector2 (-1), I_G_Psi0pWAH;
(Psi1, Psim, WHp, AH), Scalar2_Vector2 1, I_G_Psi0pWHAH;
(Psi1, Psip, WHm, AH), Scalar2_Vector2 (-1), I_G_Psi0pWHAH;
(Psip, Psim, AH, AH), Scalar2_Vector2 1, G_Psi00AH;
(Psip, Psim, Ga, AH), Scalar2_Vector2 4, G_PsippAAH;
(Psip, Psim, Z, AH), Scalar2_Vector2 4, G_PsippZAH;
(Psip, Psimm, Wp, AH), Scalar2_Vector2 1, G_PsippWAH;
(Psim, Psipp, Wm, AH), Scalar2_Vector2 1, G_PsippWAH;
(Psip, Psimm, WHp, AH), Scalar2_Vector2 1, G_PsippWHAH;
(Psim, Psipp, WHm, AH), Scalar2_Vector2 1, G_PsippWHAH;
(Psipp, Psimm, AH, AH), Scalar2_Vector2 1, G_Psi00AH;
(Psipp, Psimm, AH, ZH), Scalar2_Vector2 (-1), G_Psi00ZHAH;
(Psipp, Psimm, Ga, AH), Scalar2_Vector2 4, G_PsiccAAH;
(Psipp, Psimm, Z, AH), Scalar2_Vector2 4, G_PsiccZAH]
else [])
let standard_higgs =
[ (O H, O H, O H), Scalar_Scalar_Scalar 1, G_H3 ]
let anomaly_higgs =
List.map hgg
[ (Eta, Gl, Gl), Dim5_Scalar_Gauge2_Skew 1, G_EGIGl;
  (Eta, Ga, Ga), Dim5_Scalar_Gauge2_Skew 1, G_EGaGa;
  (Eta, Ga, Z), Dim5_Scalar_Gauge2_Skew 1, G_EGaZ]
(* @ (H, Ga, Ga), Dim5_Scalar_Gauge2 1, G_HGaGa; (H, Ga, Z), Dim5_Scalar_Gauge2 1, G_HGaZ
*)
let standard_higgs4 =
[ (O H, O H, O H, O H), Scalar4 1, G_H4 ]
let gauge_higgs =
standard_gauge_higgs
let gauge_higgs4 =
standard_gauge_higgs4
let higgs =
standard_higgs
let higgs4 =
standard_higgs4
let top_quartic =
[ ((M (U (-3)), O H, O H, M (U 3)), GBBG (1, Psibar, S2, Psi), G_HHtt);
  ((M (TopHb), O H, O H, M TopH), GBBG (1, Psibar, S2, Psi), G_HHthth);
  ((M (U (-3)), O H, O H, M TopH), GBBG (1, Psibar, S2LR, Psi), G_HHtht);
  ((M (TopHb), O H, O H, M (U 3)), GBBG (1, Psibar, S2LR, Psi), G_HHtht)]
let goldstone_vertices =
List.map hgg
[ ((Phi0, Wm, Wp), Scalar_Vector_Vector 1, I_G_ZWW);
  ((Phip, Ga, Wm), Scalar_Vector_Vector 1, I_Q_W);
  ((Phip, Z, Wm), Scalar_Vector_Vector 1, I_G_ZWW);
  ((Phim, Wp, Ga), Scalar_Vector_Vector 1, I_Q_W);
  ((Phim, Wp, Z), Scalar_Vector_Vector 1, I_G_ZWW) ]

```

```

let vertices3 =
  (ThoList.flatmap electromagnetic_currents [1; 2; 3] @
   ThoList.flatmap color_currents [1; 2; 3] @
   ThoList.flatmap neutral_currents [1; 2; 3] @
   ThoList.flatmap neutral_heavy_currents [1; 2; 3] @
   ThoList.flatmap charged_currents [1; 2; 3] @
   ThoList.flatmap charged_heavy_currents [1; 2; 3] @
   heavy_top_currents @
   (if Flags.u1_gauged then []
    else anomaly_higgs) @
   yukawa @ yukawa_add @ triple_gauge @
   gauge_higgs @ higgs @ goldstone_vertices)

let vertices4 =
  quartic_gauge @ gauge_higgs4 @ higgs4 @ top_quartic

let vertices () = (vertices3, vertices4, [])

```

For efficiency, make sure that *F.of\_vertices vertices* is evaluated only once.

```

let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 4

let flavor_of_string = function
| "e-" → M (L 1) | "e+" → M (L (-1))
| "mu-" → M (L 2) | "mu+" → M (L (-2))
| "tau-" → M (L 3) | "tau+" → M (L (-3))
| "nue" → M (N 1) | "nuebar" → M (N (-1))
| "numu" → M (N 2) | "numubar" → M (N (-2))
| "nutau" → M (N 3) | "nutaubar" → M (N (-3))
| "u" → M (U 1) | "ubar" → M (U (-1))
| "c" → M (U 2) | "cbar" → M (U (-2))
| "t" → M (U 3) | "tbar" → M (U (-3))
| "d" → M (D 1) | "dbar" → M (D (-1))
| "s" → M (D 2) | "sbar" → M (D (-2))
| "b" → M (D 3) | "bbar" → M (D (-3))
| "th" → M TopH | "thbar" → M TopHb
| "g" | "gl" → G Gl
| "A" → G Ga | "Z" | "ZO" → G Z
| "AH" | "AHO" | "Ah" | "AhO" → G AH
| "ZH" | "ZHO" | "Zh" | "ZhO" → G ZH
| "W+" → G Wp | "W-" → G Wm
| "WH+" → G WHp | "WH-" → G WHm
| "H" | "h" → O H | "eta" | "Eta" → O Eta
| "Psi" | "Psi0" | "psi" | "psi0" → O Psi0
| "Psi1" | "psi1" → O Psi1
| "Psi+" | "psi+" | "Psip" | "psip" → O Psip
| "Psi-" | "psi-" | "Psim" | "psim" → O Psim
| "Psi++" | "psi++" | "Psipp" | "psipp" → O Psipp
| "Psi--" | "psi--" | "Psimm" | "psimm" → O Psimm

```

```

| _ → invalid_arg "Modellib_BSM.Littlest.flavor_of_string"
let flavor_to_string = function
| M f →
  begin match f with
  | L 1 → "e-" | L (-1) → "e+"
  | L 2 → "mu-" | L (-2) → "mu+"
  | L 3 → "tau-" | L (-3) → "tau+"
  | L _ → invalid_arg "Modellib_BSM.Littlest.flavor_to_string"
  | N 1 → "nue" | N (-1) → "nuebar"
  | N 2 → "numu" | N (-2) → "numubar"
  | N 3 → "nutau" | N (-3) → "nutaubar"
  | N _ → invalid_arg "Modellib_BSM.Littlest.flavor_to_string"
  | U 1 → "u" | U (-1) → "ubar"
  | U 2 → "c" | U (-2) → "cbar"
  | U 3 → "t" | U (-3) → "tbar"
  | U _ → invalid_arg "Modellib_BSM.Littlest.flavor_to_string"
  | D 1 → "d" | D (-1) → "dbar"
  | D 2 → "s" | D (-2) → "sbar"
  | D 3 → "b" | D (-3) → "bbar"
  | D _ → invalid_arg "Modellib_BSM.Littlest.flavor_to_string"
  | TopH → "th" | TopHb → "thbar"
  end
| G f →
  begin match f with
  | Gl → "g"
  | Ga → "A" | Z → "Z"
  | Wp → "W+" | Wm → "W-"
  | ZH → "ZH" | AH → "AH" | WHp → "WHp" | WHm → "WHm"
  end
| O f →
  begin match f with
  | Phip → "phi+" | Phim → "phi-" | Phi0 → "phi0"
  | H → "H" | Eta → "Eta"
  | Psi0 → "Psi0" | Psi1 → "Psi1" | Psip → "Psi+"
  | Psim → "Psi-" | Psipp → "Psi++" | Psimm → "Psi--"
  end
end
let flavor_to_TeX = function
| M f →
  begin match f with
  | L 1 → "e~-" | L (-1) → "e~+"
  | L 2 → "\\mu~-" | L (-2) → "\\mu~+"
  | L 3 → "\\tau~-" | L (-3) → "\\tau~+"
  | L _ → invalid_arg "Modellib_BSM.Littlest.flavor_to_TeX"
  | N 1 → "\\nu_e" | N (-1) → "\\bar{\\nu}_e"
  | N 2 → "\\nu_\\mu" | N (-2) → "\\bar{\\nu}_\\mu"
  | N 3 → "\\nu_\\tau" | N (-3) → "\\bar{\\nu}_\\tau"
  | N _ → invalid_arg "Modellib_BSM.Littlest.flavor_to_TeX"
  | U 1 → "u" | U (-1) → "\\bar{u}"
  | U 2 → "c" | U (-2) → "\\bar{c}"

```

```

| U 3 → "t" | U (-3) → "\\bar{t}"
| U _ → invalid_arg "Modellib_BSM.Littlest.flavor_to_TeX"
| D 1 → "d" | D (-1) → "\\bar{d}"
| D 2 → "s" | D (-2) → "\\bar{s}"
| D 3 → "b" | D (-3) → "\\bar{b}"
| D _ → invalid_arg "Modellib_BSM.Littlest.flavor_to_TeX"
| TopH → "T" | TopHb → "\\bar{T}"
end
| G f →
  begin match f with
  | Gl → "g"
  | Ga → "\\gamma" | Z → "Z"
  | Wp → "W^+" | Wm → "W^- "
  | ZH → "Z_H" | AH → "\\gamma_H" | WHp → "W_H^+" |
  WHm → "W_H^- "
  end
| O f →
  begin match f with
  | Phip → "\\Phi^+" | Phim → "\\Phi^- " | Phi0 →
  "\\Phi^0"
  | H → "H" | Eta → "\\eta"
  | Psi0 → "\\Psi_S" | Psi1 → "\\Psi_P" | Psip → "\\Psi^+"
  | Psim → "\\Psi^- " | Psipp → "\\Psi^{++}" | Psimm →
  "\\Psi^{--}"
  end
let flavor_symbol = function
| M f →
  begin match f with
  | L n when n > 0 → "l" ^ string_of_int n
  | L n → "l" ^ string_of_int (abs n) ^ "b"
  | N n when n > 0 → "n" ^ string_of_int n
  | N n → "n" ^ string_of_int (abs n) ^ "b"
  | U n when n > 0 → "u" ^ string_of_int n
  | U n → "u" ^ string_of_int (abs n) ^ "b"
  | D n when n > 0 → "d" ^ string_of_int n
  | D n → "d" ^ string_of_int (abs n) ^ "b"
  | TopH → "th" | TopHb → "thb"
  end
| G f →
  begin match f with
  | Gl → "gl"
  | Ga → "a" | Z → "z"
  | Wp → "wp" | Wm → "wm"
  | ZH → "zh" | AH → "ah" | WHp → "whp" | WHm → "whm"
  end
| O f →
  begin match f with
  | Phip → "pp" | Phim → "pm" | Phi0 → "p0"
  | H → "h" | Eta → "eta"

```



```

| Psi0 → "psi0" | Psi1 → "psi1" | Psip → "psip"
| Psim → "psim" | Psipp → "psipp" | Psimm → "psimm"
end

```

There are PDG numbers for  $Z'$ ,  $Z''$ ,  $W'$ , 32-34, respectively. We just introduce a number 38 for  $Y0$  as a  $Z''$ . As well, there is the number 8 for a  $t'$ . But we cheat a little bit and take the number 35 which is reserved for a heavy scalar Higgs for the Eta scalar. For the heavy Higgs states we take 35 and 36 for the neutral ones, 37 for the charged and 38 for the doubly-charged. The pseudoscalar gets the 39.

```

let pdg = function
| M f →
  begin match f with
  | L n when n > 0 → 9 + 2 × n
  | L n → - 9 + 2 × n
  | N n when n > 0 → 10 + 2 × n
  | N n → - 10 + 2 × n
  | U n when n > 0 → 2 × n
  | U n → 2 × n
  | D n when n > 0 → - 1 + 2 × n
  | D n → 1 + 2 × n
  | TopH → 8 | TopHb → (-8)
  end
| G f →
  begin match f with
  | Gl → 21
  | Ga → 22 | Z → 23
  | Wp → 24 | Wm → (-24)
  | AH → 32 | ZH → 33 | WHP → 34 | WHm → (-34)
  end
| O f →
  begin match f with
  | Phip | Phim → 27 | Phi0 → 26
  | Psi0 → 35 | Psi1 → 36 | Psip → 37 | Psim → (-37)
  | Psipp → 38 | Psimm → (-38)
  | H → 25 | Eta → 39
  end

let mass_symbol f =
  "mass(" ^ string_of_int (abs (pdg f)) ^ ")"

let width_symbol f =
  "width(" ^ string_of_int (abs (pdg f)) ^ ")"

let constant_symbol = function
| Unit → "unit" | Pi → "PI" | VHeavy → "vheavy"
| Alpha-QED → "alpha" | E → "e" | G-weak → "g" | Vev →
"vev"
| Sin2thw → "sin2thw" | Sinthw → "sinthw" | Costhw →
"costhw"
| Sinpsi → "sinpsi" | Cospsi → "cospsi"
| Atpsi → "atpsi" | Scs → "scs"

```

```

| Supp → "vF" | Supp2 → "v2F2"
| Q_lepton → "qllep" | Q_up → "qup" | Q_down → "qdown"
| Q_Z-up → "qzup"
| G_ZHTHT → "gzhtht" | G_ZTHT → "gzhtht"
| G_AHTHTH → "gahthth" | G_AHTHT → "gahtht" | G_AHTT →
"gahtt"
| G_NC_lepton → "gnclep" | G_NC_neutrino → "gncneu"
| G_NC_up → "gncup" | G_NC_down → "gncdown"
| G_CC → "gcc" | G_CCTop → "gcctop" | G_CC_heavy →
"gcch"
| G_CC_WH → "gccwh" | G_CC_W → "gccw"
| G_NC_h_lepton → "gnchlep" | G_NC_h_neutrino → "gnchneu"
| G_NC_h-up → "gnchup" | G_NC_h-down → "gnchdown"
| G_NC_heavy → "gnch"
| I_Q-W → "iqw" | I_G-ZWW → "igzww" | I_G-WWW →
"igwww"
| I_G-AHWW → "igahww" | I_G-ZHWW → "igzhww" | I_G-ZWHW →
"igzwhw"
| I_G-AHWHWH → "igahwhwh" | I_G-ZHWHWH → "igzhwhwh"
| I_G-AHWHW → "igahwhw"
| I_Q-H → "iqh"
| G_WWWW → "gw4" | G_ZZWW → "gzzww"
| G_AZWW → "gazww" | G_AAWW → "gaaww"
| G_WH4 → "gwh4" | G_WHWHWW → "gwhwhww" | G_WHWWW →
"gwhwww"
| G_WH3W → "gwh3w"
| G_WWAAH → "gwwaah" | G_WWAZH → "gwwazh" | G_WWZZH →
"gwwzzh"
| G_WWZAH → "gwwzah" | G_WHWHAAH → "gwhwhaah"
| G_WHWHAZH → "gwhwhazh" | G_WHWHZZH → "gwhwhzzh"
| G_WHWHZAH → "gwhwhzah"
| G_WWZHAH → "gwwzhah" | G_WHWHZHHAH → "gwhwhzhah"
| G_WHWHZZ → "gwhwzz" | G_WHWAZ → "gwhwaz"
| G_WHWAHAH → "gwhwaah" | G_WHWZAH → "gwhwzah"
| G_WHWHZHHAH → "gwhwzhzh" | G_WHWHZHHAH → "gwhwzhah"
| G_WHWAZH → "gwhwazh" | G_WHWHZZH → "gwhwzzh"
| G_HWW → "ghww" | G_HZZ → "ghzz"
| G_HHWW → "ghhww" | G_HHZZ → "ghhzz"
| G_HWHW → "ghwhw" | G_HWHWH → "ghwhwh" | G_HAHAAH →
"ghahah"
| G_HZHZ → "ghzhz" | G_HZHAH → "ghzhah"
| G_HAHZ → "ghahz"
| G_Htt → "ghtt" | G_Hbb → "ghbb"
| G_Htautau → "ghtautau" | G_Hcc → "ghcc"
| G_Hthth → "ghthth" | G_Htht → "ghtht"
| G_HHtt → "ghhtt" | G_HHthth → "ghhthth" | G_HHtht →
"ghhtht"
| G_Psi0tt → "gpsi0tt" | G_Psi0bb → "gpsi0bb"
| G_Psi0cc → "gpsi0cc" | G_Psi0tautau → "gpsi0tautau"
| G_Psi1tt → "gpsi1tt" | G_Psi1bb → "gpsi1bb"

```

```

| G_Psi1cc → "gpsi1cc" | G_Psi1tautau → "gpsi1tautau"
| G_Psipq3 → "gpsipq3" | G_Psipq2 → "gpsipq2" | G_Psipl3 →
"gpsil3"
| G_Psi0tth → "gpsi0tth" | G_Psi1tth → "gpsi1tth"
| G_Psipbth → "gpsipbth"
| G_Ethth → "gethth" | G_Etht → "getht"
| G_Ett → "gett" | G_Ebb → "gebb"
| G_HGaGa → "ghgaga" | G_HGaZ → "ghgaz"
| G_EGaGa → "geaa" | G_EGaZ → "geaz" | G_EGlGl → "gegg"
| G_H3 → "gh3" | G_H4 → "gh4"
| G_PsiWW → "gpsiww" | G_PsiWHW → "gpsiwhw"
| G_PsiZZ → "gpsizz" | G_PsiZHZH → "gpsizhzh"
| G_PsiZHZ → "gpsizhz" | G_PsiZAH → "gpsizah"
| G_PsiZHAH → "gpsizhah" | G_PsiAHAAH → "gpsiahah"
| G_PsiZW → "gpsizw" | G_PsiZWH → "gpsizwh" | G_PsiAHW →
"gpsiahw"
| G_PsiAHWH → "gpsiahwh" | G_PsiZHW → "gpsizhw"
| G_PsiZHWH → "gpsizhwh"
| G_PsippWW → "gpsippww" | G_PsippWHW → "gpsippwhw"
| G_PsippWHWH → "gpsippwhwh"
| Gs → "gs" | G2 → "gs**2" | I_Gs → "igs"
| G_PsiHW → "gpsihw" | G_PsiHWH → "gpsihwh"
| G_Psi0W → "gpsi0w" | G_Psi0WH → "gpsi0wh"
| G_Psi1W → "gpsi1w" | G_Psi1WH → "gpsi1wh"
| G_PsiPPW → "gpsippw" | G_PsiPPWH → "gpsippwh"
| G_Psi1HAH → "gpsihah" | G_Psi01AH → "gpsi0ah"
| G_AHPsip → "ghapsip" | G_Psi1HZ → "gpsi1hz"
| G_Psi1HZH → "gpsi1hzh" | G_Psi01Z → "gpsi01z"
| G_Psi01ZH → "gpsi01zh" | G_ZPsip → "gzpsip"
| G_ZPsipp → "gzpsipp" | G_ZHPsipp → "gzhpsipp"
| G_HHAA → "ghhaa" | G_HHWHW → "ghhwhw" | G_HHZHZ →
"ghhzhz"
| G_HHAHZ → "ghhahz" | G_HHZHAH → "ghhzhah"
| G_HPsi0WW → "ghpsi0ww" | G_HPsi0WHW → "ghpsi0whw"
| G_HPsi0ZZ → "ghpsi0zz" | G_HPsi0ZHZH → "ghpsi0zhzh"
| G_HPsi0ZHZ → "ghpsi0zhz" | G_HPsi0AHAAH → "ghpsi0ahah"
| G_HPsi0ZAH → "ghpsi0zah" | G_HPsi0ZHAH → "ghpsi0zhah"
| G_HPsipWA → "ghpsipwa" | G_HPsipWHA → "ghpsipwha"
| G_HPsipWZ → "ghpsipwz" | G_HPsipWHZ → "ghpsiwhz"
| G_HPsipWAH → "ghpsipwah" | G_HPsipWHAH → "ghpsipwhah"
| G_HPsipWZH → "ghpsipwzh" | G_HPsipWHZH → "ghpsipwhzh"
| G_HPsippWW → "ghpsippww" | G_HPsippWHWH → "ghpsippwhwh"
| G_HPsippWHW → "ghpsippwhw" | G_Psi00ZH → "gpsi00zh"
| G_Psi00AH → "gpsi00ah" | G_Psi00ZHAH → "gpsi00zhah"
| G_Psi0pWA → "gpsi0pwa" | G_Psi0pWHA → "gpsi0pwha"
| G_Psi0pWZ → "gpsi0pwz" | G_Psi0pWHZ → "gpsi0pwhz"
| G_Psi0pWAH → "gpsi0pwah" | G_Psi0pWHAH → "gpsi0pwhah"
| G_Psi0pWZH → "gpsi0pwzh" | G_Psi0pWHZH → "gpsi0pwhzh"
| G_Psi0ppWW → "gpsi0ppww" | G_Psi0ppWHWH → "gpsi0ppwhwh"
| G_Psi0ppWHW → "gpsi0ppwhw"

```

```

| I_G_Psi0pWA → "i_gpsi0pwa" | I_G_Psi0pWHA → "i_gpsi0pwha"
| I_G_Psi0pWZ → "i_gpsi0pwz" | I_G_Psi0pWHZ → "i_gpsi0pwhz"
| I_G_Psi0pWAH → "i_gpsi0pwah" | I_G_Psi0pWHAH → "i_gpsi0pwhah"
| I_G_Psi0pWZH → "i_gpsi0pwzh" | I_G_Psi0pWHZH → "i_gpsi0pwhzh"
| I_G_Psi0ppWW → "i_gpsi0ppww" | I_G_Psi0ppWHWH →
"i_gpsi0ppwhwh"
| I_G_Psi0ppWHW → "i_gpsi0ppwhw"
| G_PsippZZ → "gpsippzz" | G_PsippZHZH → "gpsippzhzh"
| G_PsippAZ → "gpsippaz" | G_PsippAAH → "gpsippaah"
| G_PsippZAH → "gpsippzah"
| G_PsippWA → "gpsippwa" | G_PsippWHA → "gpsippwha"
| G_PsippWZ → "gpsippwz" | G_PsippWHZ → "gpsippwhz"
| G_PsippWAH → "gpsippwah" | G_PsippWHAH → "gpsippwhah"
| G_PsippWZH → "gpsippwzh" | G_PsippWHZH → "gpsippwhzh"
| G_PsiccZZ → "gpsiccz" | G_PsiccAZ → "gpsiccaz"
| G_PsiccAAH → "gpsiccaah" | G_PsiccZZH → "gpsicczzh"
| G_PsiccAZH → "gpsiccazh" | G_PsiccZAH → "gpsicczah"
| Mass f → "mass" ^ flavor_symbol f
| Width f → "width" ^ flavor_symbol f

end

module Littlest_Tpar (Flags : BSM_flags) =
struct
  let rcs = rcs_file

  open Coupling

  let default_width = ref Timelike
  let use_fudged_width = ref false

  let options = Options.create
  [ "constant_width", Arg.Unit (fun () → default_width := Constant),
    "use_constant_width(also_in_t-channel)",
    "fudged_width", Arg.Set use_fudged_width,
    "use_fudge_factor_for_charge_particle_width",
    "custom_width", Arg.String (fun f → default_width := Custom f),
    "use_custom_width",
    "cancel_widths", Arg.Unit (fun () → default_width := Vanishing),
    "use_vanishing_width" ]

  type flavor = L of int | N of int | U of int | D of int
  | Topp | Toppb
  | Ga | Wp | Wm | Z | Gl | Lodd of int | Nodd of int
  | Uodd of int | Dodd of int
  | WHp | WHm | ZH | AH | Phip | Phim | Phi0 | H | Eta |
Psi0
  | Psi1 | Psip | Psim | Psipp | Psimm

  type gauge = unit

  let gauge_symbol () =
    failwith "Modellib_BSM.Littlest_Tpar.gauge_symbol: internal error"

```

let family  $n = [L\ n; N\ n; U\ n; D\ n; Dodd\ n; Nodd\ n; Lodd\ n; Uodd\ n]$

Since *Phi* already belongs to the EW Goldstone bosons we use *Psi* for the TeV scale complex triplet.

We use the notation Todd1 = Uodd 3, Todd2 = Uodd 4.

```

let external_flavors () =
  [ "1st_Generation", ThoList.flatmap family [1; -1];
    "2nd_Generation", ThoList.flatmap family [2; -2];
    "3rd_Generation", ThoList.flatmap family [3; -3];
    "Heavy_Quarks", [Topp; Toppb; Uodd 4; Uodd (-4)];
    "HeavyScalars", [Psi0; Psi1; Psip; Psim; Psipp; Psimm];
    "GaugeBosons", if Flags.u1_gauged then
      [Ga; Z; Wp; Wm; Gl; WHp; WHm; ZH; AH]
    else
      [Ga; Z; Wp; Wm; Gl; WHp; WHm; ZH];
    "Higgs", if Flags.u1_gauged then [H]
    else [H; Eta];
    "GoldstoneBosons", [Phip; Phim; Phi0] ]

let flavors () = ThoList.flatmap snd (external_flavors ())

let spinor n =
  if n ≥ 0 then
    Spinor
  else
    ConjSpinor

let lorentz = function
  | L n → spinor n | N n → spinor n
  | U n → spinor n | D n → spinor n
  | Topp → Spinor | Toppb → ConjSpinor
  | Ga | Gl → Vector
  | Wp | Wm | Z | WHp | WHm | ZH | AH → Massive_Vector
  | _ → Scalar

let color = function
  | U n → Color.SUN (if n > 0 then 3 else -3)
  | Uodd n → Color.SUN (if n > 0 then 3 else -3)
  | D n → Color.SUN (if n > 0 then 3 else -3)
  | Dodd n → Color.SUN (if n > 0 then 3 else -3)
  | Topp → Color.SUN 3 | Toppb → Color.SUN (-3)
  | Gl → Color.AdjSUN 3
  | _ → Color.Singlet

let prop_spinor n =
  if n ≥ 0 then
    Prop_Spinor
  else
    Prop_ConjSpinor

let propagator = function
  | L n → prop_spinor n | N n → prop_spinor n
  | Lodd n → prop_spinor n | Nodd n → prop_spinor n

```

```

| U n → prop_spinor n | D n → prop_spinor n
| Uodd n → prop_spinor n | Dodd n → prop_spinor n
| Topp → Prop_Spinor | Toppb → Prop_ConjSpinor
| Ga | Gl → Prop_Feynman
| Wp | Wm | Z | WHp | WHm | ZH | AH → Prop_Unitarity
| Phip | Phim | Phi0 → Only_Insertion
| H | Eta | Psi0 | Psi1 | Psip | Psim | Psipp | Psimm →
Prop_Scalar

```

Optionally, ask for the fudge factor treatment for the widths of charged particles. Currently, this only applies to  $W^\pm$  and top.

```

let width f =
  if !use_fudged_width then
    match f with
    | Wp | Wm | U 3 | U (-3)
    | WHp | WHm | ZH | AH
    | Uodd _ | Dodd _ | Nodd _ | Lodd _
    | Topp | Toppb → Fudged
    | _ → !default_width
  else
    !default_width

let goldstone = function
| Wp → Some (Phip, Coupling.Const 1)
| Wm → Some (Phim, Coupling.Const 1)
| Z → Some (Phi0, Coupling.Const 1)
| _ → None

let conjugate = function
| L n → L (-n) | N n → N (-n)
| Lodd n → L (-n) | Nodd n → N (-n)
| U n → U (-n) | D n → D (-n)
| Uodd n → U (-n) | Dodd n → D (-n)
| Topp → Toppb | Toppb → Topp
| Gl → Gl | Ga → Ga | Z → Z
| Wp → Wm | Wm → Wp | WHm → WHp
| WHp → WHm | ZH → ZH | AH → AH
| Psi0 → Psi0 | Psi1 → Psi1 | Psip → Psim
| Psim → Psip | Psipp → Psimm | Psimm → Psipp
| Phip → Phim | Phim → Phip | Phi0 → Phi0
| H → H | Eta → Eta

let fermion = function
| L n → if n > 0 then 1 else -1
| N n → if n > 0 then 1 else -1
| U n → if n > 0 then 1 else -1
| D n → if n > 0 then 1 else -1
| Lodd n → if n > 0 then 1 else -1
| Nodd n → if n > 0 then 1 else -1
| Uodd n → if n > 0 then 1 else -1
| Dodd n → if n > 0 then 1 else -1
| Topp → 1 | Toppb → -1

```

```

| Gl | Ga | Z | Wp | Wm | WHp | WHm | AH | ZH → 0
| - → 0

module Ch = Charges.QQ
let ( // ) = Algebra.Small_Rational.make

let charge = function
| L n | Lodd n → if n > 0 then -1//1 else 1//1
| N n | Nodd n → 0//1
| U n | Uodd n → if n > 0 then 2//3 else -2//3
| D n | Dodd n → if n > 0 then -1//3 else 1//3
| Topp → 2//3
| Toppb → -2//3
| Gl | Ga | Z | AH | ZH → 0//1
| Wp | WHp → 1//1
| Wm | WHm → -1//1
| H | Phi0 | Eta | Psi1 | Psi0 → 0//1
| Phip | Psip → 1//1
| Phim | Psim → -1//1
| Psipp → 2//1
| Psimm → -2//1

let lepton = function
| L n | N n | Lodd n | Nodd n
  → if n > 0 then 1//1 else -1//1
| U - | D - | - → 0//1

let baryon = function
| L - | N - → 0//1
| U n | D n | Uodd n | Dodd n
  → if n > 0 then 1//1 else -1//1
| Topp → 1//1
| Toppb → -1//1
| - → 0//1

let charges f =
[ charge f; lepton f; baryon f]

type constant =
| Unit | Pi | Alpha_QED | Sin2thw
| Sinthw | Costhw | E | G_weak | Vev | VHeavy
| Supp | Supp2
| Sinpsi | Cospsi | Atpsi | Sccs (* Mixing angles of SU(2) *)
| Q_lepton | Q_up | Q_down | Q_Z_up | G_CC | G_CCTop
| G_NC_neutrino | G_NC_lepton | G_NC_up | G_NC_down |
G_NC_heavy
| G_NC_h_neutrino | G_NC_h_lepton | G_NC_h_up | G_NC_h_down
| G_CC_heavy | G_ZHTHT | G_ZTHT | G_AHTHTH |
G_AHTHT | G_AHTT
| G_CC_WH | G_CC_W
| Gs | I_Gs | G2
| I_Q_W | I_G_ZWW | I_G_WWW
| I_G_AHWW | I_G_ZHWW | I_G_ZWHW | I_G_AHWHWH |
I_G_ZHWHWH

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      | I_G_AHWWH | I_Q_H
      | G_WWWWW | G_ZZWW | G_AZWW | G_AAWW
      | G_WH4 | G_WHWHWW | G_WHWWW | G_WH3W
      | G_WWAAH | G_WWAZH | G_WWZZH | G_WWZAH |
G_WHWHAAH
      | G_WHWHAZH | G_WHWHZZH | G_WHWHZAH | G_WWZHAH
      | G_WHWHZHAH | G_WHWZZ | G_WHWAZ | G_WHWAH |
G_WHWZAH
      | G_WHWZHZH | G_WHWZHAH | G_WHWAZH | G_WHWZZH
      | G_HWW | G_HHWW | G_HZZ | G_HHZZ
      | G_PsiWW | G_PsiWHW | G_PsiZZ | G_PsiZHZH
      | G_PsiZHZ | G_PsiZAH | G_PsiZHAH | G_PsiAAH
      | G_PsiZW | G_PsiZWH | G_PsiAHW | G_PsiAHWH
      | G_PsiZHW | G_PsiZHWH
      | G_PsippWW | G_PsippWHW | G_PsippWHWH
      | G_PsiHW | G_PsiHWH | G_Psi0W | G_Psi0WH
      | G_Psi1W | G_Psi1WH | G_PsiPPW | G_PsiPPWH
      | G_Psi1HAH | G_Psi01AH | G_AHPsip | G_Psi1HZ
      | G_Psi1HZH | G_Psi01Z | G_Psi01ZH | G_ZPsip | G_ZPsipp |
G_ZHPsipp
      | G_HHAA | G_HHWWH | G_HHZHZ | G_HHAHZ | G_HHZHAH
      | G_HPsi0WW | G_HPsi0WHW | G_HPsi0ZZ
      | G_HPsi0ZHZH | G_HPsi0ZHZ | G_HPsi0AAH | G_HPsi0ZAH |
G_HPsi0ZHAH
      | G_HPsipWA | G_HPsipWHA | G_HPsipWZ | G_HPsipWHZ |
G_HPsipWAH
      | G_HPsipWHAH | G_HPsipWZH | G_HPsipWHZH | G_HPsippWW |
G_HPsippWHWH
      | G_HPsippWHW | G_Psi00ZH | G_Psi00AH | G_Psi00ZHAH
      | G_Psi0pWA | G_Psi0pWHA | G_Psi0pWZ | G_Psi0pWHZ |
G_Psi0pWAH
      | G_Psi0pWHAH | G_Psi0pWZH | G_Psi0pWHZH | G_Psi0ppWW |
G_Psi0ppWHWH
      | G_Psi0ppWHW | I_G_Psi0pWA | I_G_Psi0pWHA | I_G_Psi0pWZ |
I_G_Psi0pWHZ
      | I_G_Psi0pWAH | I_G_Psi0pWHAH | I_G_Psi0pWZH | I_G_Psi0pWHZH
      | I_G_Psi0ppWW | I_G_Psi0ppWHWH | I_G_Psi0ppWHW
      | G_PsippZZ | G_PsippZHZH | G_PsippAZ | G_PsippAAH |
G_PsippZAH
      | G_PsippWA | G_PsippWHA | G_PsippWZ | G_PsippWHZ |
G_PsippWAH
      | G_PsippWHAH | G_PsippWZH | G_PsippWHZH
      | G_PsiccZZ | G_PsiccAZ | G_PsiccAAH | G_PsiccZZH |
G_PsiccAZH
      | G_PsiccZAH
      | G_Htt | G_Hbb | G_Hcc | G_Htautau | G_H3 | G_H4
      | G_Hthth | G_Htht | G_Ethth | G_Etht | G_Ett
      | G_HHtt | G_HHthth | G_HHtht
      | G_Psi0tt | G_Psi0bb | G_Psi0cc | G_Psi0tautau
      | G_Psi1tt | G_Psi1bb | G_Psi1cc | G_Psi1tautau

```



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```

      | G_Psipq3 | G_Psipq2 | G_Psipl3 | G_Psi0tth | G_Psi1tth
      | G_Psipbth | G_Ebb
      | G_HGaGa | G_HGaZ | G_EGaGa | G_EGaZ | G_EGIGl
      | G_HWHW | G_HWHWH | G_HAHAH | G_HZHZ | G_HZHAH |
G_HAHZ
      | Mass of flavor | Width of flavor

```

Two integer counters for the QCD and EW order of the couplings.

```

type orders = int × int

let orders = function
  | - → (0,0)

let input_parameters =
  []

let derived_parameters =
  []

let g_over_2_csth =
  Quot (Neg (Atom G_weak), Prod [Const 2; Atom Costhw])

let nc_coupling c t3 q =
  (Real_Array c,
   [Prod [g_over_2_csth; Diff (t3, Prod [Const 2; q; Atom Sin2thw])];
    Prod [g_over_2_csth; t3]])

let half = Quot (Const 1, Const 2)

let derived_parameter_arrays =
  [ nc_coupling G_NC_neutrino half (Const 0);
    nc_coupling G_NC_lepton (Neg half) (Const (-1));
    nc_coupling G_NC_up half (Quot (Const 2, Const 3));
    nc_coupling G_NC_down (Neg half) (Quot (Const (-1), Const 3));
    nc_coupling G_NC_h_neutrino half (Const 0);
    nc_coupling G_NC_h_lepton (Neg half) (Const (-1));
    nc_coupling G_NC_h_up half (Quot (Const 2, Const 3));
    nc_coupling G_NC_h_down (Neg half) (Quot (Const (-1), Const 3)) ]

let parameters () =
  { input = input_parameters;
    derived = derived_parameters;
    derived_arrays = derived_parameter_arrays }

module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)

let electromagnetic_currents n =
  [ ((L (-n), Ga, L n), FBF (1, Psibar, V, Psi), Q_lepton);
    ((U (-n), Ga, U n), FBF (1, Psibar, V, Psi), Q_up);
    ((D (-n), Ga, D n), FBF (1, Psibar, V, Psi), Q_down) ]

```

```

let color_currents n =
  [ ((U (-n), Gl, U n), FBF ((-1), Psibar, V, Psi), Gs);
    ((D (-n), Gl, D n), FBF ((-1), Psibar, V, Psi), Gs) ]

let neutral_currents n =
  [ ((L (-n), Z, L n), FBF (1, Psibar, VA, Psi), G_NC_lepton);
    ((N (-n), Z, N n), FBF (1, Psibar, VA, Psi), G_NC_neutrino);
    ((U (-n), Z, U n), FBF (1, Psibar, VA, Psi), G_NC_up);
    ((D (-n), Z, D n), FBF (1, Psibar, VA, Psi), G_NC_down) ]

```

The sign of this coupling is just the one of the T3, being  $-(1/2)$  for leptons and down quarks, and  $+(1/2)$  for neutrinos and up quarks.

```

let neutral_heavy_currents n =
  [ ((L (-n), ZH, L n), FBF ((-1), Psibar, VL, Psi), G_NC_heavy);
    ((N (-n), ZH, N n), FBF (1, Psibar, VL, Psi), G_NC_heavy);
    ((U (-n), ZH, U n), FBF (1, Psibar, VL, Psi), G_NC_heavy);
    ((D (-n), ZH, D n), FBF ((-1), Psibar, VL, Psi), G_NC_heavy)]
  @
  (if Flags.u1_gauged then
    [ ((L (-n), AH, L n), FBF (1, Psibar, VA, Psi), G_NC_h_lepton);
      ((N (-n), AH, N n), FBF (1, Psibar, VA, Psi), G_NC_h_neutrino);
      ((D (-n), AH, D n), FBF (1, Psibar, VA, Psi), G_NC_h_down)]
    else
    [])

```

```

let heavy_top_currents =
  [ ((Toppb, Ga, Topp), FBF (1, Psibar, V, Psi), Q_up);
    ((Toppb, Z, Topp), FBF (1, Psibar, V, Psi), Q_Z_up);
    ((Toppb, Z, U 3), FBF (1, Psibar, VL, Psi), G_ZTHT);
    ((U (-3), Z, Topp), FBF (1, Psibar, VL, Psi), G_ZTHT);
    ((Toppb, ZH, U 3), FBF (1, Psibar, VL, Psi), G_ZHTHT);
    ((U (-3), ZH, Topp), FBF (1, Psibar, VL, Psi), G_ZHTHT);
    ((U (-3), Wp, D 3), FBF (1, Psibar, VL, Psi), G_CCtop);
    ((D (-3), Wm, U 3), FBF (1, Psibar, VL, Psi), G_CCtop);
    ((Toppb, WHp, D 3), FBF (1, Psibar, VL, Psi), G_CC_WH);
    ((D (-3), WHm, Topp), FBF (1, Psibar, VL, Psi), G_CC_WH);
    ((Toppb, Wp, D 3), FBF (1, Psibar, VL, Psi), G_CC_W);
    ((D (-3), Wm, Topp), FBF (1, Psibar, VL, Psi), G_CC_W)]
  @
  (if Flags.u1_gauged then
    [ ((U (-3), AH, U 3), FBF (1, Psibar, VA, Psi), G_AHTT);
      ((Toppb, AH, Topp), FBF (1, Psibar, VA, Psi), G_AHTHTH);
      ((Toppb, AH, U 3), FBF (1, Psibar, VR, Psi), G_AHTHT);
      ((U (-3), AH, Topp), FBF (1, Psibar, VR, Psi), G_AHTHT)]
    else
    [])

```

$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}} \sum_i \bar{\psi}_i (T^+ W^+ + T^- W^-) (1 - \gamma_5) \psi_i \quad (13.44)$$

```

let charged_currents n =

```

```

[ ((L (-n), Wm, N n), FBF (1, Psibar, VL, Psi), G_CC);
  ((N (-n), Wp, L n), FBF (1, Psibar, VL, Psi), G_CC);
  ((L (-n), WHm, N n), FBF (1, Psibar, VL, Psi), G_CC_heavy);
  ((N (-n), WHp, L n), FBF (1, Psibar, VL, Psi), G_CC_heavy);
  ((D (-n), WHm, U n), FBF (1, Psibar, VL, Psi), G_CC_heavy);
  ((U (-n), WHp, D n), FBF (1, Psibar, VL, Psi), G_CC_heavy)]

let quark_currents n =
  [ ((D (-n), Wm, U n), FBF (1, Psibar, VL, Psi), G_CC);
    ((U (-n), Wp, D n), FBF (1, Psibar, VL, Psi), G_CC)]
  @
  (if Flags.u1_gauged then
    [ ((U (-n), AH, U n), FBF (1, Psibar, VA, Psi), G_NC_h_up)]
    else
    [])

```

We specialize the third generation since there is an additional shift coming from the admixture of the heavy top quark. The universal shift, coming from the mixing in the non-Abelian gauge boson sector is unobservable. (Redefinition of coupling constants by measured ones.

```

let yukawa =
  [ ((U (-3), H, U 3), FBF (1, Psibar, S, Psi), G_Htt);
    ((D (-3), H, D 3), FBF (1, Psibar, S, Psi), G_Hbb);
    ((U (-2), H, U 2), FBF (1, Psibar, S, Psi), G_Hcc);
    ((L (-3), H, L 3), FBF (1, Psibar, S, Psi), G_Htautau)]

let yukawa_add' =
  [ ((Toppb, H, Topp), FBF (1, Psibar, S, Psi), G_Hthth);
    ((Toppb, H, U 3), FBF (1, Psibar, SLR, Psi), G_Htht);
    ((U (-3), H, Topp), FBF (1, Psibar, SLR, Psi), G_Htht);
    ((U (-3), Psi0, U 3), FBF (1, Psibar, S, Psi), G_Psi0tt);
    ((D (-3), Psi0, D 3), FBF (1, Psibar, S, Psi), G_Psi0bb);
    ((U (-2), Psi0, U 2), FBF (1, Psibar, S, Psi), G_Psi0cc);
    ((L (-3), Psi0, L 3), FBF (1, Psibar, S, Psi), G_Psi0tautau);
    ((U (-3), Psi1, U 3), FBF (1, Psibar, P, Psi), G_Psi1tt);
    ((D (-3), Psi1, D 3), FBF (1, Psibar, P, Psi), G_Psi1bb);
    ((U (-2), Psi1, U 2), FBF (1, Psibar, P, Psi), G_Psi1cc);
    ((L (-3), Psi1, L 3), FBF (1, Psibar, P, Psi), G_Psi1tautau);
    ((U (-3), Psip, D 3), FBF (1, Psibar, SLR, Psi), G_Psipq3);
    ((U (-2), Psip, D 2), FBF (1, Psibar, SLR, Psi), G_Psipq2);
    ((N (-3), Psip, L 3), FBF (1, Psibar, SR, Psi), G_Psipl3);
    ((D (-3), Psim, U 3), FBF (1, Psibar, SLR, Psi), G_Psipq3);
    ((D (-2), Psim, U 2), FBF (1, Psibar, SLR, Psi), G_Psipq2);
    ((L (-3), Psim, N 3), FBF (1, Psibar, SL, Psi), G_Psipl3);
    ((Toppb, Psi0, U 3), FBF (1, Psibar, SL, Psi), G_Psi0tth);
    ((U (-3), Psi0, Topp), FBF (1, Psibar, SR, Psi), G_Psi0tth);
    ((Toppb, Psi1, U 3), FBF (1, Psibar, SL, Psi), G_Psi1tth);
    ((U (-3), Psi1, Topp), FBF (1, Psibar, SR, Psi), G_Psi1tth);
    ((Toppb, Psip, D 3), FBF (1, Psibar, SL, Psi), G_Psipbth);
    ((D (-3), Psim, Topp), FBF (1, Psibar, SR, Psi), G_Psipbth)]

```

```

let yukawa_add =
  if Flags.u1_gauged then
    yukawa_add'
  else
    yukawa_add' @
    [ ((U (-3), Eta, U 3), FBF (1, Psibar, P, Psi), G_Ett);
      ((Toppb, Eta, U 3), FBF (1, Psibar, SLR, Psi), G_Etht);
      ((D (-3), Eta, D 3), FBF (1, Psibar, P, Psi), G_Ebb);
      ((U (-3), Eta, Topp), FBF (1, Psibar, SLR, Psi), G_Etht)]

```

$$\mathcal{L}_{\text{TGC}} = -e\partial_\mu A_\nu W_+^\mu W_-^\nu + \dots - e\cot\theta_w\partial_\mu Z_\nu W_+^\mu W_-^\nu + \dots \quad (13.45)$$

Check.

```

let standard_triple_gauge =
  [ ((Ga, Wm, Wp), Gauge_Gauge_Gauge 1, I_Q_W);
    ((Z, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_ZWW);
    ((Gl, Gl, Gl), Gauge_Gauge_Gauge 1, I_Gs) ]

let heavy_triple_gauge =
  [ ((Ga, WHm, WHp), Gauge_Gauge_Gauge 1, I_Q_W);
    ((Z, WHm, WHp), Gauge_Gauge_Gauge 1, I_G_ZWW);
    ((ZH, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_ZHWW);
    ((Z, WHm, Wp), Gauge_Gauge_Gauge 1, I_G_ZWHW);
    ((Z, Wm, WHp), Gauge_Gauge_Gauge (-1), I_G_ZWHW);
    ((ZH, WHm, Wp), Gauge_Gauge_Gauge 1, I_G_WWW);
    ((ZH, Wm, WHp), Gauge_Gauge_Gauge (-1), I_G_WWW);
    ((ZH, WHm, WHp), Gauge_Gauge_Gauge (-1), I_G_ZHWHWH) ]
  @
  (if Flags.u1_gauged then
    [ ((AH, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_AHWW);
      ((AH, WHm, Wp), Gauge_Gauge_Gauge 1, I_G_AHWHW);
      ((AH, Wm, WHp), Gauge_Gauge_Gauge (-1), I_G_AHWHW);
      ((AH, WHm, WHp), Gauge_Gauge_Gauge 1, I_G_AHWHWH) ]
    else
      [])

let triple_gauge =
  standard_triple_gauge @ heavy_triple_gauge

let gauge4 = Vector4 [(2, C_13_42); (-1, C_12_34); (-1, C_14_23)]
let minus_gauge4 = Vector4 [(-2, C_13_42); (1, C_12_34); (1, C_14_23)]
let standard_quartic_gauge =
  [ (Wm, Wp, Wm, Wp), gauge4, G_WWWW;
    (Wm, Z, Wp, Z), minus_gauge4, G_ZZWW;
    (Wm, Z, Wp, Ga), minus_gauge4, G_AZWW;
    (Wm, Ga, Wp, Ga), minus_gauge4, G_AAWW;
    (Gl, Gl, Gl, Gl), gauge4, G2 ]

let heavy_quartic_gauge =
  [ (WHm, Wp, WHm, Wp), gauge4, G_WWWW;
    (Wm, WHp, Wm, WHp), gauge4, G_WWWW;

```

```

(WHm, WHp, WHm, WHp), gauge4, G_WH4;
(Wm, Wp, WHm, WHp), gauge4, G_WHWHWW;
(Wm, Wp, Wm, WHp), gauge4, G_WHWWW;
(Wm, Wp, WHm, Wp), gauge4, G_WHWWW;
(WHm, WHp, Wm, WHp), gauge4, G_WH3W;
(WHm, WHp, WHm, Wp), gauge4, G_WH3W;
(WHm, Z, WHp, Z), minus_gauge4, G_ZZWW;
(WHm, Z, WHp, Ga), minus_gauge4, G_AZWW;
(WHm, Ga, WHp, ZH), minus_gauge4, G_AA WW;
(WHm, Z, WHp, ZH), minus_gauge4, G_ZZWW;
(Wm, ZH, Wp, ZH), minus_gauge4, G_WWWW;
(Wm, Ga, Wp, ZH), minus_gauge4, G_WWAZH;
(Wm, Z, Wp, ZH), minus_gauge4, G_WWZZH;
(WHm, Ga, WHp, ZH), minus_gauge4, G_WHWHAZH;
(WHm, Z, WHp, ZH), minus_gauge4, G_WHWHZZH;
(WHm, ZH, WHp, ZH), minus_gauge4, G_WH4;
(WHm, Z, Wp, Z), minus_gauge4, G_WHWZZ;
(Wm, Z, WHp, Z), minus_gauge4, G_WHWZZ;
(WHm, Ga, Wp, Z), minus_gauge4, G_WHWAZ;
(Wm, Ga, WHp, Z), minus_gauge4, G_WHWAZ;
(WHm, ZH, Wp, ZH), minus_gauge4, G_WHWZHZH;
(Wm, ZH, WHp, ZH), minus_gauge4, G_WHWZHZH;
(WHm, Ga, Wp, ZH), minus_gauge4, G_WHWAZH;
(Wm, Ga, WHp, ZH), minus_gauge4, G_WHWAZH;
(WHm, Z, Wp, ZH), minus_gauge4, G_WHWZZH;
(Wm, Z, WHp, ZH), minus_gauge4, G_WHWZZH]
@
  (if Flags.u1_gauged then
[ (Wm, Ga, Wp, AH), minus_gauge4, G_WWA AH;
  (Wm, Z, Wp, AH), minus_gauge4, G_WWZ AH;
  (WHm, Ga, WHp, AH), minus_gauge4, G_WHWHAAH;
  (WHm, Z, WHp, AH), minus_gauge4, G_WHWHZAH;
  (Wm, ZH, Wp, AH), minus_gauge4, G_WWZH AH;
  (WHm, ZH, WHp, AH), minus_gauge4, G_WHWHZH AH;
  (WHm, Ga, Wp, AH), minus_gauge4, G_WHWAAH;
  (Wm, Ga, WHp, AH), minus_gauge4, G_WHWAAH;
  (WHm, Z, Wp, AH), minus_gauge4, G_WHWZAH;
  (Wm, Z, WHp, AH), minus_gauge4, G_WHWZAH;
  (WHm, ZH, Wp, AH), minus_gauge4, G_WHWZH AH;
  (Wm, ZH, WHp, AH), minus_gauge4, G_WHWZH AH]
  else
  [])
let quartic_gauge =
  standard_quartic_gauge @ heavy_quartic_gauge
let standard_gauge_higgs' =
  [ ((H, Wp, Wm), Scalar_Vector_Vector 1, G_HWW);
    ((H, Z, Z), Scalar_Vector_Vector 1, G_HZZ) ]
let heavy_gauge_higgs =
  [ ((H, Wp, WHm), Scalar_Vector_Vector 1, G_HWHW);

```

```

((H, WHp, Wm), Scalar_Vector_Vector 1, G_HWHW);
((H, WHp, WHm), Scalar_Vector_Vector 1, G_HWHWH);
((H, ZH, ZH), Scalar_Vector_Vector 1, G_HWHWH);
((H, ZH, Z), Scalar_Vector_Vector 1, G_HZHZ);
((H, Wp, Wm), Scalar_Vector_Vector 1, G_HZHAH)]
@
  (if Flags.u1_gauged then
[ ((H, AH, AH), Scalar_Vector_Vector 1, G_HAHAH);
  ((H, Z, AH), Scalar_Vector_Vector 1, G_HAHZ)]
  else
  [])
let triplet_gauge_higgs =
[ ((Psi0, Wp, Wm), Scalar_Vector_Vector 1, G_PsiWW);
  ((Psi0, WHp, WHm), Scalar_Vector_Vector (-1), G_PsiWW);
  ((Psi0, WHp, Wm), Scalar_Vector_Vector 1, G_PsiWHW);
  ((Psi0, WHm, Wp), Scalar_Vector_Vector 1, G_PsiWHW);
  ((Psi0, Z, Z), Scalar_Vector_Vector 1, G_PsiZZ);
  ((Psi0, ZH, ZH), Scalar_Vector_Vector 1, G_PsiZHZH);
  ((Psi0, ZH, Z), Scalar_Vector_Vector 1, G_PsiZHZ);
  ((Psim, Wp, Z), Scalar_Vector_Vector 1, G_PsiZW);
  ((Psip, Wm, Z), Scalar_Vector_Vector 1, G_PsiZW);
  ((Psim, WHp, Z), Scalar_Vector_Vector 1, G_PsiZWH);
  ((Psip, WHm, Z), Scalar_Vector_Vector 1, G_PsiZWH);
  ((Psim, Wp, ZH), Scalar_Vector_Vector 1, G_PsiZHW);
  ((Psip, Wm, ZH), Scalar_Vector_Vector 1, G_PsiZHW);
  ((Psim, WHp, ZH), Scalar_Vector_Vector 1, G_PsiZHWH);
  ((Psip, WHm, ZH), Scalar_Vector_Vector 1, G_PsiZHWH);
  ((Psimm, Wp, Wp), Scalar_Vector_Vector 1, G_PsippWW);
  ((Psipp, Wm, Wm), Scalar_Vector_Vector 1, G_PsippWW);
  ((Psimm, WHp, Wp), Scalar_Vector_Vector 1, G_PsippWHW);
  ((Psipp, WHm, Wm), Scalar_Vector_Vector 1, G_PsippWHW);
  ((Psimm, WHp, WHp), Scalar_Vector_Vector 1, G_PsippWHWH);
  ((Psipp, WHm, WHm), Scalar_Vector_Vector 1, G_PsippWHWH)]
@
  (if Flags.u1_gauged then
[ ((Psi0, AH, Z), Scalar_Vector_Vector 1, G_PsiZAH);
  ((Psi0, AH, ZH), Scalar_Vector_Vector 1, G_PsiZHAH);
  ((Psi0, AH, AH), Scalar_Vector_Vector 1, G_PsiAHAH);
  ((Psim, Wp, AH), Scalar_Vector_Vector 1, G_PsiAHW);
  ((Psip, Wm, AH), Scalar_Vector_Vector 1, G_PsiAHW);
  ((Psim, WHp, AH), Scalar_Vector_Vector 1, G_PsiAHWH);
  ((Psip, WHm, AH), Scalar_Vector_Vector 1, G_PsiAHWH)]
  else
  [])
let triplet_gauge2_higgs =
[ ((Wp, H, Psim), Vector_Scalar_Scalar 1, G_PsiHW);
  ((Wm, H, Psip), Vector_Scalar_Scalar 1, G_PsiHW);
  ((WHp, H, Psim), Vector_Scalar_Scalar 1, G_PsiHWH);
  ((WHm, H, Psip), Vector_Scalar_Scalar 1, G_PsiHWH);

```

```

((Wp, Psi0, Psim), Vector_Scalar_Scalar 1, G_Psi0W);
((Wm, Psi0, Psip), Vector_Scalar_Scalar 1, G_Psi0W);
((WHp, Psi0, Psim), Vector_Scalar_Scalar 1, G_Psi0WH);
((WHm, Psi0, Psip), Vector_Scalar_Scalar 1, G_Psi0WH);
((Wp, Psi1, Psim), Vector_Scalar_Scalar 1, G_Psi1W);
((Wm, Psi1, Psip), Vector_Scalar_Scalar (-1), G_Psi1W);
((WHp, Psi1, Psim), Vector_Scalar_Scalar 1, G_Psi1WH);
((WHm, Psi1, Psip), Vector_Scalar_Scalar (-1), G_Psi1WH);
((Wp, Psip, Psimm), Vector_Scalar_Scalar 1, G_PsiPPW);
((Wm, Psim, Psipp), Vector_Scalar_Scalar 1, G_PsiPPW);
((WHp, Psip, Psimm), Vector_Scalar_Scalar 1, G_PsiPPWH);
((WHm, Psim, Psipp), Vector_Scalar_Scalar 1, G_PsiPPWH);
((Ga, Psip, Psim), Vector_Scalar_Scalar 1, Q_lepton);
((Ga, Psipp, Psimm), Vector_Scalar_Scalar 2, Q_lepton);
((Z, H, Psi1), Vector_Scalar_Scalar 1, G_Psi1HZ);
((ZH, H, Psi1), Vector_Scalar_Scalar 1, G_Psi1HZH);
((Z, Psi0, Psi1), Vector_Scalar_Scalar 1, G_Psi01Z);
((ZH, Psi0, Psi1), Vector_Scalar_Scalar 1, G_Psi01ZH);
((Z, Psip, Psim), Vector_Scalar_Scalar 1, G_ZPsip);
((Z, Psipp, Psimm), Vector_Scalar_Scalar 2, G_ZPsipp);
((ZH, Psipp, Psimm), Vector_Scalar_Scalar 2, G_ZHPsipp)]
@
  (if Flags.u1_gauged then
[ (AH, H, Psi1), Vector_Scalar_Scalar 1, G_Psi1HAH);
  (AH, Psi0, Psi1), Vector_Scalar_Scalar 1, G_Psi01AH);
  (AH, Psip, Psim), Vector_Scalar_Scalar 1, G_AHPsip);
  (AH, Psipp, Psimm), Vector_Scalar_Scalar 2, G_AHPsipp)]
  else [])

let standard_gauge_higgs =
  standard_gauge_higgs' @ heavy_gauge_higgs @ triplet_gauge_higgs @
  triplet_gauge2_higgs

let standard_gauge_higgs4 =
  [ (H, H, Wp, Wm), Scalar2_Vector2 1, G_HHWW;
    (H, H, Z, Z), Scalar2_Vector2 1, G_HHZZ ]

let littlest_gauge_higgs4 =
  [ (H, H, WHp, WHm), Scalar2_Vector2 (-1), G_HHWW;
    (H, H, ZH, ZH), Scalar2_Vector2 (-1), G_HHWW;
    (H, H, Wp, WHm), Scalar2_Vector2 1, G_HHWW;
    (H, H, WHp, Wm), Scalar2_Vector2 1, G_HHWW;
    (H, H, ZH, Z), Scalar2_Vector2 (-1), G_HHZZ;
    (H, Psi0, Wp, Wm), Scalar2_Vector2 1, G_HPsi0WW;
    (H, Psi0, WHp, WHm), Scalar2_Vector2 (-1), G_HPsi0WW;
    (H, Psi0, WHp, Wm), Scalar2_Vector2 1, G_HPsi0WW;
    (H, Psi0, Wp, WHm), Scalar2_Vector2 1, G_HPsi0WW;
    (H, Psi0, Z, Z), Scalar2_Vector2 1, G_HPsi0ZZ;
    (H, Psi0, ZH, ZH), Scalar2_Vector2 1, G_HPsi0ZZ;
    (H, Psi0, ZH, Z), Scalar2_Vector2 1, G_HPsi0ZZ;
    (H, Psim, Wp, Ga), Scalar2_Vector2 1, G_HPsipWA;
    (H, Psip, Wm, Ga), Scalar2_Vector2 1, G_HPsipWA;

```

$(H, Psim, WHp, Ga), \text{Scalar2\_Vector2 } 1, G\_HPsipWHA;$   
 $(H, Psip, WHm, Ga), \text{Scalar2\_Vector2 } 1, G\_HPsipWHA;$   
 $(H, Psim, Wp, Z), \text{Scalar2\_Vector2 } 1, G\_HPsipWZ;$   
 $(H, Psip, Wm, Z), \text{Scalar2\_Vector2 } 1, G\_HPsipWZ;$   
 $(H, Psim, WHp, Z), \text{Scalar2\_Vector2 } 1, G\_HPsipWHZ;$   
 $(H, Psip, WHm, Z), \text{Scalar2\_Vector2 } 1, G\_HPsipWHZ;$   
 $(H, Psim, Wp, ZH), \text{Scalar2\_Vector2 } 1, G\_HPsipWZH;$   
 $(H, Psip, Wm, ZH), \text{Scalar2\_Vector2 } 1, G\_HPsipWZH;$   
 $(H, Psim, WHp, ZH), \text{Scalar2\_Vector2 } 1, G\_HPsipWHZH;$   
 $(H, Psip, WHm, ZH), \text{Scalar2\_Vector2 } 1, G\_HPsipWHZH;$   
 $(H, Psimm, Wp, Wp), \text{Scalar2\_Vector2 } 1, G\_HPsippWW;$   
 $(H, Psipp, Wm, Wm), \text{Scalar2\_Vector2 } 1, G\_HPsippWW;$   
 $(H, Psimm, WHp, WHp), \text{Scalar2\_Vector2 } 1, G\_HPsippWHWH;$   
 $(H, Psipp, WHm, WHm), \text{Scalar2\_Vector2 } 1, G\_HPsippWHWH;$   
 $(H, Psimm, WHp, Wp), \text{Scalar2\_Vector2 } 1, G\_HPsippWHW;$   
 $(H, Psipp, WHm, Wm), \text{Scalar2\_Vector2 } 1, G\_HPsippWHW;$   
 $(Psi0, Psi0, Wp, Wm), \text{Scalar2\_Vector2 } 2, G\_HHWW;$   
 $(Psi0, Psi0, WHp, WHm), \text{Scalar2\_Vector2 } (-2), G\_HHWW;$   
 $(Psi0, Psi0, Z, Z), \text{Scalar2\_Vector2 } 4, G\_HHZZ;$   
 $(Psi0, Psi0, ZH, ZH), \text{Scalar2\_Vector2 } 1, G\_Psi00ZH;$   
 $(Psi0, Psi0, WHp, Wm), \text{Scalar2\_Vector2 } 2, G\_HHWHW;$   
 $(Psi0, Psi0, Wp, WHm), \text{Scalar2\_Vector2 } 2, G\_HHWHW;$   
 $(Psi0, Psi0, Z, ZH), \text{Scalar2\_Vector2 } 4, G\_HHZHZ;$   
 $(Psi0, Psim, Wp, Ga), \text{Scalar2\_Vector2 } 1, G\_Psi0pWA;$   
 $(Psi0, Psip, Wm, Ga), \text{Scalar2\_Vector2 } 1, G\_Psi0pWA;$   
 $(Psi0, Psim, WHp, Ga), \text{Scalar2\_Vector2 } 1, G\_Psi0pWHA;$   
 $(Psi0, Psip, WHm, Ga), \text{Scalar2\_Vector2 } 1, G\_Psi0pWHA;$   
 $(Psi0, Psim, Wp, Z), \text{Scalar2\_Vector2 } 1, G\_Psi0pWZ;$   
 $(Psi0, Psip, Wm, Z), \text{Scalar2\_Vector2 } 1, G\_Psi0pWZ;$   
 $(Psi0, Psim, WHp, Z), \text{Scalar2\_Vector2 } 1, G\_Psi0pWHZ;$   
 $(Psi0, Psip, WHm, Z), \text{Scalar2\_Vector2 } 1, G\_Psi0pWHZ;$   
 $(Psi0, Psim, Wp, ZH), \text{Scalar2\_Vector2 } 1, G\_Psi0pWZH;$   
 $(Psi0, Psip, Wm, ZH), \text{Scalar2\_Vector2 } 1, G\_Psi0pWZH;$   
 $(Psi0, Psim, WHp, ZH), \text{Scalar2\_Vector2 } 1, G\_Psi0pWHZH;$   
 $(Psi0, Psip, WHm, ZH), \text{Scalar2\_Vector2 } 1, G\_Psi0pWHZH;$   
 $(Psi0, Psimm, Wp, Wp), \text{Scalar2\_Vector2 } 1, G\_Psi0ppWW;$   
 $(Psi0, Psipp, Wm, Wm), \text{Scalar2\_Vector2 } 1, G\_Psi0ppWW;$   
 $(Psi0, Psimm, WHp, WHp), \text{Scalar2\_Vector2 } 1, G\_Psi0ppWHWH;$   
 $(Psi0, Psipp, WHm, WHm), \text{Scalar2\_Vector2 } 1, G\_Psi0ppWHWH;$   
 $(Psi0, Psimm, WHp, Wp), \text{Scalar2\_Vector2 } 1, G\_Psi0ppWHW;$   
 $(Psi0, Psipp, WHm, Wm), \text{Scalar2\_Vector2 } 1, G\_Psi0ppWHW;$   
 $(Psi1, Psi1, Wp, Wm), \text{Scalar2\_Vector2 } 2, G\_HHWW;$   
 $(Psi1, Psi1, WHp, WHm), \text{Scalar2\_Vector2 } (-2), G\_HHWW;$   
 $(Psi1, Psi1, Z, Z), \text{Scalar2\_Vector2 } 4, G\_HHZZ;$   
 $(Psi1, Psi1, ZH, ZH), \text{Scalar2\_Vector2 } 1, G\_Psi100ZH;$   
 $(Psi1, Psi1, WHp, Wm), \text{Scalar2\_Vector2 } 2, G\_HHWHW;$   
 $(Psi1, Psi1, Wp, WHm), \text{Scalar2\_Vector2 } 2, G\_HHWHW;$   
 $(Psi1, Psi1, Z, ZH), \text{Scalar2\_Vector2 } 4, G\_HHZHZ;$   
 $(Psi1, Psim, Wp, Ga), \text{Scalar2\_Vector2 } 1, I\_G\_Psi0pWA;$   
 $(Psi1, Psip, Wm, Ga), \text{Scalar2\_Vector2 } (-1), I\_G\_Psi0pWA;$



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(Psi1, Psim, WHp, Ga), Scalar2_Vector2 1, I_G_Psi0pWHA;
(Psi1, Psip, WHm, Ga), Scalar2_Vector2 (-1), I_G_Psi0pWHA;
(Psi1, Psim, Wp, Z), Scalar2_Vector2 1, I_G_Psi0pWZ;
(Psi1, Psip, Wm, Z), Scalar2_Vector2 (-1), I_G_Psi0pWZ;
(Psi1, Psim, WHp, Z), Scalar2_Vector2 1, I_G_Psi0pWHZ;
(Psi1, Psip, WHm, Z), Scalar2_Vector2 (-1), I_G_Psi0pWHZ;
(Psi1, Psim, Wp, ZH), Scalar2_Vector2 1, I_G_Psi0pWZH;
(Psi1, Psip, Wm, ZH), Scalar2_Vector2 (-1), I_G_Psi0pWZH;
(Psi1, Psim, WHp, ZH), Scalar2_Vector2 1, I_G_Psi0pWHZH;
(Psi1, Psip, WHm, ZH), Scalar2_Vector2 (-1), I_G_Psi0pWHZH;
(Psi1, Psimm, Wp, Wp), Scalar2_Vector2 1, I_G_Psi0ppWW;
(Psi1, Psipp, Wm, Wm), Scalar2_Vector2 (-1), I_G_Psi0ppWW;
(Psi1, Psimm, WHp, WHp), Scalar2_Vector2 1, I_G_Psi0ppWHWH;
(Psi1, Psipp, WHm, WHm), Scalar2_Vector2 (-1), I_G_Psi0ppWHWH;
(Psi1, Psimm, WHp, Wp), Scalar2_Vector2 1, I_G_Psi0ppWHW;
(Psi1, Psipp, WHm, Wm), Scalar2_Vector2 (-1), I_G_Psi0ppWHW;
(Psip, Psim, Wp, Wm), Scalar2_Vector2 4, G_HHWW;
(Psip, Psim, WHp, WHm), Scalar2_Vector2 1, G_Psi00ZH;
(Psip, Psim, WHp, Wm), Scalar2_Vector2 4, G_HHWHW;
(Psip, Psim, Wp, WHm), Scalar2_Vector2 4, G_HHWHW;
(Psip, Psim, Z, Z), Scalar2_Vector2 1, G_PsippZZ;
(Psip, Psim, Ga, Ga), Scalar2_Vector2 2, G_AAWW;
(Psip, Psim, ZH, ZH), Scalar2_Vector2 1, G_PsippZHZH;
(Psip, Psim, Ga, Z), Scalar2_Vector2 4, G_PsippAZ;
(Psip, Psimm, Wp, Ga), Scalar2_Vector2 1, G_PsippWA;
(Psim, Psipp, Wm, Ga), Scalar2_Vector2 1, G_PsippWA;
(Psip, Psimm, WHp, Ga), Scalar2_Vector2 1, G_PsippWHA;
(Psim, Psipp, WHm, Ga), Scalar2_Vector2 1, G_PsippWHA;
(Psip, Psimm, Wp, Z), Scalar2_Vector2 1, G_PsippWZ;
(Psim, Psipp, Wm, Z), Scalar2_Vector2 1, G_PsippWZ;
(Psip, Psimm, WHp, Z), Scalar2_Vector2 1, G_PsippWHZ;
(Psim, Psipp, WHm, Z), Scalar2_Vector2 1, G_PsippWHZ;
(Psip, Psimm, Wp, ZH), Scalar2_Vector2 1, G_PsippWZH;
(Psim, Psipp, Wm, ZH), Scalar2_Vector2 1, G_PsippWZH;
(Psip, Psimm, WHp, ZH), Scalar2_Vector2 1, G_PsippWHZH;
(Psim, Psipp, WHm, ZH), Scalar2_Vector2 1, G_PsippWHZH;
(Psipp, Psimm, Wp, Wm), Scalar2_Vector2 2, G_HHWW;
(Psipp, Psimm, WHp, WHm), Scalar2_Vector2 (-2), G_HHWW;
(Psipp, Psimm, WHp, Wm), Scalar2_Vector2 2, G_HHWHW;
(Psipp, Psimm, Wp, WHm), Scalar2_Vector2 2, G_HHWHW;
(Psipp, Psimm, Z, Z), Scalar2_Vector2 1, G_PsiccZZ;
(Psipp, Psimm, Ga, Ga), Scalar2_Vector2 8, G_AAWW;
(Psipp, Psimm, ZH, ZH), Scalar2_Vector2 1, G_Psi00ZH;
(Psipp, Psimm, Ga, Z), Scalar2_Vector2 1, G_PsiccAZ;
(Psipp, Psimm, Z, ZH), Scalar2_Vector2 4, G_PsiccZZH;
(Psipp, Psimm, Ga, ZH), Scalar2_Vector2 4, G_PsiccAZH]
@
(if Flags.u1_gauged then
[(H, H, AH, AH), Scalar2_Vector2 1, G_HHAA;
(H, H, AH, Z), Scalar2_Vector2 (-1), G_HHAHZ;

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(H, H, ZH, AH), Scalar2_Vector2 (-1), G_HHZHAH;
(H, Psi0, AH, AH), Scalar2_Vector2 1, G_HPsi0AHAH;
(H, Psi0, Z, AH), Scalar2_Vector2 1, G_HPsi0ZAH;
(H, Psi0, ZH, AH), Scalar2_Vector2 1, G_HPsi0ZHAH;
(H, Psim, Wp, AH), Scalar2_Vector2 1, G_HPsipWAH;
(H, Psip, Wm, AH), Scalar2_Vector2 1, G_HPsipWAH;
(H, Psim, WHp, AH), Scalar2_Vector2 1, G_HPsipWHAH;
(H, Psip, WHm, AH), Scalar2_Vector2 1, G_HPsipWHAH;
(Psi0, Psi0, AH, AH), Scalar2_Vector2 1, G_Psi00AH;
(Psi0, Psi0, Z, AH), Scalar2_Vector2 4, G_HHAHZ;
(Psi0, Psi0, AH, ZH), Scalar2_Vector2 1, G_Psi00ZHAH;
(Psi0, Psim, Wp, AH), Scalar2_Vector2 1, G_Psi0pWAH;
(Psi0, Psip, Wm, AH), Scalar2_Vector2 1, G_Psi0pWAH;
(Psi0, Psim, WHp, AH), Scalar2_Vector2 1, G_Psi0pWHAH;
(Psi0, Psip, WHm, AH), Scalar2_Vector2 1, G_Psi0pWHAH;
(Psi1, Psi1, AH, AH), Scalar2_Vector2 1, G_Psi00AH;
(Psi1, Psi1, Z, AH), Scalar2_Vector2 4, G_HHAHZ;
(Psi1, Psi1, AH, ZH), Scalar2_Vector2 1, G_Psi00ZHAH;
(Psi1, Psim, Wp, AH), Scalar2_Vector2 1, I_G_Psi0pWAH;
(Psi1, Psip, Wm, AH), Scalar2_Vector2 (-1), I_G_Psi0pWAH;
(Psi1, Psim, WHp, AH), Scalar2_Vector2 1, I_G_Psi0pWHAH;
(Psi1, Psip, WHm, AH), Scalar2_Vector2 (-1), I_G_Psi0pWHAH;
(Psip, Psim, AH, AH), Scalar2_Vector2 1, G_Psi00AH;
(Psip, Psim, Ga, AH), Scalar2_Vector2 4, G_PsippAAH;
(Psip, Psim, Z, AH), Scalar2_Vector2 4, G_PsippZAH;
(Psip, Psimm, Wp, AH), Scalar2_Vector2 1, G_PsippWAH;
(Psim, Psipp, Wm, AH), Scalar2_Vector2 1, G_PsippWAH;
(Psip, Psimm, WHp, AH), Scalar2_Vector2 1, G_PsippWHAH;
(Psim, Psipp, WHm, AH), Scalar2_Vector2 1, G_PsippWHAH;
(Psipp, Psimm, AH, AH), Scalar2_Vector2 1, G_Psi00AH;
(Psipp, Psimm, AH, ZH), Scalar2_Vector2 (-1), G_Psi00ZHAH;
(Psipp, Psimm, Ga, AH), Scalar2_Vector2 4, G_PsiccAAH;
(Psipp, Psimm, Z, AH), Scalar2_Vector2 4, G_PsiccZAH]
else []
let standard_higgs =
  [ (H, H, H), Scalar_Scalar_Scalar 1, G_H3 ]
let anomaly_higgs =
  [ (Eta, Gl, Gl), Dim5_Scalar_Gauge2_Skew 1, G_EGIGl;
    (Eta, Ga, Ga), Dim5_Scalar_Gauge2_Skew 1, G_EGaGa;
    (Eta, Ga, Z), Dim5_Scalar_Gauge2_Skew 1, G_EGaZ]
(* @ (H, Ga, Ga), Dim5_Scalar_Gauge2 1, G_HGaGa; (H, Ga, Z), Dim5_Scalar_Gauge2 1, G_HGaZ
*)
let standard_higgs4 =
  [ (H, H, H, H), Scalar4 1, G_H4 ]
let gauge_higgs =
  standard_gauge_higgs
let gauge_higgs4 =
  standard_gauge_higgs4

```

```

let higgs =
  standard_higgs

let higgs4 =
  standard_higgs4

let top_quartic =
  [ ((U (-3), H, H, U 3), GBBG (1, Psibar, S2, Psi), G_HHtt);
    ((Toppb, H, H, Topp), GBBG (1, Psibar, S2, Psi), G_HHthth);
    ((U (-3), H, H, Topp), GBBG (1, Psibar, S2LR, Psi), G_HHtht);
    ((Toppb, H, H, U 3), GBBG (1, Psibar, S2LR, Psi), G_HHtht)]

let goldstone_vertices =
  [ ((Phi0, Wm, Wp), Scalar_Vector_Vector 1, I-G-ZWW);
    ((Phip, Ga, Wm), Scalar_Vector_Vector 1, I-Q-W);
    ((Phip, Z, Wm), Scalar_Vector_Vector 1, I-G-ZWW);
    ((Phim, Wp, Ga), Scalar_Vector_Vector 1, I-Q-W);
    ((Phim, Wp, Z), Scalar_Vector_Vector 1, I-G-ZWW) ]

let vertices3 =
  (ThoList.flatmap electromagnetic_currents [1;2;3] @
   ThoList.flatmap neutral_currents [1;2;3] @
   ThoList.flatmap color_currents [1;2;3] @
   ThoList.flatmap neutral_heavy_currents [1;2;3] @
   ThoList.flatmap charged_currents [1;2;3] @
   ThoList.flatmap quark_currents [1;2] @
   heavy_top_currents @
   (if Flags.u1_gauged then []
    else anomaly_higgs) @
   yukawa @ yukawa_add @ triple_gauge @
   gauge_higgs @ higgs @ goldstone_vertices)

let vertices4 =
  quartic_gauge @ gauge_higgs4 @ higgs4 @ top_quartic

let vertices () = (vertices3, vertices4, [])

```

For efficiency, make sure that *F.of\_vertices vertices* is evaluated only once.

```

let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 4

let flavor_of_string = function
| "e-" → L 1 | "e+" → L (-1)
| "mu-" → L 2 | "mu+" → L (-2)
| "tau-" → L 3 | "tau+" → L (-3)
| "nue" → N 1 | "nuebar" → N (-1)
| "numu" → N 2 | "numubar" → N (-2)
| "nutau" → N 3 | "nutaubar" → N (-3)
| "u" → U 1 | "ubar" → U (-1)
| "c" → U 2 | "cbar" → U (-2)
| "t" → U 3 | "tbar" → U (-3)

```

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| "d" → D 1 | "d̄" → D (-1)
| "s" → D 2 | "s̄" → D (-2)
| "b" → D 3 | "b̄" → D (-3)
| "tp" → Topp | "tp̄" → Toppb
| "g" → Gl
| "A" → Ga | "Z" | "Z0" → Z
| "AH" | "AH0" | "Ah" | "Ah0" → AH
| "ZH" | "ZH0" | "Zh" | "Zh0" → ZH
| "W+" → Wp | "W-" → Wm
| "WH+" → WHp | "WH-" → WHm
| "H" | "h" → H | "eta" | "Eta" → Eta
| "Psi" | "Psi0" | "psi" | "psi0" → Psi0
| "Psi1" | "psi1" → Psi1
| "Psi+" | "psi+" | "Psip" | "psip" → Psip
| "Psi-" | "psi-" | "Psim" | "psim" → Psim
| "Psi++" | "psi++" | "Psipp" | "psipp" → Psipp
| "Psi--" | "psi--" | "Psim" | "psim" → Psim
| _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_of_string"

let flavor_to_string = function
| L 1 → "e-" | L (-1) → "e+"
| L 2 → "mu-" | L (-2) → "mu+"
| L 3 → "tau-" | L (-3) → "tau+"
| L _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_to_string"
| N 1 → "nue" | N (-1) → "nuebar"
| N 2 → "numu" | N (-2) → "numubar"
| N 3 → "nutau" | N (-3) → "nutaubar"
| N _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_to_string"
| Lodd 1 → "l1odd-" | Lodd (-1) → "l1odd+"
| Lodd 2 → "l2odd-" | Lodd (-2) → "l2odd+"
| Lodd 3 → "l3odd-" | Lodd (-3) → "l3odd+"
| Lodd _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_to_string"
| Nodd 1 → "n1odd" | Nodd (-1) → "n1oddbar"
| Nodd 2 → "n2odd" | Nodd (-2) → "n2oddbar"
| Nodd 3 → "n3odd" | Nodd (-3) → "n3oddbar"
| Nodd _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_to_string"
| U 1 → "u" | U (-1) → "ubar"
| U 2 → "c" | U (-2) → "cbar"
| U 3 → "t" | U (-3) → "tbar"
| U _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_to_string"
| D 1 → "d" | D (-1) → "d̄"
| D 2 → "s" | D (-2) → "s̄"
| D 3 → "b" | D (-3) → "b̄"
| D _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_to_string"
| Uodd 1 → "uodd" | Uodd (-1) → "uoddbar"
| Uodd 2 → "codd" | Uodd (-2) → "coddbar"
| Uodd 3 → "t1odd" | Uodd (-3) → "t1oddbar"
| Uodd 4 → "t2odd" | Uodd (-4) → "t2oddbar"
| Uodd _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_to_string"
| Dodd 1 → "dodd" | Dodd (-1) → "doddbar"

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| Dodd 2 → "sodd" | Dodd (-2) → "soddbar"
| Dodd 3 → "bodd" | Dodd (-3) → "boddbar"
| Dodd _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_to_string"
| Topp → "tp" | Toppb → "tpbar"
| Gl → "g"
| Ga → "A" | Z → "Z"
| Wp → "W+" | Wm → "W-"
| ZH → "ZH" | AH → "AH" | WHp → "WHp" | WHm → "WHm"
| Phip → "phi+" | Phim → "phi-" | Phi0 → "phi0"
| H → "H" | Eta → "Eta"
| Psi0 → "Psi0" | Psi1 → "Psi1" | Psip → "Psi+"
| Psim → "Psi-" | Psipp → "Psi++" | Psimm → "Psi--"

let flavor_to_TeX = function
| L 1 → "e^-" | L (-1) → "e^+"
| L 2 → "\\mu^-" | L (-2) → "\\mu^+"
| L 3 → "\\tau^-" | L (-3) → "\\tau^+"
| L _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_to_TeX"
| N 1 → "\\nu_e" | N (-1) → "\\bar{\\nu}_e"
| N 2 → "\\nu_\\mu" | N (-2) → "\\bar{\\nu}_\\mu"
| N 3 → "\\nu_\\tau" | N (-3) → "\\bar{\\nu}_\\tau"
| N _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_to_TeX"
| Lodd 1 → "L_1^-" | Lodd (-1) → "L_1^+"
| Lodd 2 → "L_2^-" | Lodd (-2) → "L_2^+"
| Lodd 3 → "L_3^-" | Lodd (-3) → "L_3^+"
| Lodd _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_to_TeX"
| Nodd 1 → "N_1" | Nodd (-1) → "\\bar{N}_1"
| Nodd 2 → "N_2" | Nodd (-2) → "\\bar{N}_2"
| Nodd 3 → "N_3" | Nodd (-3) → "\\bar{N}_3"
| Nodd _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_to_TeX"
| U 1 → "u" | U (-1) → "\\bar{u}"
| U 2 → "c" | U (-2) → "\\bar{c}"
| U 3 → "t" | U (-3) → "\\bar{t}"
| U _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_to_TeX"
| D 1 → "d" | D (-1) → "\\bar{d}"
| D 2 → "s" | D (-2) → "\\bar{s}"
| D 3 → "b" | D (-3) → "\\bar{b}"
| D _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_to_TeX"
| Uodd 1 → "U" | Uodd (-1) → "\\bar{U}"
| Uodd 2 → "C" | Uodd (-2) → "\\bar{C}"
| Uodd 3 → "T_1" | Uodd (-3) → "\\bar{T}_1"
| Uodd 4 → "T_2" | Uodd (-4) → "\\bar{T}_2"
| Uodd _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_to_TeX"
| Dodd 1 → "D" | Dodd (-1) → "\\bar{D}"
| Dodd 2 → "S" | Dodd (-2) → "\\bar{S}"
| Dodd 3 → "B" | Dodd (-3) → "\\bar{B}"
| Dodd _ → invalid_arg "Modellib_BSM.Littlest_Tpar.flavor_to_TeX"
| Topp → "T^\\prime" | Toppb → "\\bar{T}^\\prime"
| Gl → "g"
| Ga → "\\gamma" | Z → "Z"

```

```

| Wp → "W^+" | Wm → "W^-"  

| ZH → "Z-H" | AH → "\\gamma-H" | WHp → "W-H^+" |  

WHm → "W-H^-"  

| Phip → "\\Phi^+" | Phim → "\\Phi^-" | Phi0 → "\\Phi^0"  

| H → "H" | Eta → "\\eta"  

| Psi0 → "\\Psi_S" | Psi1 → "\\Psi_P" | Psip → "\\Psi^+"  

| Psim → "\\Psi^-" | Psipp → "\\Psi^{++}" | Psimm →  

"\\Psi^{--}"  

let flavor_symbol = function  

| L n when n > 0 → "l" ^ string_of_int n  

| L n → "l" ^ string_of_int (abs n) ^ "b"  

| Lodd n when n > 0 → "lodd" ^ string_of_int n  

| Lodd n → "lodd" ^ string_of_int (abs n) ^ "b"  

| N n when n > 0 → "n" ^ string_of_int n  

| N n → "n" ^ string_of_int (abs n) ^ "b"  

| Nodd n when n > 0 → "nodd" ^ string_of_int n  

| Nodd n → "nodd" ^ string_of_int (abs n) ^ "b"  

| U n when n > 0 → "u" ^ string_of_int n  

| U n → "u" ^ string_of_int (abs n) ^ "b"  

| D n when n > 0 → "d" ^ string_of_int n  

| D n → "d" ^ string_of_int (abs n) ^ "b"  

| Uodd n when n > 0 → "uodd" ^ string_of_int n  

| Uodd n → "uodd" ^ string_of_int (abs n) ^ "b"  

| Dodd n when n > 0 → "dodd" ^ string_of_int n  

| Dodd n → "dodd" ^ string_of_int (abs n) ^ "b"  

| Topp → "tp" | Toppb → "tpb"  

| Gl → "gl"  

| Ga → "a" | Z → "z"  

| Wp → "wp" | Wm → "wm"  

| ZH → "zh" | AH → "ah" | WHp → "whp" | WHm → "whm"  

| Phip → "pp" | Phim → "pm" | Phi0 → "p0"  

| H → "h" | Eta → "eta"  

| Psi0 → "psi0" | Psi1 → "psi1" | Psip → "psip"  

| Psim → "psim" | Psipp → "psipp" | Psimm → "psimm"

```

There are PDG numbers for Z', Z'', W', 32-34, respectively. We just introduce a number 38 for Y0 as a Z''. As well, there is the number 8 for a t'. But we cheat a little bit and take the number 35 which is reserved for a heavy scalar Higgs for the Eta scalar. For the heavy Higgs states we take 35 and 36 for the neutral ones, 37 for the charged and 38 for the doubly-charged. The pseudoscalar gets the 39. For the odd fermions we add 40 to the values for the SM particles.

```

let pdg = function  

| L n when n > 0 → 9 + 2 × n  

| L n → - 9 + 2 × n  

| N n when n > 0 → 10 + 2 × n  

| N n → - 10 + 2 × n  

| U n when n > 0 → 2 × n  

| U n → 2 × n  

| D n when n > 0 → - 1 + 2 × n  

| D n → 1 + 2 × n

```

```

| Lodd n when n > 0 → 49 + 2 × n
| Lodd n → - 49 + 2 × n
| Nodd n when n > 0 → 50 + 2 × n
| Nodd n → - 50 + 2 × n
| Uodd n when n > 0 → 40 + 2 × n
| Uodd n → - 40 + 2 × n
| Dodd n when n > 0 → 39 + 2 × n
| Dodd n → - 39 + 2 × n
| Toppp → 8 | Toppb → (-8)
| Gl → 21
| Ga → 22 | Z → 23
| Wp → 24 | Wm → (-24)
| AH → 32 | ZH → 33 | WHp → 34 | WHm → (-34)
| Phip | Phim → 27 | Phi0 → 26
| Psi0 → 35 | Psi1 → 36 | Psip → 37 | Psim → (-37)
| Psipp → 38 | Psimm → (-38)
| H → 25 | Eta → 39

let mass_symbol f =
  "mass(" ^ string_of_int (abs (pdg f)) ^ ")"

let width_symbol f =
  "width(" ^ string_of_int (abs (pdg f)) ^ ")"

let constant_symbol = function
| Unit → "unit" | Pi → "PI" | VHeavy → "vheavy"
| Alpha_QED → "alpha" | E → "e" | G_weak → "g" | Vev →
"vev"
| Sin2thw → "sin2thw" | Sinthw → "sinthw" | Costhw →
"costhw"
| Sinpsi → "sinpsi" | Cospsi → "cospsi"
| Atpsi → "atpsi" | Sccs → "sccs"
| Supp → "vF" | Supp2 → "v2F2"
| Q_lepton → "qllep" | Q_up → "qup" | Q_down → "qdown"
| Q_Z_up → "qzup"
| G_ZHTHT → "gzhtht" | G_ZTHT → "gzhtht"
| G_AHTHTH → "gahthth" | G_AHTHT → "gahtht" | G_AHTT →
"gahtt"
| G_NC_lepton → "gnclep" | G_NC_neutrino → "gncneu"
| G_NC_up → "gncup" | G_NC_down → "gncdown"
| G_CC → "gcc" | G_CCtop → "gcctop" | G_CC_heavy →
"gcch"
| G_CC_WH → "gccwh" | G_CC_W → "gccw"
| G_NC_h_lepton → "gnchlep" | G_NC_h_neutrino → "gnchneu"
| G_NC_h_up → "gnchup" | G_NC_h_down → "gnchdown"
| G_NC_heavy → "gnch"
| I_Q_W → "iqw" | I_G_ZWW → "igzww" | I_G_WWW →
"igwww"
| I_G_AHWW → "igahww" | I_G_ZHWW → "igzhww" | I_G_ZWHW →
"igzwhw"
| I_G_AHWHWH → "igahwhwh" | I_G_ZHWHWH → "igzhwhwh"
| I_G_AHWHW → "igahwhw"

```

```

| I_Q_H → "iqh"
| G_s → "gs" | I_Gs → "igs" | G2 → "gs**2"
| G_WWW → "gw4" | G_ZZW → "gzzw"
| G_AZW → "gazw" | G_AAW → "gaaw"
| G_WH4 → "gwh4" | G_WHWHWW → "gwhwhww" | G_WHWWW →
"ghwww"
| G_WH3W → "gwh3w"
| G_WWAAH → "gwaaah" | G_WWAZH → "gwazh" | G_WWZZH →
"gwzzh"
| G_WWZAH → "gwzah" | G_WHWHAAH → "gwhhaah"
| G_WHWHAZH → "gwhhazh" | G_WHWHZZH → "gwhhzzh"
| G_WHWHZAH → "gwhwhzah"
| G_WWZHAH → "gwz zah" | G_WHWHZHAH → "gwhwhzhah"
| G_WHWZZ → "gwhwzz" | G_WHWAZ → "gwhwaz"
| G_WHWAH → "gwhwah" | G_WHWZAH → "gwhwzah"
| G_WHWZHZH → "gwhwzhzh" | G_WHWZHAH → "gwhwzhah"
| G_WHWAZH → "gwhwazh" | G_WHWZZH → "gwhwzzh"
| G_HWW → "ghww" | G_HZZ → "ghzz"
| G_HHWW → "ghhww" | G_HHZZ → "ghhzz"
| G_HWHW → "ghwhw" | G_HWHWH → "ghwhwh" | G_HAHAAH →
"ghahah"
| G_HZHZ → "ghzhz" | G_HZHAH → "ghzhah"
| G_HAHZ → "ghahz"
| G_Htt → "ghtt" | G_Hbb → "ghbb"
| G_Htautau → "ghtautau" | G_Hcc → "ghcc"
| G_Hthth → "ghthth" | G_Htht → "ghtht"
| G_HHtt → "ghhtht" | G_HHthth → "ghhthth" | G_HHtht →
"ghhtht"
| G_Psi0tt → "gpsi0tt" | G_Psi0bb → "gpsi0bb"
| G_Psi0cc → "gpsi0cc" | G_Psi0tautau → "gpsi0tautau"
| G_Psi1tt → "gpsi1tt" | G_Psi1bb → "gpsi1bb"
| G_Psi1cc → "gpsi1cc" | G_Psi1tautau → "gpsi1tautau"
| G_Psipq3 → "gpsipq3" | G_Psipq2 → "gpsipq2" | G_Psipl3 →
"gpsil3"
| G_Psi0th → "gpsi0th" | G_Psi1th → "gpsi1th"
| G_Psipbth → "gpsipbth"
| G_Ethth → "gethth" | G_Etht → "getht"
| G_Ett → "gett" | G_Ebb → "gebb"
| G_HGaGa → "ghgaga" | G_HGaZ → "ghgaz"
| G_EGaGa → "geaa" | G_EGaZ → "geaz" | G_EGIGI → "gegg"
| G_H3 → "gh3" | G_H4 → "gh4"
| G_PsiWW → "gpsiw" | G_PsiWHW → "gpsiwhw"
| G_PsiZZ → "gpsizz" | G_PsiZHZH → "gpsizhzh"
| G_PsiZHZ → "gpsizhz" | G_PsiZAH → "gpsizah"
| G_PsiZHAH → "gpsizhah" | G_PsiAHAAH → "gpsiahah"
| G_PsiZW → "gpsizw" | G_PsiZWH → "gpsizwh" | G_PsiAHW →
"gpsiahw"
| G_PsiAHWH → "gpsiahwh" | G_PsiZHW → "gpsizhw"
| G_PsiZHWH → "gpsizhwh"
| G_PsippWW → "gpsippww" | G_PsippWHW → "gpsippwhw"

```



```

| G_PsippWHWH → "gpsippwhwh"
| G_PsiHW → "gpsihw" | G_PsiHWH → "gpsihwh"
| G_Psi0W → "gpsi0w" | G_Psi0WH → "gpsi0wh"
| G_Psi1W → "gpsi1w" | G_Psi1WH → "gpsi1wh"
| G_PsiPPW → "gpsippw" | G_PsiPPWH → "gpsippwh"
| G_Psi1HAH → "gpsihah" | G_Psi01AH → "gpsi0ah"
| G_AHPsip → "gahpsip" | G_Psi1HZ → "gpsi1hz"
| G_Psi1HZH → "gpsi1hzh" | G_Psi01Z → "gpsi01z"
| G_Psi01ZH → "gpsi01zh" | G_ZPsip → "gzpsip"
| G_ZPsipp → "gzpsipp" | G_ZHPsipp → "gzhpsipp"
| G_HHAA → "ghhaa" | G_HHWHW → "ghhwhw" | G_HHZHZ →
"ghhzhz"
| G_HHAHZ → "ghhahz" | G_HHZHAH → "ghhzhah"
| G_HPsi0WW → "ghpsi0ww" | G_HPsi0WHW → "ghpsi0whw"
| G_HPsi0ZZ → "ghpsi0zz" | G_HPsi0ZHZH → "ghpsi0zhzh"
| G_HPsi0ZHZ → "ghpsi0zhz" | G_HPsi0AAH → "ghpsi0ahah"
| G_HPsi0ZAH → "ghpsi0zah" | G_HPsi0ZHAH → "ghpsi0zhah"
| G_HPsipWA → "ghpsipwa" | G_HPsipWHA → "ghpsipwha"
| G_HPsipWZ → "ghpsipwz" | G_HPsipWHZ → "ghpsiwzh"
| G_HPsipWAH → "ghpsipwah" | G_HPsipWHAH → "ghpsipwhah"
| G_HPsipWZH → "ghpsipwzh" | G_HPsipWHZH → "ghpsipwhzh"
| G_HPsippWW → "ghpsippww" | G_HPsippWHWH → "ghpsippwhwh"
| G_HPsippWHW → "ghpsippwhw" | G_Psi00ZH → "gpsi00zh"
| G_Psi00AH → "gpsi00ah" | G_Psi00ZHAH → "gpsi00zhah"
| G_Psi0pWA → "gpsi0pwa" | G_Psi0pWHA → "gpsi0pwha"
| G_Psi0pWZ → "gpsi0pwz" | G_Psi0pWHZ → "gpsi0pwhz"
| G_Psi0pWAH → "gpsi0pwah" | G_Psi0pWHAH → "gpsi0pwhah"
| G_Psi0pWZH → "gpsi0pwzh" | G_Psi0pWHZH → "gpsi0pwhzh"
| G_Psi0ppWW → "gpsi0ppww" | G_Psi0ppWHWH → "gpsi0ppwhwh"
| G_Psi0ppWHW → "gpsi0ppwhw"
| I_G_Psi0pWA → "i_gpsi0pwa" | I_G_Psi0pWHA → "i_gpsi0pwha"
| I_G_Psi0pWZ → "i_gpsi0pwz" | I_G_Psi0pWHZ → "i_gpsi0pwhz"
| I_G_Psi0pWAH → "i_gpsi0pwah" | I_G_Psi0pWHAH → "i_gpsi0pwhah"
| I_G_Psi0pWZH → "i_gpsi0pwzh" | I_G_Psi0pWHZH → "i_gpsi0pwhzh"
| I_G_Psi0ppWW → "i_gpsi0ppww" | I_G_Psi0ppWHWH →
|i_gpsi0ppwhwh"
| I_G_Psi0ppWHW → "i_gpsi0ppwhw"
| G_PsippZZ → "gpsippzz" | G_PsippZHZH → "gpsippzhzh"
| G_PsippAZ → "gpsippaz" | G_PsippAAH → "gpsippaah"
| G_PsippZAH → "gpsippzah"
| G_PsippWA → "gpsippwa" | G_PsippWHA → "gpsippwha"
| G_PsippWZ → "gpsippwz" | G_PsippWHZ → "gpsippwhz"
| G_PsippWAH → "gpsippwah" | G_PsippWHAH → "gpsippwhah"
| G_PsippWZH → "gpsippwzh" | G_PsippWHZH → "gpsippwhzh"
| G_PsiccZZ → "gpsiccz" | G_PsiccAZ → "gpsiccaz"
| G_PsiccAAH → "gpsiccaah" | G_PsiccZZH → "gpsicczzh"
| G_PsiccAZH → "gpsiccazh" | G_PsiccZAH → "gpsicczah"
| Mass f → "mass" ^ flavor_symbol f
| Width f → "width" ^ flavor_symbol f
end

```

```

module Simplest (Flags : BSM_flags) =
  struct
    let rcs = rcs_file

    open Coupling

    let default_width = ref Timelike
    let use_fudged_width = ref false

    let options = Options.create
    [ "constant_width", Arg.Unit (fun () → default_width := Constant),
      "use_constant_width_also_in_t-channel";
      "fudged_width", Arg.Set use_fudged_width,
      "use_fudge_factor_for_charge_particle_width";
      "custom_width", Arg.String (fun f → default_width := Custom f),
      "use_custom_width";
      "cancel_widths", Arg.Unit (fun () → default_width := Vanishing),
      "use_vanishing_width" ]
  
```

We do not introduce the Goldstones for the heavy vectors here. The heavy quarks are simply numerated by their generation, the assignments whether they are up- or down-type will be defined by the model.

```

type flavor = L of int | N of int | U of int | D of int | QH of int
            | NH of int | Wp | Wm | Ga | Z | Xp | Xm | X0 | Y0 | ZH
            | Phip | Phim | Phi0 | H | Eta | Gl

type gauge = unit

let gauge_symbol () =
  failwith "Modellib_BSM.Simplest.gauge_symbol: internal error"

let family n = [ L n; N n; U n; D n; QH n; NH n ]
  
```

Note that we add all heavy quarks,  $U$ ,  $D$ ,  $C$ ,  $S$ , in order to have both embeddings included.

```

let external_flavors () =
  [ "1st_Generation_(incl._heavy)", ThoList.flatmap family [1; -1];
    "2nd_Generation_(incl._heavy)", ThoList.flatmap family [2; -2];
    "3rd_Generation_(incl._heavy)", ThoList.flatmap family [3; -3];
    "Gauge_Bosons", [Ga; Z; Wp; Wm; Gl; Xp; Xm; X0; Y0; ZH];
    "Higgs", [H; Eta];
    "Goldstone_Bosons", [Phip; Phim; Phi0] ]

let flavors () = ThoList.flatmap snd (external_flavors ())

let spinor n =
  if n ≥ 0 then
    Spinor
  else
    ConjSpinor

let lorentz = function
  | L n → spinor n | N n → spinor n
  | U n → spinor n | D n → spinor n
  | QH n → spinor n | NH n → spinor n
  
```

```

| Ga | Gl → Vector
| Wp | Wm | Z | Xp | Xm | X0 | Y0 | ZH → Massive_Vector
| _ → Scalar

let color = function
| U n → Color.SUN (if n > 0 then 3 else -3)
| D n → Color.SUN (if n > 0 then 3 else -3)
| QH n → Color.SUN (if n > 0 then 3 else -3)
| Gl → Color.AdjSUN 3
| _ → Color.Singlet

let prop_spinor n =
if n ≥ 0 then
  Prop_Spinor
else
  Prop_ConjSpinor

let propagator = function
| L n → prop_spinor n | N n → prop_spinor n
| U n → prop_spinor n | D n → prop_spinor n
| QH n → prop_spinor n | NH n → prop_spinor n
| Ga | Gl → Prop_Feynman
| Wp | Wm | Z | Xp | Xm | X0 | Y0 | ZH → Prop_Unitarity
| Phip | Phim | Phi0 → Only_Insertion
| H | Eta → Prop_Scalar

```

Optionally, ask for the fudge factor treatment for the widths of charged particles. Currently, this only applies to  $W^\pm$  and top.

```

let width f =
if !use_fudged_width then
  match f with
  | Wp | Wm | U 3 | U (-3) | QH _ | NH _ → Fudged
  | _ → !default_width
else
  !default_width

let goldstone = function
| Wp → Some (Phip, Coupling.Const 1)
| Wm → Some (Phim, Coupling.Const 1)
| Z → Some (Phi0, Coupling.Const 1)
| _ → None

let conjugate = function
| L n → L (-n) | N n → N (-n)
| U n → U (-n) | D n → D (-n)
| QH n → QH (-n) | NH n → NH (-n)
| Ga → Ga | Gl → Gl | Z → Z
| Wp → Wm | Wm → Wp
| Xp → Xm | Xm → Xp | X0 → X0 | Y0 → Y0 | ZH → ZH
| Phip → Phim | Phim → Phip | Phi0 → Phi0
| H → H | Eta → Eta

let fermion = function

```

```

|  $L\ n \rightarrow \text{if } n > 0 \text{ then } 1 \text{ else } -1$ 
|  $N\ n \rightarrow \text{if } n > 0 \text{ then } 1 \text{ else } -1$ 
|  $U\ n \rightarrow \text{if } n > 0 \text{ then } 1 \text{ else } -1$ 
|  $D\ n \rightarrow \text{if } n > 0 \text{ then } 1 \text{ else } -1$ 
|  $QH\ n \rightarrow \text{if } n > 0 \text{ then } 1 \text{ else } -1$ 
|  $NH\ n \rightarrow \text{if } n > 0 \text{ then } 1 \text{ else } -1$ 
|  $Ga\ |\ Gl\ |\ Z\ |\ Wp\ |\ Wm\ |\ Xp\ |\ Xm\ |\ X0\ |\ Y0\ |\ ZH \rightarrow 0$ 
|  $- \rightarrow 0$ 

module Ch = Charges.QQ
let ( // ) = Algebra.Small_Rational.make

let charge = function
|  $L\ n \rightarrow \text{if } n > 0 \text{ then } -1//1 \text{ else } 1//1$ 
|  $N\ n\ |\ NH\ n \rightarrow 0//1$ 
|  $U\ n \rightarrow \text{if } n > 0 \text{ then } 2//3 \text{ else } -2//3$ 
|  $QH\ 3 \rightarrow 2//3\ |\ QH\ (-3) \rightarrow -2//3$ 
|  $QH\ (1\ |\ 2) \rightarrow$ 
|   if Flags.anom_ferm_ass then
|     2//3
|   else
|     -1//3
|  $QH\ ((-1)\ |\ (-2)) \rightarrow$ 
|   if Flags.anom_ferm_ass then
|     -2//3
|   else
|     1//3
|  $QH\ n \rightarrow \text{invalid\_arg } ("Simplest.charge:\_\square\_\square" ^ \text{string\_of\_int } n)$ 
|  $D\ n \rightarrow \text{if } n > 0 \text{ then } -1//3 \text{ else } 1//3$ 
|  $Gl\ |\ Ga\ |\ Z\ |\ ZH\ |\ X0\ |\ Y0 \rightarrow 0//1$ 
|  $Wp\ |\ Xp \rightarrow 1//1$ 
|  $Wm\ |\ Xm \rightarrow -1//1$ 
|  $H\ |\ Phi0\ |\ Eta \rightarrow 0//1$ 
|  $Phip \rightarrow 1//1$ 
|  $Phim \rightarrow -1//1$ 

let lepton = function
|  $L\ n\ |\ N\ n\ |\ NH\ n$ 
|    $\rightarrow \text{if } n > 0 \text{ then } 1//1 \text{ else } -1//1$ 
|  $U\ -\ |\ D\ -\ |\ - \rightarrow 0//1$ 

let baryon = function
|  $L\ -\ |\ N\ - \rightarrow 0//1$ 
|  $U\ n\ |\ D\ n\ |\ QH\ n$ 
|    $\rightarrow \text{if } n > 0 \text{ then } 1//1 \text{ else } -1//1$ 
|  $- \rightarrow 0//1$ 

let charges f =
[ charge f; lepton f; baryon f ]

type constant =
| Unit | Pi | Alpha_QED | Sin2thw
| Sinhw | Costhw | E | G_weak | Vev | VHeavy

```

```

| Supp | Supp2
| Sinpsi | Cospsi | Atpsi | Sccs (* Mixing angles of SU(2) *)
| Q_lepton | Q_up | Q_down | Q_Z_up | G_CC | I_G_CC
| G_NC_neutrino | G_NC_lepton | G_NC_up | G_NC_down
| G_NC_X | G_NC_X_t | G_NC_Y | G_NC_Y_t | G_NC_H
| G_NC_h_neutrino | G_NC_h_lepton | G_NC_h_up | G_NC_h_down
| G_NC_h_top | G_NC_h_bot | G_NCH_N | G_NCH_U |
G_NCH_D | G_NCHt
| G_zhthth
| I_Q_W | I_G_ZWW | I_G_WWW
| I_G_Z1 | I_G_Z2 | I_G_Z3 | I_G_Z4 | I_G_Z5 | I_G_Z6
| I_Q_H | G_s | I_G_s | G2
| G_WWW | G_ZZWW | G_AZWW | G_AAWW
| I_Q_ZH
| G_HWW | G_HHWW | G_HZZ | G_HHZZ | G_HHZZH
| G_heavy_HVV | G_heavy_HWW | G_heavy_HZZ | G_HHthth
| G_Htt | G_Hbb | G_Hcc | G_Htautau | G_H3 | G_H4
| G_Hthth | G_Htht | G_Ethth | G_Etht | G_Ett | G_Hqhq
| G_Ebb | G_ZEH | G_ZHEH | G_Hgg
| G_HGaGa | G_HGaZ | G_EGaGa | G_EGaZ | G_EGIGl
| Mass of flavor | Width of flavor

```

Two integer counters for the QCD and EW order of the couplings.

```

type orders = int × int
let orders = function
| _ → (0,0)

```



The current abstract syntax for parameter dependencies is admittedly tedious. Later, there will be a parser for a convenient concrete syntax as a part of a concrete syntax for models. But as these examples show, it should include simple functions.

```

let input_parameters =
[]
let derived_parameters =
[]
let g_over_2_costh =
Quot (Neg (Atom G_weak), Prod [Const 2; Atom Costhw])
let nc_coupling c t3 q =
(Real_Array c,
[Prod [g_over_2_costh; Diff (t3, Prod [Const 2; q; Atom Sin2thw]);
Prod [g_over_2_costh; t3]])
let half = Quot (Const 1, Const 2)
let derived_parameter_arrays =
[ nc_coupling G_NC_neutrino half (Const 0);
  nc_coupling G_NC_lepton (Neg half) (Const (-1));
  nc_coupling G_NC_up half (Quot (Const 2, Const 3));

```

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nc_coupling G_NC_down (Neg half) (Quot (Const (-1), Const 3));
nc_coupling G_NC_h_neutrino half (Const 0);
nc_coupling G_NC_h_lepton (Neg half) (Const (-1));
nc_coupling G_NC_h_up half (Quot (Const 2, Const 3));
nc_coupling G_NC_h_down (Neg half) (Quot (Const (-1), Const 3)) ]

let parameters () =
{ input = input_parameters;
  derived = derived_parameters;
  derived_arrays = derived_parameter_arrays }

module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)

let electromagnetic_currents n =
[ ((L (-n), Ga, L n), FBF (1, Psibar, V, Psi), Q_lepton);
  ((U (-n), Ga, U n), FBF (1, Psibar, V, Psi), Q_up);
  ((D (-n), Ga, D n), FBF (1, Psibar, V, Psi), Q_down) ]

let color_currents n =
[ ((D (-n), Gl, D n), FBF ((-1), Psibar, V, Psi), Gs);
  ((U (-n), Gl, U n), FBF ((-1), Psibar, V, Psi), Gs);
  ((QH (-n), Gl, QH n), FBF ((-1), Psibar, V, Psi), Gs)]

let neutral_currents n =
[ ((L (-n), Z, L n), FBF (1, Psibar, VA, Psi), G_NC_lepton);
  ((N (-n), Z, N n), FBF (1, Psibar, VA, Psi), G_NC_neutrino);
  ((U (-n), Z, U n), FBF (1, Psibar, VA, Psi), G_NC_up);
  ((D (-n), Z, D n), FBF (1, Psibar, VA, Psi), G_NC_down) ]

let xy_currents =
  ThoList.flatmap
    (fun n → [ ((N (-n), X0, N n), FBF ((-1), Psibar, VL, Psi), G_NC_X);
                ((L (-n), Xm, N n), FBF ((-1), Psibar, VL, Psi), G_NC_X);
                ((N (-n), Xp, L n), FBF ((-1), Psibar, VL, Psi), G_NC_X);
                ((N (-n), Y0, N n), FBF ((-1), Psibar, VL, Psi), G_NC_Y);
                ((NH (-n), X0, N n), FBF ((-1), Psibar, VL, Psi), G_CC);
                ((N (-n), X0, NH n), FBF ((-1), Psibar, VL, Psi), G_CC);
                ((NH (-n), Y0, N n), FBF ((-1), Psibar, VL, Psi), I_G_CC);
                ((N (-n), Y0, NH n), FBF ((-1), Psibar, VL, Psi), I_G_CC);
                ((L (-n), Xm, NH n), FBF ((-1), Psibar, VL, Psi), G_CC);
                ((NH (-n), Xp, L n), FBF ((-1), Psibar, VL, Psi), G_CC))]
    [1; 2; 3]
  @
  [ ((U (-3), X0, U 3), FBF (1, Psibar, VL, Psi), G_NC_X_t);
    ((U (-3), Y0, U 3), FBF (1, Psibar, VL, Psi), G_NC_Y_t);
    ((U (-3), X0, QH 3), FBF (1, Psibar, VL, Psi), G_CC);
    ((QH (-3), X0, U 3), FBF (1, Psibar, VL, Psi), G_CC);
    ((U (-3), Y0, QH 3), FBF (1, Psibar, VL, Psi), I_G_CC);

```

```

((QH (-3), Y0, U 3), FBF (1, Psibar, VL, Psi), I_G_CC);
((D (-3), Xm, U 3), FBF (1, Psibar, VL, Psi), G_NC_X_t);
((U (-3), Xp, D 3), FBF (1, Psibar, VL, Psi), G_NC_X_t);
((D (-3), Xm, QH 3), FBF (1, Psibar, VL, Psi), G_CC);
((QH (-3), Xp, D 3), FBF (1, Psibar, VL, Psi), G_CC);
((QH (-3), Wp, D 3), FBF (1, Psibar, VL, Psi), G_NC_X_t);
((D (-3), Wm, QH 3), FBF (1, Psibar, VL, Psi), G_NC_X_t);
((QH (-3), Z, U 3), FBF (1, Psibar, VL, Psi), G_NCHt);
((U (-3), Z, QH 3), FBF (1, Psibar, VL, Psi), G_NCHt)]
@
ThoList.flatmap
(fun n →
  if Flags.anom_ferm_ass then
    [((U (-n), X0, U n), FBF ((-1), Psibar, VL, Psi), G_NC_X);
      ((U (-n), Y0, U n), FBF ((-1), Psibar, VL, Psi), G_NC_Y);
      ((D (-n), Xm, U n), FBF ((-1), Psibar, VL, Psi), G_NC_X);
      ((U (-n), Xp, D n), FBF ((-1), Psibar, VL, Psi), G_NC_X);
      ((QH (-n), X0, U n), FBF ((-1), Psibar, VL, Psi), G_CC);
      ((U (-n), X0, QH n), FBF ((-1), Psibar, VL, Psi), G_CC);
      ((QH (-n), Y0, U n), FBF ((-1), Psibar, VL, Psi), I_G_CC);
      ((U (-n), Y0, QH n), FBF ((-1), Psibar, VL, Psi), I_G_CC);
      ((D (-n), Xm, QH n), FBF ((-1), Psibar, VL, Psi), G_CC);
      ((QH (-n), Xp, D n), FBF ((-1), Psibar, VL, Psi), G_CC);
      ((QH (-n), Wp, D n), FBF ((-1), Psibar, VL, Psi), G_NC_X);
      ((D (-n), Wm, QH n), FBF ((-1), Psibar, VL, Psi), G_NC_X);
      ((QH (-n), Z, U n), FBF (1, Psibar, VL, Psi), G_NC_H);
      ((U (-n), Z, QH n), FBF (1, Psibar, VL, Psi), G_NC_H)]
  else
    [((D (-n), X0, D n), FBF (1, Psibar, VL, Psi), G_NC_X);
      ((D (-n), Y0, D n), FBF (1, Psibar, VL, Psi), G_NC_Y);
      ((D (-n), Xm, U n), FBF (1, Psibar, VL, Psi), G_NC_X);
      ((U (-n), Xp, D n), FBF (1, Psibar, VL, Psi), G_NC_X);
      ((QH (-n), X0, D n), FBF ((-1), Psibar, VL, Psi), G_CC);
      ((D (-n), X0, QH n), FBF ((-1), Psibar, VL, Psi), G_CC);
      ((QH (-n), Y0, D n), FBF ((-1), Psibar, VL, Psi), I_G_CC);
      ((D (-n), Y0, QH n), FBF ((-1), Psibar, VL, Psi), I_G_CC);
      ((QH (-n), Xm, U n), FBF (1, Psibar, VL, Psi), G_CC);
      ((U (-n), Xp, QH n), FBF (1, Psibar, VL, Psi), G_CC);
      ((QH (-n), Wm, U n), FBF (1, Psibar, VL, Psi), G_NC_X);
      ((U (-n), Wp, QH n), FBF (1, Psibar, VL, Psi), G_NC_X);
      ((QH (-n), Z, D n), FBF (1, Psibar, VL, Psi), G_NC_H);
      ((D (-n), Z, QH n), FBF (1, Psibar, VL, Psi), G_NC_H))]
[1; 2]

```

The sign of this coupling is just the one of the T3, being  $-(1/2)$  for leptons and down quarks, and  $+(1/2)$  for neutrinos and up quarks.

```

let neutral_heavy_currents n =
  [((L (-n), ZH, L n), FBF (1, Psibar, VLR, Psi), G_NC_h_lepton);
    ((N (-n), ZH, N n), FBF ((-1), Psibar, VLR, Psi), G_NC_h_neutrino);
    ((U (-n), ZH, U n), FBF ((-1), Psibar, VLR, Psi), (if n = 3 then

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      G_NC_h_top else G_NC_h_up));
    ((D (-n), ZH, D n), FBF (1, Psibar, VLR, Psi), (if n = 3 then
      G_NC_h_bot else G_NC_h_down));
    ((NH (-n), ZH, NH n), FBF (1, Psibar, VLR, Psi), G_NCH_N);
    ((QH (-n), ZH, QH n), FBF (1, Psibar, VLR, Psi), (if n = 3 then
      G_NCH_U else if Flags.anom_ferm_ass then G_NCH_U else G_NCH_D)))
let heavy_currents n =
  [ ((QH (-n), Ga, QH n), FBF (1, Psibar, V, Psi), (if n = 3 then Q_up else
    if Flags.anom_ferm_ass then Q_up else Q_down))]
let charged_currents n =
  [ ((L (-n), Wm, N n), FBF (1, Psibar, VL, Psi), G_CC);
    ((N (-n), Wp, L n), FBF (1, Psibar, VL, Psi), G_CC);
    ((D (-n), Wm, U n), FBF (1, Psibar, VL, Psi), G_CC);
    ((U (-n), Wp, D n), FBF (1, Psibar, VL, Psi), G_CC) ]
let yukawa =
  [ ((U (-3), H, U 3), FBF (1, Psibar, S, Psi), G_Htt);
    ((D (-3), H, D 3), FBF (1, Psibar, S, Psi), G_Hbb);
    ((U (-2), H, U 2), FBF (1, Psibar, S, Psi), G_Hcc);
    ((L (-3), H, L 3), FBF (1, Psibar, S, Psi), G_Htautau) ]
let yukawa_add =
  [ ((QH (-3), H, U 3), FBF (1, Psibar, SL, Psi), G_Htht);
    ((U (-3), H, QH 3), FBF (1, Psibar, SR, Psi), G_Htht);
    ((QH (-3), Eta, U 3), FBF (1, Psibar, SR, Psi), G_Etht);
    ((U (-3), Eta, QH 3), FBF (1, Psibar, SL, Psi), G_Etht);
    ((D (-3), Eta, D 3), FBF (1, Psibar, P, Psi), G_Ebb);
    ((U (-3), Eta, U 3), FBF (1, Psibar, P, Psi), G_Ett)]
  @
  ThoList.flatmap
    (fun n →
      if Flags.anom_ferm_ass then
        [ ((QH (-n), H, U n), FBF (1, Psibar, SL, Psi), G_Hqhq);
          ((U (-n), H, QH n), FBF (1, Psibar, SR, Psi), G_Hqhq)]
        else
        [ ((QH (-n), H, D n), FBF (1, Psibar, SL, Psi), G_Hqhq);
          ((D (-n), H, QH n), FBF (1, Psibar, SR, Psi), G_Hqhq)]
        [1; 2]
    )
let standard_triple_gauge =
  [ ((Ga, Wm, Wp), Gauge_Gauge_Gauge 1, I_Q_W);
    ((Z, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_ZWW);
    ((Gl, Gl, Gl), Gauge_Gauge_Gauge 1, I_Gs)]
let heavy_triple_gauge =
  [ ((Ga, Xm, Xp), Gauge_Gauge_Gauge 1, I_Q_W);
    ((Z, Xm, Xp), Gauge_Gauge_Gauge 1, I_Q_ZH);
    ((Z, X0, Y0), Gauge_Gauge_Gauge 1, I_G_Z1);
    ((ZH, X0, Y0), Gauge_Gauge_Gauge 1, I_G_Z2);
    ((Y0, Wm, Xp), Gauge_Gauge_Gauge 1, I_G_Z3);
    ((Y0, Wp, Xm), Gauge_Gauge_Gauge (-1), I_G_Z3);

```



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      ((X0, Wm, Xp), Gauge_Gauge_Gauge 1, I_G_Z4);
      ((X0, Wp, Xm), Gauge_Gauge_Gauge 1, I_G_Z4);
      ((ZH, Xm, Xp), Gauge_Gauge_Gauge 1, I_G_Z5);
      ((ZH, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_Z6)]

let triple_gauge =
  standard_triple_gauge @ heavy_triple_gauge

let gauge4 = Vector4 [(2, C_13_42); (-1, C_12_34); (-1, C_14_23)]
let minus_gauge4 = Vector4 [(-2, C_13_42); (1, C_12_34); (1, C_14_23)]
let standard_quartic_gauge =
  [ (Wm, Wp, Wm, Wp), gauge4, G_WWWW;
    (Wm, Z, Wp, Z), minus_gauge4, G_ZZWW;
    (Wm, Z, Wp, Ga), minus_gauge4, G_AZWW;
    (Wm, Ga, Wp, Ga), minus_gauge4, G_AAWW;
    (Gl, Gl, Gl, Gl), gauge4, G2]

let heavy_quartic_gauge =
  []

let quartic_gauge =
  standard_quartic_gauge @ heavy_quartic_gauge

let standard_gauge_higgs' =
  [ ((H, Wp, Wm), Scalar_Vector_Vector 1, G_HWW);
    ((H, Z, Z), Scalar_Vector_Vector 1, G_HZZ) ]

let heavy_gauge_higgs =
  [ ((H, Wp, Xm), Scalar_Vector_Vector 1, G_heavy_HWW);
    ((H, Wm, Xp), Scalar_Vector_Vector 1, G_heavy_HWW);
    ((H, Z, X0), Scalar_Vector_Vector 1, G_heavy_HVV);
    ((H, ZH, X0), Scalar_Vector_Vector 1, G_heavy_HVV)]

let standard_gauge_higgs =
  standard_gauge_higgs' @ heavy_gauge_higgs

let standard_gauge_higgs4 =
  [ (H, H, Wp, Wm), Scalar2_Vector2 1, G_HHWW;
    (H, H, Z, Z), Scalar2_Vector2 1, G_HHZZ ]

let heavy_gauge_higgs4 =
  [ (H, H, Z, ZH), Scalar2_Vector2 1, G_HHZZH;
    (H, H, Xp, Xm), Scalar2_Vector2 (-1), G_HHWW;
    (H, H, ZH, ZH), Scalar2_Vector2 (-1), G_HHZZ ]

let standard_higgs =
  [ (H, H, H), Scalar_Scalar_Scalar 1, G_H3 ]

let anomaly_higgs =
  [ (Eta, Gl, Gl), Dim5_Scalar_Gauge2_Skew 1, G_EGIGl;
    (Eta, Ga, Ga), Dim5_Scalar_Gauge2_Skew 1, G_EGaGa;
    (Eta, Ga, Z), Dim5_Scalar_Gauge2_Skew 1, G_EGaZ ]
(* @ (H, Ga, Ga), Dim5_Scalar_Gauge2 1, G_HGaGa; (H, Ga, Z), Dim5_Scalar_Gauge2 1, G_HGaZ
*)

let standard_higgs4 =

```

```

[ (H, H, H, H), Scalar4 1, G-H4 ]

let gauge_higgs =
  standard_gauge_higgs

let gauge_higgs4 =
  standard_gauge_higgs4 @ heavy_gauge_higgs4

let higgs =
  standard_higgs

let eta_higgs_gauge =
  [ (Z, Eta, H), Vector_Scalar_Scalar 1, G-ZEH;
    (ZH, Eta, H), Vector_Scalar_Scalar 1, G-ZHEH;
    (X0, Eta, H), Vector_Scalar_Scalar 1, G-CC ]

let top_quartic =
  [ ((QH (-3), H, H, QH 3), GBBG (1, Psibar, S2, Psi), G-HHthth)]

let higgs4 =
  standard_higgs4

let goldstone_vertices =
  [ ((Phi0, Wm, Wp), Scalar_Vector_Vector 1, I-G-ZWW);
    ((Phip, Ga, Wm), Scalar_Vector_Vector 1, I-Q-W);
    ((Phip, Z, Wm), Scalar_Vector_Vector 1, I-G-ZWW);
    ((Phim, Wp, Ga), Scalar_Vector_Vector 1, I-Q-W);
    ((Phim, Wp, Z), Scalar_Vector_Vector 1, I-G-ZWW) ]

let vertices3 =
  (ThoList.flatmap electromagnetic_currents [1;2;3] @
   ThoList.flatmap color_currents [1;2;3] @
   ThoList.flatmap neutral_currents [1;2;3] @
   ThoList.flatmap neutral_heavy_currents [1;2;3] @
   ThoList.flatmap heavy_currents [1;2;3] @
   ThoList.flatmap charged_currents [1;2;3] @
   xy_currents @ anomaly_higgs @
   eta_higgs_gauge @
   yukawa @ yukawa_add @
   triple_gauge @
   gauge_higgs @ higgs @ goldstone_vertices)

let vertices4 =
  quartic_gauge @ gauge_higgs4 @ higgs4

let vertices () = (vertices3, vertices4, [])

```

For efficiency, make sure that *F.of\_vertices vertices* is evaluated only once.

```

let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 4

let flavor_of_string = function
| "e-" → L 1 | "e+" → L (-1)

```

```

| "mu-" → L 2 | "mu+" → L (-2)
| "tau-" → L 3 | "tau+" → L (-3)
| "nue" → N 1 | "nuebar" → N (-1)
| "numu" → N 2 | "numubar" → N (-2)
| "nutau" → N 3 | "nutaubar" → N (-3)
| "nh1" → NH 1 | "nh1bar" → NH (-1)
| "nh2" → NH 2 | "nh2bar" → NH (-2)
| "nh3" → NH 3 | "nh3bar" → NH (-3)
| "u" → U 1 | "ubar" → U (-1)
| "c" → U 2 | "cbar" → U (-2)
| "t" → U 3 | "tbar" → U (-3)
| "d" → D 1 | "dbar" → D (-1)
| "s" → D 2 | "sbar" → D (-2)
| "b" → D 3 | "bbar" → D (-3)
| "uh" → if Flags.anom_ferm_ass then QH 1 else invalid_arg
| "dh" → if Flags.anom_ferm_ass then invalid_arg
| "uhbar" → if Flags.anom_ferm_ass then QH (-1) else invalid_arg
| "dhbar" → if Flags.anom_ferm_ass then invalid_arg
| "ch" → if Flags.anom_ferm_ass then QH 2 else invalid_arg
| "sh" → if Flags.anom_ferm_ass then invalid_arg
| "chbar" → if Flags.anom_ferm_ass then QH (-2) else invalid_arg
| "shbar" → if Flags.anom_ferm_ass then invalid_arg
| "th" → QH 3 | "thbar" → QH (-3)
| "eta" | "Eta" → Eta
| "A" → Ga | "Z" | "Z0" → Z | "g" | "g1" → Gl
| "ZH" | "ZH0" | "Zh" | "Zh0" → ZH
| "W+" → Wp | "W-" → Wm
| "X+" → Xp | "X-" → Xm
| "X0" → X0 | "Y0" → Y0
| "H" → H
| _ → invalid_arg "Modellib_BSM.Simplest.flavor_of_string"

let flavor_to_string = function
| L 1 → "e-" | L (-1) → "e+"
| L 2 → "mu-" | L (-2) → "mu+"
| L 3 → "tau-" | L (-3) → "tau+"
| L _ → invalid_arg
| N 1 → "nue" | N (-1) → "nuebar"
| N 2 → "numu" | N (-2) → "numubar"
| N 3 → "nutau" | N (-3) → "nutaubar"
| N _ → invalid_arg
| NH 1 → "nh1" | NH (-1) → "nh1bar"
| NH 2 → "nh2" | NH (-2) → "nh2bar"
| NH 3 → "nh3" | NH (-3) → "nh3bar"
| U 1 → "u" | U (-1) → "ubar"
| U 2 → "c" | U (-2) → "cbar"
| U 3 → "t" | U (-3) → "tbar"
| D 1 → "d" | D (-1) → "dbar"
| D 2 → "s" | D (-2) → "sbar"
| D 3 → "b" | D (-3) → "bbar"
| QH 1 → "uh"
| QH 2 → "ch"
| QH 3 → "th"
| QH (-1) → "uhbar"
| QH (-2) → "chbar"
| QH (-3) → "thbar"
| Eta → "eta"
| Ga → "A"
| Z → "Z"
| Z0 → "Z0"
| Gl → "g"
| Wp → "W+"
| Wm → "W-"
| Xm → "X+"
| X0 → "X0"
| Y0 → "Y0"
| H → "H"
| _ → invalid_arg "Modellib_BSM.Simplest.flavor_to_string"

```

```

    "Modellib_BSM.Simplest.flavor_to_string:␣invalid␣neutrino"
| U 1 → "u" | U (-1) → "ubar"
| U 2 → "c" | U (-2) → "cbar"
| U 3 → "t" | U (-3) → "tbar"
| U _ → invalid_arg
    "Modellib_BSM.Simplest.flavor_to_string:␣invalid␣up␣type␣quark"
| D 1 → "d" | D (-1) → "dbar"
| D 2 → "s" | D (-2) → "sbar"
| D 3 → "b" | D (-3) → "bbar"
| D _ → invalid_arg
    "Modellib_BSM.Simplest.flavor_to_string:␣invalid␣down␣type␣quark"
| QH 1 → if Flags.anom_ferm_ass then "uh" else "dh"
| QH 2 → if Flags.anom_ferm_ass then "ch" else "sh"
| QH 3 → "th"
| QH (-1) → if Flags.anom_ferm_ass then "uhbar" else "dhbar"
| QH (-2) → if Flags.anom_ferm_ass then "chbar" else "shbar"
| QH (-3) → "thbar"
| QH _ → invalid_arg
    "Modellib_BSM.Simplest.flavor_to_string:␣invalid␣heavy␣quark"
| NH n when n > 0 → "nh" ^ string_of_int n
| NH n → "nh" ^ string_of_int (abs n) ^ "bar"
| Ga → "A" | Z → "Z" | Gl → "gl"
| Wp → "W+" | Wm → "W-"
| Xp → "X+" | Xm → "X-" | X0 → "X0" | Y0 → "Y0" | ZH →
"ZH"
| Phip → "phi+" | Phim → "phi-" | Phi0 → "phi0"
| H → "H" | Eta → "Eta"

let flavor_to_TeX = function
| L 1 → "e~-" | L (-1) → "\\e~+"
| L 2 → "\\mu~-" | L (-2) → "\\mu~+"
| L 3 → "\\tau~-" | L (-3) → "\\tau~+"
| L _ → invalid_arg
    "Modellib_BSM.Simplest.flavor_to_TeX:␣invalid␣lepton"
| N 1 → "\\nu_e" | N (-1) → "\\bar{\\nu}_e"
| N 2 → "\\nu_\\mu" | N (-2) → "\\bar{\\nu}_\\mu"
| N 3 → "\\nu_\\tau" | N (-3) → "\\bar{\\nu}_\\tau"
| N _ → invalid_arg
    "Modellib_BSM.Simplest.flavor_to_TeX:␣invalid␣neutrino"
| U 1 → "u" | U (-1) → "\\bar{u}"
| U 2 → "c" | U (-2) → "\\bar{c}"
| U 3 → "t" | U (-3) → "\\bar{t}"
| U _ → invalid_arg
    "Modellib_BSM.Simplest.flavor_to_TeX:␣invalid␣up␣type␣quark"
| D 1 → "d" | D (-1) → "\\bar{d}"
| D 2 → "s" | D (-2) → "\\bar{s}"
| D 3 → "b" | D (-3) → "\\bar{b}"
| D _ → invalid_arg
    "Modellib_BSM.Simplest.flavor_to_TeX:␣invalid␣down␣type␣quark"
| QH 1 → if Flags.anom_ferm_ass then "U" else "D"

```

```

| QH 2 → if Flags.anom_ferm_ass then "C" else "S"
| QH 3 → "T"
| QH (-1) → if Flags.anom_ferm_ass then "\\bar{U}" else "\\bar{D}"
| QH (-2) → if Flags.anom_ferm_ass then "\\bar{C}" else "\\bar{S}"
| QH (-3) → "thbar"
| QH _ → invalid_arg
| "Modellib_BSM.Simplest.flavor_to_TeX:␣invalid␣heavy␣quark"
| NH n when n > 0 → "N_" ^ string_of_int n
| NH n → "\\bar{N}" ^ string_of_int (abs n)
| Ga → "\\gamma" | Z → "Z" | Gl → "g"
| Wp → "W^+" | Wm → "W^- "
| Xp → "X^+" | Xm → "X^- " | X0 → "X^0" | Y0 → "Y^0" |
ZH → "Z_H"
| Phip → "\\phi^+" | Phim → "\\phi^- " | Phi0 → "\\phi^0"
| H → "H" | Eta → "\\eta"
let flavor_symbol = function
| L n when n > 0 → "l" ^ string_of_int n
| L n → "l" ^ string_of_int (abs n) ^ "b"
| N n when n > 0 → "n" ^ string_of_int n
| N n → "n" ^ string_of_int (abs n) ^ "b"
| U n when n > 0 → "u" ^ string_of_int n
| U n → "u" ^ string_of_int (abs n) ^ "b"
| D n when n > 0 → "d" ^ string_of_int n
| D n → "d" ^ string_of_int (abs n) ^ "b"
| NH n when n > 0 → "nh" ^ string_of_int n
| NH n → "nh" ^ string_of_int (abs n) ^ "b"
| QH n when n > 0 → "qh" ^ string_of_int n
| QH n → "qh" ^ string_of_int (abs n) ^ "b"
| Ga → "a" | Z → "z" | Gl → "gl"
| Wp → "wp" | Wm → "wm"
| Xp → "xp" | Xm → "xm" | X0 → "x0" | Y0 → "y0" | ZH →
"zh"
| Phip → "pp" | Phim → "pm" | Phi0 → "p0"
| H → "h" | Eta → "eta"

```

There are PDG numbers for  $Z'$ ,  $Z$ ,  $W$ , 32-34, respectively. We just introduce a number 38 for  $Y0$  as a  $Z''$ . As well, there is the number 8 for a  $t'$ . But we cheat a little bit and take the number 35 which is reserved for a heavy scalar Higgs for the Eta scalar.

We abuse notation for the heavy quarks and take the PDG code for their SUSY partners!!! (What about an update of the PDG numbering scheme?) Thereby we take only those for up-type (s)quarks. The heavy neutrinos get the numbers of the sneutrinos.

```

let pdg = function
| L n when n > 0 → 9 + 2 × n
| L n → - 9 + 2 × n
| N n when n > 0 → 10 + 2 × n
| N n → - 10 + 2 × n
| U n when n > 0 → 2 × n
| U n → 2 × n

```

```

|  $D\ n\ \text{when } n > 0 \rightarrow -1 + 2 \times n$ 
|  $D\ n \rightarrow 1 + 2 \times n$ 
|  $NH\ n\ \text{when } n > 0 \rightarrow 1000010 + 2 \times n$ 
|  $NH\ n \rightarrow -1000010 + 2 \times n$ 
|  $QH\ 3 \rightarrow 1000006$ 
|  $QH\ (-3) \rightarrow -1000006$ 
|  $QH\ n\ \text{when } n > 0 \rightarrow \text{if } Flags.anom\_ferm\_ass \text{ then}$ 
|    $1000000 + 2 \times n \text{ else } 999999 + 2 \times n$ 
|  $QH\ n \rightarrow \text{if } Flags.anom\_ferm\_ass \text{ then}$ 
|    $-1000000 + 2 \times n \text{ else } -999999 + 2 \times n$ 
|  $Gl \rightarrow 21$ 
|  $Ga \rightarrow 22 \mid Z \rightarrow 23$ 
|  $Wp \rightarrow 24 \mid Wm \rightarrow (-24)$ 
|  $Xp \rightarrow 34 \mid Xm \rightarrow (-34) \mid ZH \rightarrow 32 \mid X0 \rightarrow 33 \mid Y0 \rightarrow 38$ 
|  $Phip \mid Phim \rightarrow 27 \mid Phi0 \rightarrow 26$ 
|  $H \rightarrow 25 \mid Eta \rightarrow 36$ 

```

As in the case of SUSY we introduce an internal dummy pdf code in order to have manageable arrays. Heavy neutrinos get numbers 41,43,45, while the heavy quarks have the numbers 40,42,44. I take them all as up type here.

```

let pdg_mw = function
|  $L\ n\ \text{when } n > 0 \rightarrow 9 + 2 \times n$ 
|  $L\ n \rightarrow -9 + 2 \times n$ 
|  $N\ n\ \text{when } n > 0 \rightarrow 10 + 2 \times n$ 
|  $N\ n \rightarrow -10 + 2 \times n$ 
|  $U\ n\ \text{when } n > 0 \rightarrow 2 \times n$ 
|  $U\ n \rightarrow 2 \times n$ 
|  $D\ n\ \text{when } n > 0 \rightarrow -1 + 2 \times n$ 
|  $D\ n \rightarrow 1 + 2 \times n$ 
|  $NH\ n\ \text{when } n > 0 \rightarrow 39 + 2 \times n$ 
|  $NH\ n \rightarrow -39 + 2 \times n$ 
|  $QH\ n\ \text{when } n > 0 \rightarrow 38 + 2 \times n$ 
|  $QH\ n \rightarrow -38 + 2 \times n$ 
|  $Gl \rightarrow 21$ 
|  $Ga \rightarrow 22 \mid Z \rightarrow 23$ 
|  $Wp \rightarrow 24 \mid Wm \rightarrow (-24)$ 
|  $Xp \rightarrow 34 \mid Xm \rightarrow (-34) \mid ZH \rightarrow 32 \mid X0 \rightarrow 33 \mid Y0 \rightarrow 38$ 
|  $Phip \mid Phim \rightarrow 27 \mid Phi0 \rightarrow 26$ 
|  $H \rightarrow 25 \mid Eta \rightarrow 36$ 

let mass_symbol f =
  "mass(" ^ string_of_int (abs (pdg_mw f)) ^ ")"

let width_symbol f =
  "width(" ^ string_of_int (abs (pdg_mw f)) ^ ")"

let constant_symbol = function
| Unit → "unit" | Pi → "PI" | VHeavy → "vheavy"
| Alpha_QED → "alpha" | E → "e" | G_weak → "g" | Vev →
"vev"
| Sin2thw → "sin2thw" | Sinthw → "sinthw" | Costhw →
"costhw"

```

```

| Sinpsi → "sinpsi" | Cospsi → "cospsi"
| Atpsi → "atpsi" | Scs → "scs"
| Supp → "vF" | Supp2 → "v2F2"
| Q_lepton → "qlep" | Q_up → "qup" | Q_down → "qdown"
| Q_Z_up → "qzup"
| G_zhthth → "gzhthth"
| G_NC_lepton → "gnclep" | G_NC_neutrino → "gncneu"
| G_NC_up → "gncup" | G_NC_down → "gncdown"
| G_NC_X → "gncx" | G_NC_X_t → "gncxt"
| G_NC_Y → "gncy" | G_NC_Y_t → "gncyt" | G_NC_H →
"gnch"
| G_CC → "gcc" | I_G_CC → "i_gcc"
| G_NC_h_lepton → "gnchlep" | G_NC_h_neutrino → "gnchneu"
| G_NC_h_up → "gnchup" | G_NC_h_down → "gnchdown"
| G_NC_h_top → "gnchtop" | G_NC_h_bot → "gnchbot"
| G_NCH_N → "gnchn" | G_NCH_U → "gnchu" | G_NCH_D →
"gnchd"
| G_NCHt → "gncht"
| I_Q_W → "iqw" | I_G_ZWW → "igzww" | I_G_WWW →
"igwww"
| I_Q_H → "iqh" | I_Q_ZH → "iqzh"
| I_G_Z1 → "igz1" | I_G_Z2 → "igz2" | I_G_Z3 → "igz3"
| I_G_Z4 → "igz4" | I_G_Z5 → "igz5" | I_G_Z6 → "igz6"
| G_HHthth → "ghhthth"
| G_WWWW → "gw4" | G_ZZWW → "gzzww"
| G_AZWW → "gazww" | G_AAWW → "gaaww"
| G_HWW → "ghww" | G_HZZ → "ghzz"
| G_heavy_HVV → "ghyhvv"
| G_heavy_HWW → "ghyhww"
| G_heavy_HZZ → "ghyhzz"
| G_HHWW → "ghhww" | G_HHZZ → "ghhzz"
| G_HHZZH → "ghhzzh"
| G_Hgg → "ghgg"
| G_Htt → "ghtt" | G_Hbb → "ghbb"
| G_Htautau → "ghtautau" | G_Hcc → "ghcc"
| G_Hthth → "ghthth" | G_Htht → "ghtht"
| G_Hqh → "ghqh"
| G_Ethth → "gethth" | G_Etht → "getht"
| G_Ett → "gett" | G_Ebb → "gebb"
| G_HGaGa → "ghgaga" | G_HGaZ → "ghgaz"
| G_EGaGa → "geaa" | G_EGaZ → "geaz" | G_EGIGl → "gegg"
| G_ZEH → "gzeh" | G_ZHEH → "gzheh"
| G_H3 → "gh3" | G_H4 → "gh4"
| Mass f → "mass" ^ flavor_symbol f
| Width f → "width" ^ flavor_symbol f
| Gs → "gs" | I_Gs → "igs" | G2 → "gs**2"
end

module Xdim (Flags : BSM_flags) =
  struct

```

```

let rcs = RCS.rename rcs_file "Modellib_BSM.Xdim"
  [ "SM_with_extradimensional_resonances" ]

open Coupling

let default_width = ref Timelike
let use_fudged_width = ref false

let options = Options.create
  [ "constant_width", Arg.Unit (fun () → default_width := Constant),
    "use_constant_width(also_in_t-channel)",
    "fudged_width", Arg.Set use_fudged_width,
    "use_fudge_factor_for_charge_particle_width",
    "custom_width", Arg.String (fun f → default_width := Custom f),
    "use_custom_width",
    "cancel_widths", Arg.Unit (fun () → default_width := Vanishing),
    "use_vanishing_width" ]

type matter_field = L of int | N of int | U of int | D of int
type gauge_boson = Ga | Wp | Wm | Z | Gl
type other = Phip | Phim | Phi0 | H | Grav
type flavor = M of matter_field | G of gauge_boson | O of other

let matter_field f = M f
let gauge_boson f = G f
let other f = O f

type field =
  | Matter of matter_field
  | Gauge of gauge_boson
  | Other of other

let field = function
  | M f → Matter f
  | G f → Gauge f
  | O f → Other f

type gauge = unit

let gauge_symbol () =
  failwith "Modellib_BSM.Xdim.gauge_symbol: internal error"

let family n = List.map matter_field [ L n; N n; U n; D n ]

let external_flavors () =
  [ "1st_Generation", ThoList.flatmap family [1; -1];
    "2nd_Generation", ThoList.flatmap family [2; -2];
    "3rd_Generation", ThoList.flatmap family [3; -3];
    "Gauge_Bosons", List.map gauge_boson [Ga; Z; Wp; Wm; Gl];
    "Higgs", List.map other [H];
    "Graviton", List.map other [Grav];
    "Goldstone_Bosons", List.map other [Phip; Phim; Phi0] ]

let flavors () = ThoList.flatmap snd (external_flavors ())

let spinor n =
  if n ≥ 0 then

```



```

    Spinor
  else
    ConjSpinor
let lorentz = function
| M f →
  begin match f with
  | L n → spinor n | N n → spinor n
  | U n → spinor n | D n → spinor n
  end
| G f →
  begin match f with
  | Ga | Gl → Vector
  | Wp | Wm | Z → Massive_Vector
  end
| O f →
  begin match f with
  | Grav → Tensor_2
  | _ → Scalar
  end
end

let color = function
| M (U n) → Color.SUN (if n > 0 then 3 else -3)
| M (D n) → Color.SUN (if n > 0 then 3 else -3)
| G Gl → Color.AdjSUN 3
| _ → Color.Singlet
end

let prop_spinor n =
  if n ≥ 0 then
    Prop_Spinor
  else
    Prop_ConjSpinor
end

let propagator = function
| M f →
  begin match f with
  | L n → prop_spinor n | N n → prop_spinor n
  | U n → prop_spinor n | D n → prop_spinor n
  end
| G f →
  begin match f with
  | Ga | Gl → Prop_Feynman
  | Wp | Wm | Z → Prop_Unitarity
  end
| O f →
  begin match f with
  | Phip | Phim | Phi0 → Only_Insertion
  | H → Prop_Scalar
  | Grav → Prop_Tensor_2
  end
end

```

Optionally, ask for the fudge factor treatment for the widths of charged particles.  
Currently, this only applies to  $W^\pm$  and top.

```

let width f =
  if !use_fudged_width then
    match f with
    | G Wp | G Wm | M (U 3) | M (U (-3)) | O Grav → Fudged
    | _ → !default_width
  else
    !default_width
let goldstone = function
| G f →
  begin match f with
  | Wp → Some (O Phip, Coupling.Const 1)
  | Wm → Some (O Phim, Coupling.Const 1)
  | Z → Some (O Phi0, Coupling.Const 1)
  | _ → None
  end
| _ → None
let conjugate = function
| M f →
  M (begin match f with
  | L n → L (-n) | N n → N (-n)
  | U n → U (-n) | D n → D (-n)
  end)
| G f →
  G (begin match f with
  | Gl → Gl | Ga → Ga | Z → Z
  | Wp → Wm | Wm → Wp
  end)
| O f →
  O (begin match f with
  | Phip → Phim | Phim → Phip | Phi0 → Phi0
  | H → H | Grav → Grav
  end)
let fermion = function
| M f →
  begin match f with
  | L n → if n > 0 then 1 else -1
  | N n → if n > 0 then 1 else -1
  | U n → if n > 0 then 1 else -1
  | D n → if n > 0 then 1 else -1
  end
| G f →
  begin match f with
  | Gl | Ga | Z | Wp | Wm → 0
  end
| O _ → 0
module Ch = Charges.QQ
let ( // ) = Algebra.Small_Rational.make

```

```

let generation' = function
| 1 → [ 1//1; 0//1; 0//1]
| 2 → [ 0//1; 1//1; 0//1]
| 3 → [ 0//1; 0//1; 1//1]
| -1 → [-1//1; 0//1; 0//1]
| -2 → [ 0//1; -1//1; 0//1]
| -3 → [ 0//1; 0//1; -1//1]
| n → invalid_arg ("Xdim.generation':␣" ^ string_of_int n)

let generation f =
  match f with
  | M (L n | N n | U n | D n) → generation' n
  | G _ | O _ → [0//1; 0//1; 0//1]

let charge = function
| M f →
  begin match f with
  | L n → if n > 0 then -1//1 else 1//1
  | N n → 0//1
  | U n → if n > 0 then 2//3 else -2//3
  | D n → if n > 0 then -1//3 else 1//3
  end
| G f →
  begin match f with
  | Gl | Ga | Z → 0//1
  | Wp → 1//1
  | Wm → -1//1
  end
| O f →
  begin match f with
  | H | Phi0 | Grav → 0//1
  | Phip → 1//1
  | Phim → -1//1
  end

let lepton = function
| M f →
  begin match f with
  | L n | N n → if n > 0 then 1//1 else -1//1
  | U _ | D _ → 0//1
  end
| G _ | O _ → 0//1

let baryon = function
| M f →
  begin match f with
  | L _ | N _ → 0//1
  | U n | D n → if n > 0 then 1//1 else -1//1
  end
| G _ | O _ → 0//1

let charges f =
  [ charge f; lepton f; baryon f ] @ generation f

```

```

type constant =
  | Unit | Pi | Alpha_QED | Sin2thw
  | Sinthw | Costhw | E | G_weak | Vev
  | Q_lepton | Q_up | Q_down | G_CC | G_CCQ of int × int
  | G_NC_neutrino | G_NC_lepton | G_NC_up | G_NC_down
  | Gs | I_Gs | G2
  | I_Q_W | I_G_ZWW
  | G_WWWW | G_ZZWW | G_AZWW | G_AAWW
  | G_HWW | G_HHWW | G_HZZ | G_HHZZ
  | G_Htt | G_Hbb | G_Hcc | G_Htautau | G_H3 | G_H4
  | G_HGaZ | G_HGaGa | G_Hgg | G_Grav
  | Mass of flavor | Width of flavor

```

Two integer counters for the QCD and EW order of the couplings.

```

type orders = int × int

let orders = function
  | _ → (0, 0)

let input_parameters =
  []

let derived_parameters =
  []

let g_over_2_costh =
  Quot (Neg (Atom G_weak), Prod [Const 2; Atom Costhw])

let nc_coupling c t3 q =
  (Real_Array c,
   [Prod [g_over_2_costh; Diff (t3, Prod [Const 2; q; Atom Sin2thw]);
    Prod [g_over_2_costh; t3]])

let half = Quot (Const 1, Const 2)

let derived_parameter_arrays =
  [ nc_coupling G_NC_neutrino half (Const 0);
    nc_coupling G_NC_lepton (Neg half) (Const (-1));
    nc_coupling G_NC_up half (Quot (Const 2, Const 3));
    nc_coupling G_NC_down (Neg half) (Quot (Const (-1), Const 3)) ]

let parameters () =
  { input = input_parameters;
    derived = derived_parameters;
    derived_arrays = derived_parameter_arrays }

module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)

let mgm ((m1, g, m2), fbf, c) = ((M m1, G g, M m2), fbf, c)
let mom ((m1, o, m2), fbf, c) = ((M m1, O o, M m2), fbf, c)

```

```

let electromagnetic_currents n =
  List.map mgm
    [ ((L (-n), Ga, L n), FBF (1, Psibar, V, Psi), Q_lepton);
      ((U (-n), Ga, U n), FBF (1, Psibar, V, Psi), Q_up);
      ((D (-n), Ga, D n), FBF (1, Psibar, V, Psi), Q_down) ]

let neutral_currents n =
  List.map mgm
    [ ((L (-n), Z, L n), FBF (1, Psibar, VA, Psi), G_NC_lepton);
      ((N (-n), Z, N n), FBF (1, Psibar, VA, Psi), G_NC_neutrino);
      ((U (-n), Z, U n), FBF (1, Psibar, VA, Psi), G_NC_up);
      ((D (-n), Z, D n), FBF (1, Psibar, VA, Psi), G_NC_down) ]

let color_currents n =
  List.map mgm
    [ ((U (-n), Gl, U n), FBF ((-1), Psibar, V, Psi), Gs);
      ((D (-n), Gl, D n), FBF ((-1), Psibar, V, Psi), Gs) ]

let charged_currents n =
  List.map mgm
    [ ((L (-n), Wm, N n), FBF (1, Psibar, VL, Psi), G_CC);
      ((N (-n), Wp, L n), FBF (1, Psibar, VL, Psi), G_CC);
      ((D (-n), Wm, U n), FBF (1, Psibar, VL, Psi), G_CC);
      ((U (-n), Wp, D n), FBF (1, Psibar, VL, Psi), G_CC) ]

let gravity_currents n =
  List.map mom
    [ ((L (-n), Grav, L n), Graviton_Spinor_Spinor 1, G_Grav);
      ((N (-n), Grav, N n), Graviton_Spinor_Spinor 1, G_Grav);
      ((U (-n), Grav, U n), Graviton_Spinor_Spinor 1, G_Grav);
      ((D (-n), Grav, D n), Graviton_Spinor_Spinor 1, G_Grav) ]

let yukawa =
  List.map mom
    [ ((U (-3), H, U 3), FBF (1, Psibar, S, Psi), G_Htt);
      ((D (-3), H, D 3), FBF (1, Psibar, S, Psi), G_Hbb);
      ((U (-2), H, U 2), FBF (1, Psibar, S, Psi), G_Hcc);
      ((L (-3), H, L 3), FBF (1, Psibar, S, Psi), G_Htautau) ]

let tgc ((g1, g2, g3), t, c) = ((G g1, G g2, G g3), t, c)

let standard_triple_gauge =
  List.map tgc
    [ ((Ga, Wm, Wp), Gauge_Gauge_Gauge 1, I_Q_W);
      ((Z, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_ZWW);
      ((Gl, Gl, Gl), Gauge_Gauge_Gauge 1, I_Gs) ]

let triple_gauge =
  standard_triple_gauge

let qgc ((g1, g2, g3, g4), t, c) = ((G g1, G g2, G g3, G g4), t, c)

let gauge4 = Vector4 [(2, C_13_42); (-1, C_12_34); (-1, C_14_23)]
let minus_gauge4 = Vector4 [(-2, C_13_42); (1, C_12_34); (1, C_14_23)]
let standard_quartic_gauge =

```

```

List.map qgc
  [ (Wm, Wp, Wm, Wp), gauge4, G_WWWW;
    (Wm, Z, Wp, Z), minus_gauge4, G_ZZWW;
    (Wm, Z, Wp, Ga), minus_gauge4, G_AZWW;
    (Wm, Ga, Wp, Ga), minus_gauge4, G_AAWW;
    (Gl, Gl, Gl, Gl), gauge4, G2]

let quartic_gauge =
  standard_quartic_gauge

let gravity_gauge =
  [ (O Grav, G Z, G Z), Graviton_Vector_Vector 1, G_Grav;
    (O Grav, G Wp, G Wm), Graviton_Vector_Vector 1, G_Grav;
    (O Grav, G Ga, G Ga), Graviton_Vector_Vector 1, G_Grav;
    (O Grav, G Gl, G Gl), Graviton_Vector_Vector 1, G_Grav ]

let standard_gauge_higgs =
  [ ((O H, G Wp, G Wm), Scalar_Vector_Vector 1, G_HWW);
    ((O H, G Z, G Z), Scalar_Vector_Vector 1, G_HZZ) ]

let standard_gauge_higgs4 =
  [ (O H, O H, G Wp, G Wm), Scalar2_Vector2 1, G_HHWW;
    (O H, O H, G Z, G Z), Scalar2_Vector2 1, G_HHZZ ]

let standard_higgs =
  [ (O H, O H, O H), Scalar_Scalar_Scalar 1, G_H3 ]

let standard_higgs4 =
  [ (O H, O H, O H, O H), Scalar4 1, G_H4 ]

let gravity_higgs =
  [ (O Grav, O H, O H), Graviton_Scalar_Scalar 1, G_Grav ]

let anomalous_gauge_higgs =
  []

let anomalous_gauge_higgs4 =
  []

let anomalous_higgs =
  []

let anomaly_higgs =
  [ (O H, G Ga, G Ga), Dim5_Scalar_Gauge2 1, G_HGaGa;
    (O H, G Ga, G Z), Dim5_Scalar_Gauge2 1, G_HGaZ;
    (O H, G Gl, G Gl), Dim5_Scalar_Gauge2 1, G_Hgg ]

let anomalous_higgs4 =
  []

let gauge_higgs =
  standard_gauge_higgs

let gauge_higgs4 =
  standard_gauge_higgs4

let higgs =
  standard_higgs @ gravity_higgs

```

```

let higgs4 =
  standard_higgs4

let goldstone_vertices =
  [ ((O Phi0, G Wm, G Wp), Scalar_Vector_Vector 1, I-G-ZWW);
    ((O Phip, G Ga, G Wm), Scalar_Vector_Vector 1, I-Q-W);
    ((O Phip, G Z, G Wm), Scalar_Vector_Vector 1, I-G-ZWW);
    ((O Phim, G Wp, G Ga), Scalar_Vector_Vector 1, I-Q-W);
    ((O Phim, G Wp, G Z), Scalar_Vector_Vector 1, I-G-ZWW) ]

let vertices3 =
  (ThoList.flatmap electromagnetic_currents [1;2;3] @
   ThoList.flatmap neutral_currents [1;2;3] @
   ThoList.flatmap color_currents [1;2;3] @
   ThoList.flatmap charged_currents [1;2;3] @
   ThoList.flatmap gravity_currents [1;2;3] @
   yukawa @ triple_gauge @ gravity_gauge @
   gauge_higgs @ higgs @ anomaly_higgs
   @ goldstone_vertices)

let vertices4 =
  quartic_gauge @ gauge_higgs4 @ higgs4

let vertices () = (vertices3, vertices4, [])

```

For efficiency, make sure that *F.of\_vertices vertices* is evaluated only once.

```

let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 4

let flavor_of_string = function
| "e-" → M (L 1) | "e+" → M (L (-1))
| "mu-" → M (L 2) | "mu+" → M (L (-2))
| "tau-" → M (L 3) | "tau+" → M (L (-3))
| "nue" → M (N 1) | "nuebar" → M (N (-1))
| "numu" → M (N 2) | "numubar" → M (N (-2))
| "nutau" → M (N 3) | "nutaubar" → M (N (-3))
| "u" → M (U 1) | "ubar" → M (U (-1))
| "c" → M (U 2) | "cbar" → M (U (-2))
| "t" → M (U 3) | "tbar" → M (U (-3))
| "d" → M (D 1) | "dbar" → M (D (-1))
| "s" → M (D 2) | "sbar" → M (D (-2))
| "b" → M (D 3) | "bbar" → M (D (-3))
| "g" | "gl" → G Gl
| "A" → G Ga | "Z" | "ZO" → G Z
| "W+" → G Wp | "W-" → G Wm
| "H" → O H
| "GG" → O Grav
| _ → invalid_arg "Modellib_BSM.Xdim.flavor_of_string"

let flavor_to_string = function

```

```

| M f →
  begin match f with
  | L 1 → "e-" | L (-1) → "e+"
  | L 2 → "mu-" | L (-2) → "mu+"
  | L 3 → "tau-" | L (-3) → "tau+"
  | L _ → invalid_arg
    "Modellib_BSM.Xdim.flavor_to_string:␣invalid␣lepton"
  | N 1 → "nue" | N (-1) → "nuebar"
  | N 2 → "numu" | N (-2) → "numubar"
  | N 3 → "nutau" | N (-3) → "nutaubar"
  | N _ → invalid_arg
    "Modellib_BSM.Xdim.flavor_to_string:␣invalid␣neutrino"
  | U 1 → "u" | U (-1) → "ubar"
  | U 2 → "c" | U (-2) → "cbar"
  | U 3 → "t" | U (-3) → "tbar"
  | U _ → invalid_arg
    "Modellib_BSM.Xdim.flavor_to_string:␣invalid␣up␣type␣quark"
  | D 1 → "d" | D (-1) → "dbar"
  | D 2 → "s" | D (-2) → "sbar"
  | D 3 → "b" | D (-3) → "bbar"
  | D _ → invalid_arg
    "Modellib_BSM.Xdim.flavor_to_string:␣invalid␣down␣type␣quark"
  end
| G f →
  begin match f with
  | Gl → "g"
  | Ga → "A" | Z → "Z"
  | Wp → "W+" | Wm → "W-"
  end
| O f →
  begin match f with
  | Phip → "phi+" | Phim → "phi-" | Phi0 → "phi0"
  | H → "H" | Grav → "GG"
  end
end

let flavor_to_TeX = function
| M f →
  begin match f with
  | L 1 → "e~-" | L (-1) → "e~+"
  | L 2 → "\\mu~-" | L (-2) → "\\mu~+"
  | L 3 → "\\tau~-" | L (-3) → "\\tau~+"
  | L _ → invalid_arg
    "Modellib_BSM.Xdim.flavor_to_TeX:␣invalid␣lepton"
  | N 1 → "\\nu_e" | N (-1) → "\\bar{\\nu}_e"
  | N 2 → "\\nu_\\mu" | N (-2) → "\\bar{\\nu}_\\mu"
  | N 3 → "\\nu_\\tau" | N (-3) → "\\bar{\\nu}_\\tau"
  | N _ → invalid_arg
    "Modellib_BSM.Xdim.flavor_to_TeX:␣invalid␣neutrino"
  | U 1 → "u" | U (-1) → "\\bar{u}"
  | U 2 → "c" | U (-2) → "\\bar{c}"

```



```

| U 3 → "t" | U (-3) → "\\bar{t}"
| U _ → invalid_arg
      "Modellib_BSM.Xdim.flavor_to_TeX:_invalid_up_type_quark"
| D 1 → "d" | D (-1) → "\\bar{d}"
| D 2 → "s" | D (-2) → "\\bar{s}"
| D 3 → "b" | D (-3) → "\\bar{b}"
| D _ → invalid_arg
      "Modellib_BSM.Xdim.flavor_to_TeX:_invalid_down_type_quark"
end
| G f →
  begin match f with
  | Gl → "g"
  | Ga → "\\gamma" | Z → "Z"
  | Wp → "W^+" | Wm → "W^- "
  end
| O f →
  begin match f with
  | Phip → "\\phi^+" | Phim → "\\phi^-" | Phi0 →
    "\\phi^0"
  | H → "H" | Grav → "G"
  end
let flavor_symbol = function
| M f →
  begin match f with
  | L n when n > 0 → "l" ^ string_of_int n
  | L n → "l" ^ string_of_int (abs n) ^ "b"
  | N n when n > 0 → "n" ^ string_of_int n
  | N n → "n" ^ string_of_int (abs n) ^ "b"
  | U n when n > 0 → "u" ^ string_of_int n
  | U n → "u" ^ string_of_int (abs n) ^ "b"
  | D n when n > 0 → "d" ^ string_of_int n
  | D n → "d" ^ string_of_int (abs n) ^ "b"
  end
| G f →
  begin match f with
  | Gl → "gl"
  | Ga → "a" | Z → "z"
  | Wp → "wp" | Wm → "wm"
  end
| O f →
  begin match f with
  | Phip → "pp" | Phim → "pm" | Phi0 → "p0"
  | H → "h" | Grav → "gv"
  end
let pdg = function
| M f →
  begin match f with
  | L n when n > 0 → 9 + 2 × n
  | L n → - 9 + 2 × n

```

```

      |  $N\ n\ \text{when } n > 0 \rightarrow 10 + 2 \times n$ 
      |  $N\ n \rightarrow -10 + 2 \times n$ 
      |  $U\ n\ \text{when } n > 0 \rightarrow 2 \times n$ 
      |  $U\ n \rightarrow 2 \times n$ 
      |  $D\ n\ \text{when } n > 0 \rightarrow -1 + 2 \times n$ 
      |  $D\ n \rightarrow 1 + 2 \times n$ 
    end
  |  $G\ f \rightarrow$ 
    begin match  $f$  with
    |  $Gl \rightarrow 21$ 
    |  $Ga \rightarrow 22$  |  $Z \rightarrow 23$ 
    |  $Wp \rightarrow 24$  |  $Wm \rightarrow (-24)$ 
    end
  |  $O\ f \rightarrow$ 
    begin match  $f$  with
    |  $Phip$  |  $Phim \rightarrow 27$  |  $Phi0 \rightarrow 26$ 
    |  $H \rightarrow 25$  |  $Grav \rightarrow 39$ 
    end
end

let mass_symbol  $f =$ 
  "mass(" ^ string_of_int (abs (pdg  $f$ )) ^ ")"

let width_symbol  $f =$ 
  "width(" ^ string_of_int (abs (pdg  $f$ )) ^ ")"

let constant_symbol = function
  |  $Unit \rightarrow$  "unit" |  $Pi \rightarrow$  "PI"
  |  $Alpha\_QED \rightarrow$  "alpha" |  $E \rightarrow$  "e" |  $G\_weak \rightarrow$  "g" |  $Vev \rightarrow$ 
"vev"
  |  $Sin2thw \rightarrow$  "sin2thw" |  $Sinthw \rightarrow$  "sinthw" |  $Costhw \rightarrow$ 
"costhw"
  |  $Q\_lepton \rightarrow$  "qlep" |  $Q\_up \rightarrow$  "qup" |  $Q\_down \rightarrow$  "qdwn"
  |  $G\_NC\_lepton \rightarrow$  "gnclep" |  $G\_NC\_neutrino \rightarrow$  "gncneu"
  |  $G\_NC\_up \rightarrow$  "gncup" |  $G\_NC\_down \rightarrow$  "gncdwn"
  |  $Gs \rightarrow$  "gs" |  $I\_Gs \rightarrow$  "igs" |  $G2 \rightarrow$  "gs**2"
  |  $G\_CC \rightarrow$  "gcc"
  |  $G\_CCQ\ (n1, n2) \rightarrow$  "gccq" ^ string_of_int  $n1$  ^ string_of_int  $n2$ 
  |  $I\_Q\_W \rightarrow$  "iqw" |  $I\_G\_ZWW \rightarrow$  "igzww"
  |  $G\_WWWW \rightarrow$  "gw4" |  $G\_ZZWW \rightarrow$  "gzzww"
  |  $G\_AZWW \rightarrow$  "gazww" |  $G\_AAWW \rightarrow$  "gaaww"
  |  $G\_HWW \rightarrow$  "ghww" |  $G\_HZZ \rightarrow$  "ghzz"
  |  $G\_HHWW \rightarrow$  "ghhww" |  $G\_HHZZ \rightarrow$  "ghhzz"
  |  $G\_Htt \rightarrow$  "ghtt" |  $G\_Hbb \rightarrow$  "ghbb"
  |  $G\_Htautau \rightarrow$  "ghtautau" |  $G\_Hcc \rightarrow$  "ghcc"
  |  $G\_HGaZ \rightarrow$  "ghgaz" |  $G\_HGaGa \rightarrow$  "ghgaga" |  $G\_Hgg \rightarrow$ 
"ghgg"
  |  $G\_H3 \rightarrow$  "gh3" |  $G\_H4 \rightarrow$  "gh4" |  $G\_Grav \rightarrow$  "ggrav"
  |  $Mass\ f \rightarrow$  "mass" ^ flavor_symbol  $f$ 
  |  $Width\ f \rightarrow$  "width" ^ flavor_symbol  $f$ 
end

module UED (Flags : BSM_flags) =
```

```

struct
  let rcs = RCS.rename rcs_file "Modellib_BSM.UED"
    [ "Universal_Extra_Dimensions" ]

  open Coupling

  let default_width = ref Timelike
  let use_fudged_width = ref false

  let options = Options.create
    [ "constant_width", Arg.Unit (fun () → default_width := Constant),
      "use_constant_width(also_in_t-channel)",
      "fudged_width", Arg.Set use_fudged_width,
      "use_fudge_factor_for_charge_particle_width",
      "custom_width", Arg.String (fun f → default_width := Custom f),
      "use_custom_width",
      "cancel_widths", Arg.Unit (fun () → default_width := Vanishing),
      "use_vanishing_width" ]

  type matter_field = L of int | N of int | U of int | D of int
    | L_K1_L of int | L_K1_R of int | N_K1 of int
    | L_K2_L of int | L_K2_R of int | N_K2 of int
    | U_K1_L of int | U_K2_L of int | D_K1_L of int | D_K2_L of int
    | U_K1_R of int | U_K2_R of int | D_K1_R of int | D_K2_R of int
  type gauge_boson = Ga | Wp | Wm | Z | Gl | Gl_K1 | Gl_K2
    | B1 | B2 | Z1 | Z2 | Wp1 | Wm1 | Wp2 | Wm2
  type other = Phip | Phim | Phi0 | H | H1up | H1um
    | H1dp | H1dm | H2up | H2um | H2dp | H2dm
    | Grav
  type flavor = M of matter_field | G of gauge_boson | O of other

  let matter_field f = M f
  let gauge_boson f = G f
  let other f = O f

  type field =
    | Matter of matter_field
    | Gauge of gauge_boson
    | Other of other

  let field = function
    | M f → Matter f
    | G f → Gauge f
    | O f → Other f

  type gauge = unit

  let gauge_symbol () =
    failwith "Modellib_BSM.UED.gauge_symbol:_internal_error"

  let family n = List.map matter_field [ L n; N n; U n; D n; L_K1_L n;
    L_K1_R n; L_K2_L n; L_K2_R n; N_K1 n; N_K2 n; U_K1_L n; U_K2_L n;
    D_K1_L n; D_K2_L n; U_K1_R n; U_K2_R n; D_K1_R n; D_K2_R n ]

```

We don't introduce a special index for the higher excitations but make them parts of the particles' names.

```

let external_flavors () =
  [ "1st_Generation", ThoList.flatmap family [1; -1];
    "2nd_Generation", ThoList.flatmap family [2; -2];
    "3rd_Generation", ThoList.flatmap family [3; -3];
    "Gauge_Bosons", List.map gauge_boson [Ga; Z; Wp; Wm; Gl;
      Gl_K1; Gl_K2; B1; B2; Z1; Z2; Wp1; Wm1; Wp2; Wm2];
    "Higgs", List.map other [H; H1up; H1um; H1dp; H1dm;
      H2up; H2um; H2dp; H2dm];
    "Graviton", List.map other [Grav];
    "Goldstone_Bosons", List.map other [Phip; Phim; Phi0] ]

let flavors () = ThoList.flatmap snd (external_flavors ())

let spinor n =
  if n ≥ 0 then
    Spinor
  else
    ConjSpinor

let lorentz = function
| M f →
  begin match f with
  | L n → spinor n | N n → spinor n
  | U n → spinor n | D n → spinor n
  | L_K1_L n → spinor n | L_K1_R n → spinor n
  | L_K2_L n → spinor n | L_K2_R n → spinor n
  | N_K1 n → spinor n | N_K2 n → spinor n
  | U_K1_L n → spinor n | U_K1_R n → spinor n
  | U_K2_L n → spinor n | U_K2_R n → spinor n
  | D_K1_L n → spinor n | D_K1_R n → spinor n
  | D_K2_L n → spinor n | D_K2_R n → spinor n
  end
| G f →
  begin match f with
  | Ga | Gl → Vector
  | Wp | Wm | Z | Gl_K1 | Gl_K2 | B1 | B2
  | Z1 | Z2 | Wp1 | Wm1 | Wp2 | Wm2 → Massive_Vector
  end
| O f →
  begin match f with
  | Grav → Tensor_2
  | _ → Scalar
  end

let color = function
| M (U n) → Color.SUN (if n > 0 then 3 else -3)
| M (D n) → Color.SUN (if n > 0 then 3 else -3)
| M (U_K1_L n) → Color.SUN (if n > 0 then 3 else -3)
| M (D_K1_L n) → Color.SUN (if n > 0 then 3 else -3)
| M (U_K1_R n) → Color.SUN (if n > 0 then 3 else -3)
| M (D_K1_R n) → Color.SUN (if n > 0 then 3 else -3)
| M (U_K2_L n) → Color.SUN (if n > 0 then 3 else -3)

```

```

| M (D_K2_L n) → Color.SUN (if n > 0 then 3 else -3)
| M (U_K2_R n) → Color.SUN (if n > 0 then 3 else -3)
| M (D_K2_R n) → Color.SUN (if n > 0 then 3 else -3)
| G Gl | G Gl_K1 | G Gl_K2 → Color.AdjSUN 3
| _ → Color.Singlet

let prop_spinor n =
  if n ≥ 0 then
    Prop_Spinor
  else
    Prop_ConjSpinor

let propagator = function
| M f →
  begin match f with
  | L n → prop_spinor n | N n → prop_spinor n
  | U n → prop_spinor n | D n → prop_spinor n
  | L_K1_L n → prop_spinor n | L_K1_R n → prop_spinor n
  | L_K2_L n → prop_spinor n | L_K2_R n → prop_spinor n
  | N_K1 n → prop_spinor n | N_K2 n → prop_spinor n
  | U_K1_L n → prop_spinor n | U_K1_R n → prop_spinor n
  | U_K2_L n → prop_spinor n | U_K2_R n → prop_spinor n
  | D_K1_L n → prop_spinor n | D_K1_R n → prop_spinor n
  | D_K2_L n → prop_spinor n | D_K2_R n → prop_spinor n
  end
| G f →
  begin match f with
  | Ga | Gl → Prop_Feynman
  | Wp | Wm | Z | Gl_K1 | Gl_K2 | B1 | B2
  | Z1 | Z2 | Wp1 | Wm1 | Wp2 | Wm2 → Prop_Unitarity
  end
| O f →
  begin match f with
  | Phip | Phim | Phi0 → Only_Insertion
  | H | H1up | H1um | H1dp | H1dm | H2up
  | H2um | H2dp | H2dm → Prop_Scalar
  | Grav → Prop_Tensor_2
  end

```

Optionally, ask for the fudge factor treatment for the widths of charged particles. Currently, this only applies to  $W^\pm$  and top.

```

let width f =
  if !use_fudged_width then
    match f with
    | G Wp | G Wm | M (U 3) | M (U (-3)) | O Grav → Fudged
    | _ → !default_width
  else
    !default_width

let goldstone = function
| G f →
  begin match f with

```

```

| Wp → Some (O Phip, Coupling.Const 1)
| Wm → Some (O Phim, Coupling.Const 1)
| Z → Some (O Phi0, Coupling.Const 1)
| _ → None
end
| _ → None

let conjugate = function
| M f →
  M (begin match f with
    | L n → L (-n) | N n → N (-n)
    | U n → U (-n) | D n → D (-n)
    | L_K1_L n → L_K1_L (-n) | L_K1_R n → L_K1_R (-n)
    | L_K2_L n → L_K2_L (-n) | L_K2_R n → L_K2_R (-n)
    | N_K1 n → N_K1 (-n) | N_K2 n → N_K2 (-n)
    | U_K1_L n → U_K1_L (-n) | U_K1_R n → U_K1_R (-n)
    | U_K2_L n → U_K2_L (-n) | U_K2_R n → U_K2_R (-n)
    | D_K1_L n → D_K1_L (-n) | D_K1_R n → D_K1_R (-n)
    | D_K2_L n → D_K2_L (-n) | D_K2_R n → D_K2_R (-n)
  end)
| G f →
  G (begin match f with
    | Gl → Gl | Ga → Ga | Z → Z
    | Wp → Wm | Wm → Wp
    | Gl_K1 → Gl_K1 | Gl_K2 → Gl_K2 | B1 → B1 | B2 →
B2
    | Z1 → Z1 | Z2 → Z2 | Wp1 → Wm1 | Wm1 → Wp1
    | Wp2 → Wm2 | Wm2 → Wp2
  end)
| O f →
  O (begin match f with
    | Phip → Phim | Phim → Phip | Phi0 → Phi0
    | H → H | H1up → H1um | H1um → H1up
    | H1dp → H1dm | H1dm → H1dp
    | H2up → H2um | H2um → H2up
    | H2dp → H2dm | H2dm → H2dp
    | Grav → Grav
  end)

let fermion = function
| M f →
  begin match f with
    | L n → if n > 0 then 1 else -1
    | N n → if n > 0 then 1 else -1
    | U n → if n > 0 then 1 else -1
    | D n → if n > 0 then 1 else -1
    | L_K1_L n → if n > 0 then 1 else -1
    | L_K2_L n → if n > 0 then 1 else -1
    | L_K1_R n → if n > 0 then 1 else -1
    | L_K2_R n → if n > 0 then 1 else -1
    | U_K1_L n → if n > 0 then 1 else -1

```

```

| U_K2_L n → if n > 0 then 1 else -1
| U_K1_R n → if n > 0 then 1 else -1
| U_K2_R n → if n > 0 then 1 else -1
| D_K1_L n → if n > 0 then 1 else -1
| D_K2_L n → if n > 0 then 1 else -1
| D_K1_R n → if n > 0 then 1 else -1
| D_K2_R n → if n > 0 then 1 else -1
| N_K1 n → if n > 0 then 1 else -1
| N_K2 n → if n > 0 then 1 else -1
end
| G f →
  begin match f with
  | Gl | Ga | Z | Wp | Wm | Gl_K1 | Gl_K2
  | B1 | B2 | Z1 | Z2 | Wp1 | Wm1 | Wp2
  | Wm2 → 0
  end
| O _ → 0
module Ch = Charges.QQ
let ( // ) = Algebra.Small_Rational.make
let generation' = function
| 1 → [ 1//1; 0//1; 0//1]
| 2 → [ 0//1; 1//1; 0//1]
| 3 → [ 0//1; 0//1; 1//1]
| -1 → [-1//1; 0//1; 0//1]
| -2 → [ 0//1; -1//1; 0//1]
| -3 → [ 0//1; 0//1; -1//1]
| n → invalid_arg ("SM.generation':␣" ^ string_of_int n)
let generation f =
  match f with
  | M (L n | N n | U n | D n | L_K1_L n | L_K2_L n
    | L_K1_R n | L_K2_R n | N_K1 n | N_K2 n | U_K1_L n
    | U_K2_L n | U_K1_R n | U_K2_R n | D_K1_L n |
D_K2_L n
    | D_K1_R n | D_K2_R n) → generation' n
  | G _ | O _ → [0//1; 0//1; 0//1]
let charge = function
| M f →
  begin match f with
  | L n | L_K1_L n | L_K2_L n | L_K1_R n
  | L_K2_R n → if n > 0 then -1//1 else 1//1
  | N n | N_K1 n | N_K2 n → 0//1
  | U n | U_K1_L n | U_K2_L n | U_K1_R n
  | U_K2_R n → if n > 0 then 2//3 else -2//3
  | D n | D_K1_L n | D_K2_L n | D_K1_R n
  | D_K2_R n → if n > 0 then -1//3 else 1//3
  end
| G f →
  begin match f with

```

```

      | Gl | Gl_K1 | Gl_K2 | Ga | Z
      | B1 | B2 | Z1 | Z2 → 0//1
      | Wp | Wp1 | Wp2 → 1//1
      | Wm | Wm1 | Wm2 → -1//1
    end
  | O f →
    begin match f with
    | H | Phi0 | Grav → 0//1
    | H1up | H1dp | H2up | H2dp | Phip → 1//1
    | H1um | H1dm | H2um | H2dm | Phim → -1//1
    end

let lepton = function
  | M f →
    begin match f with
    | L n | N n | L_K1_L n | L_K1_R n | L_K2_L n
    | L_K2_R n | N_K1 n | N_K2 n → if n > 0 then 1//1 else -
1//1
    | U _ | D _ | _ → 0//1
    end
  | G _ | O _ → 0//1

let baryon = function
  | M f →
    begin match f with
    | U n | D n | U_K1_L n | U_K1_R n | U_K2_L n
    | U_K2_R n | D_K1_L n | D_K1_R n | D_K2_L n
    | D_K2_R n → if n > 0 then 1//1 else -1//1
    | L _ | N _ | _ → 0//1
    end
  | G _ | O _ → 0//1

let charges f =
  [ charge f; lepton f; baryon f ] @ generation f

type constant =
  | Unit | Pi | Alpha_QED | Sin2thw
  | Sinthw | Costhw | E | G_weak | Vev
  | Q_lepton | Q_up | Q_down | G_CC | G_CCQ of int×int
  | G_NC_neutrino | G_NC_lepton | G_NC_up | G_NC_down
  | I_Q_W | I_G_ZWW | I_Q_W_K | I_G_ZWW_K1 |
I_G_ZWW_K2
  | I_G_ZWW_K3
  | G_WWWW | G_ZZWW | G_AZWW | G_AAWW
  | G_HWW | G_HHWW | G_HZZ | G_HHZZ
  | G_Htt | G_Hbb | G_Hcc | G_Htautau | G_H3 | G_H4
  | G_HGaZ | G_HGaGa | G_Hgg
  | Gs | I_Gs | I_GsRt2 | G2 | G22 | G_Grav
  | Mass of flavor | Width of flavor

```

Two integer counters for the QCD and EW order of the couplings.

```
type orders = int × int
```



```

let orders = function
| - → (0,0)

let input_parameters =
[]

let derived_parameters =
[]

let g_over_2_csth =
Quot (Neg (Atom G_weak), Prod [Const 2; Atom Costhw])

let nc_coupling c t3 q =
(Real_Array c,
 [Prod [g_over_2_csth; Diff (t3, Prod [Const 2; q; Atom Sin2thw]);
  Prod [g_over_2_csth; t3]])

let half = Quot (Const 1, Const 2)

let derived_parameter_arrays =
[ nc_coupling G_NC_neutrino half (Const 0);
  nc_coupling G_NC_lepton (Neg half) (Const (-1));
  nc_coupling G_NC_up half (Quot (Const 2, Const 3));
  nc_coupling G_NC_down (Neg half) (Quot (Const (-1), Const 3)) ]

let parameters () =
{ input = input_parameters;
  derived = derived_parameters;
  derived_arrays = derived_parameter_arrays }

module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)

let mgm ((m1, g, m2), fbf, c) = ((M m1, G g, M m2), fbf, c)
let mom ((m1, o, m2), fbf, c) = ((M m1, O o, M m2), fbf, c)

let electromagnetic_currents n =
List.map mgm
[ ((L (-n), Ga, L n), FBF (1, Psibar, V, Psi), Q_lepton);
  ((U (-n), Ga, U n), FBF (1, Psibar, V, Psi), Q_up);
  ((D (-n), Ga, D n), FBF (1, Psibar, V, Psi), Q_down) ]

let neutral_currents n =
List.map mgm
[ ((L (-n), Z, L n), FBF (1, Psibar, VA, Psi), G_NC_lepton);
  ((N (-n), Z, N n), FBF (1, Psibar, VA, Psi), G_NC_neutrino);
  ((U (-n), Z, U n), FBF (1, Psibar, VA, Psi), G_NC_up);
  ((D (-n), Z, D n), FBF (1, Psibar, VA, Psi), G_NC_down) ]

let charged_currents n =
List.map mgm
[ ((L (-n), Wm, N n), FBF (1, Psibar, VL, Psi), G_CC);

```

```

      ((N (-n), Wp, L n), FBF (1, Psibar, VL, Psi), G_CC);
      ((D (-n), Wm, U n), FBF (1, Psibar, VL, Psi), G_CC);
      ((U (-n), Wp, D n), FBF (1, Psibar, VL, Psi), G_CC) ]

let color_currents n =
  List.map mgm
    [ ((U (-n), Gl, U n), FBF ((-1), Psibar, V, Psi), Gs);
      ((D (-n), Gl, D n), FBF ((-1), Psibar, V, Psi), Gs) ]

let gravity_currents n =
  List.map mom
    [ ((L (-n), Grav, L n), Graviton_Spinor_Spinor 1, G_Grav);
      ((N (-n), Grav, N n), Graviton_Spinor_Spinor 1, G_Grav);
      ((U (-n), Grav, U n), Graviton_Spinor_Spinor 1, G_Grav);
      ((D (-n), Grav, D n), Graviton_Spinor_Spinor 1, G_Grav) ]

let yukawa =
  List.map mom
    [ ((U (-3), H, U 3), FBF (1, Psibar, S, Psi), G_Htt);
      ((D (-3), H, D 3), FBF (1, Psibar, S, Psi), G_Hbb);
      ((U (-2), H, U 2), FBF (1, Psibar, S, Psi), G_Hcc);
      ((L (-3), H, L 3), FBF (1, Psibar, S, Psi), G_Htautau) ]

let tgc ((g1, g2, g3), t, c) = ((G g1, G g2, G g3), t, c)

Gluons should be included in just that way.

let standard_triple_gauge =
  List.map tgc
    [ ((Ga, Wm, Wp), Gauge_Gauge_Gauge 1, I_Q_W);
      ((Ga, Wm1, Wp1), Gauge_Gauge_Gauge 1, I_Q_W_K);
      ((Z, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_ZWW);
      ((Z, Wm1, Wp1), Gauge_Gauge_Gauge 1, I_G_ZWW_K1);
      ((Z1, Wm, Wp1), Gauge_Gauge_Gauge 1, I_G_ZWW_K2);
      ((Z1, Wm1, Wp), Gauge_Gauge_Gauge 1, I_G_ZWW_K2);
      ((Z2, Wm1, Wp2), Gauge_Gauge_Gauge 1, I_G_ZWW_K3);
      ((Gl, Gl, Gl), Gauge_Gauge_Gauge 1, I_Gs);
      ((Gl, Gl_K2, Gl_K2), Gauge_Gauge_Gauge (-1), I_Gs);
      ((Gl, Gl_K1, Gl_K1), Gauge_Gauge_Gauge 1, I_Gs);
      ((Gl_K2, Gl_K1, Gl_K1), Gauge_Gauge_Gauge 1, I_GsRt2)]

let triple_gauge =
  standard_triple_gauge

let qgc ((g1, g2, g3, g4), t, c) = ((G g1, G g2, G g3, G g4), t, c)

let gauge4 = Vector4 [(2, C_13_42); (-1, C_12_34); (-1, C_14_23)]
let minus_gauge4 = Vector4 [(-2, C_13_42); (1, C_12_34); (1, C_14_23)]
let standard_quartic_gauge =
  List.map qgc
    [ (Wm, Wp, Wm, Wp), gauge4, G_WWWW;
      (Wm, Z, Wp, Z), minus_gauge4, G_ZZWW;
      (Wm, Z, Wp, Ga), minus_gauge4, G_AZWW;
      (Wm, Ga, Wp, Ga), minus_gauge4, G_AAWW;
      ((Gl, Gl, Gl, Gl), gauge4, G2);

```

```

      ((Gl, Gl, Gl_K1, Gl_K1), gauge4, G2);
      ((Gl, Gl, Gl_K2, Gl_K2), gauge4, G2);
      ((Gl_K1, Gl_K1, Gl_K2, Gl_K2), gauge4, G2);
      ((Gl_K2, Gl_K2, Gl_K2, Gl_K2), gauge4, G22)]

let quartic_gauge =
  standard_quartic_gauge

let gravity_gauge =
  [ (O Grav, G Z, G Z), Graviton_Vector_Vector 1, G_Grav;
    (O Grav, G Wp, G Wm), Graviton_Vector_Vector 1, G_Grav;
    (O Grav, G Ga, G Ga), Graviton_Vector_Vector 1, G_Grav;
    (O Grav, G Gl, G Gl), Graviton_Vector_Vector 1, G_Grav ]

let standard_gauge_higgs =
  [ ((O H, G Wp, G Wm), Scalar_Vector_Vector 1, G_HWW);
    ((O H, G Z, G Z), Scalar_Vector_Vector 1, G_HZZ) ]

let standard_gauge_higgs4 =
  [ (O H, O H, G Wp, G Wm), Scalar2_Vector2 1, G_HHWW;
    (O H, O H, G Z, G Z), Scalar2_Vector2 1, G_HHZZ ]

let standard_higgs =
  [ (O H, O H, O H), Scalar_Scalar_Scalar 1, G_H3 ]

let standard_higgs4 =
  [ (O H, O H, O H, O H), Scalar4 1, G_H4 ]

let gravity_higgs =
  [ (O Grav, O H, O H), Graviton_Scalar_Scalar 1, G_Grav ]

let anomalous_gauge_higgs =
  []

let anomalous_gauge_higgs4 =
  []

let anomalous_higgs =
  []

let anomaly_higgs =
  [ (O H, G Ga, G Ga), Dim5_Scalar_Gauge2 1, G_HGaGa;
    (O H, G Ga, G Z), Dim5_Scalar_Gauge2 1, G_HGaZ;
    (O H, G Gl, G Gl), Dim5_Scalar_Gauge2 1, G_Hgg ]

let anomalous_higgs4 =
  []

let gauge_higgs =
  standard_gauge_higgs

let gauge_higgs4 =
  standard_gauge_higgs4

let higgs =
  standard_higgs @ gravity_higgs

let higgs4 =

```

```

standard_higgs4

let goldstone_vertices =
[ ((O Phi0, G Wm, G Wp), Scalar_Vector_Vector 1, I-G-ZWW);
  ((O Phip, G Ga, G Wm), Scalar_Vector_Vector 1, I-Q-W);
  ((O Phip, G Z, G Wm), Scalar_Vector_Vector 1, I-G-ZWW);
  ((O Phim, G Wp, G Ga), Scalar_Vector_Vector 1, I-Q-W);
  ((O Phim, G Wp, G Z), Scalar_Vector_Vector 1, I-G-ZWW) ]

let vertices3 =
(ThoList.flatmap electromagnetic_currents [1;2;3] @
 ThoList.flatmap neutral_currents [1;2;3] @
 ThoList.flatmap charged_currents [1;2;3] @
 ThoList.flatmap color_currents [1;2;3] @
 ThoList.flatmap gravity_currents [1;2;3] @
 yukawa @ triple_gauge @ gravity_gauge @
 gauge_higgs @ higgs @ anomaly_higgs
 @ goldstone_vertices)

let vertices4 =
quartic_gauge @ gauge_higgs4 @ higgs4

let vertices () = (vertices3, vertices4, [])

```

For efficiency, make sure that *F.of\_vertices vertices* is evaluated only once.

```

let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 4

let flavor_of_string = function
| "e-" → M (L 1) | "e+" → M (L (-1))
| "mu-" → M (L 2) | "mu+" → M (L (-2))
| "tau-" → M (L 3) | "tau+" → M (L (-3))
| "nue" → M (N 1) | "nuebar" → M (N (-1))
| "numu" → M (N 2) | "numubar" → M (N (-2))
| "nutau" → M (N 3) | "nutaubar" → M (N (-3))
| "u" → M (U 1) | "ubar" → M (U (-1))
| "c" → M (U 2) | "cbar" → M (U (-2))
| "t" → M (U 3) | "tbar" → M (U (-3))
| "d" → M (D 1) | "dbar" → M (D (-1))
| "s" → M (D 2) | "sbar" → M (D (-2))
| "b" → M (D 3) | "bbar" → M (D (-3))
| "uk1l" → M (U_K1_L 1) | "uk1lbar" → M (U_K1_L (-1))
| "ck1l" → M (U_K1_L 2) | "ck1lbar" → M (U_K1_L (-2))
| "tk1l" → M (U_K1_L 3) | "tk1lbar" → M (U_K1_L (-3))
| "dk1l" → M (D_K1_L 1) | "dk1lbar" → M (D_K1_L (-1))
| "sk1l" → M (D_K1_L 2) | "sk1lbar" → M (D_K1_L (-2))
| "bk1l" → M (D_K1_L 3) | "bk1lbar" → M (D_K1_L (-3))
| "uk1r" → M (U_K1_R 1) | "uk1rbar" → M (U_K1_R (-1))
| "ck1r" → M (U_K1_R 2) | "ck1rbar" → M (U_K1_R (-2))
| "tk1r" → M (U_K1_R 3) | "tk1rbar" → M (U_K1_R (-3))

```

---

```

| "dk1r" → M (D_K1_R 1) | "dk1rbar" → M (D_K1_R (-1))
| "sk1r" → M (D_K1_R 2) | "sk1rbar" → M (D_K1_R (-2))
| "bk1r" → M (D_K1_R 3) | "bk1rbar" → M (D_K1_R (-3))
| "uk2l" → M (U_K2_L 1) | "uk2lbar" → M (U_K2_L (-1))
| "ck2l" → M (U_K2_L 2) | "ck2lbar" → M (U_K2_L (-2))
| "tk2l" → M (U_K2_L 3) | "tk2lbar" → M (U_K2_L (-3))
| "dk2l" → M (D_K2_L 1) | "dk2lbar" → M (D_K2_L (-1))
| "sk2l" → M (D_K2_L 2) | "sk2lbar" → M (D_K2_L (-2))
| "bk2l" → M (D_K2_L 3) | "bk2lbar" → M (D_K2_L (-3))
| "uk2r" → M (U_K2_R 1) | "uk2rbar" → M (U_K2_R (-1))
| "ck2r" → M (U_K2_R 2) | "ck2rbar" → M (U_K2_R (-2))
| "tk2r" → M (U_K2_R 3) | "tk2rbar" → M (U_K2_R (-3))
| "dk2r" → M (D_K2_R 1) | "dk2rbar" → M (D_K2_R (-1))
| "sk2r" → M (D_K2_R 2) | "sk2rbar" → M (D_K2_R (-2))
| "bk2r" → M (D_K2_R 3) | "bk2rbar" → M (D_K2_R (-3))
| "g" | "gl" → G Gl
| "g_k1" | "gl_k1" → G Gl_K1
| "g_k2" | "gl_k2" → G Gl_K2
| "b1" → G B1 | "b2" → G B2 | "z1" → G Z1 | "z2" → G Z2
| "W1+" → G Wp1 | "W1-" → G Wm1
| "W2+" → G Wp2 | "W2-" → G Wm2
| "A" → G Ga | "Z" | "Z0" → G Z
| "W+" → G Wp | "W-" → G Wm
| "H" → O H | "H1u+" → O H1up | "H1u-" → O H1um
| "H1d+" → O H1dp | "H1d-" → O H1dm
| "H2u+" → O H2up | "H2u-" → O H2um
| "H2d+" → O H2dp | "H2d-" → O H2dm
| "GG" → O Grav
| "ek1l-" → M (L_K1_L 1) | "ek1l+" → M (L_K1_L (-1))
| "muk1l-" → M (L_K1_L 2) | "mu1l+" → M (L_K1_L (-2))
| "tauk1l-" → M (L_K1_L 3) | "tauk1l+" → M (L_K1_L (-3))
| "ek1r-" → M (L_K1_R 1) | "ek1r+" → M (L_K1_R (-1))
| "muk1r-" → M (L_K1_R 2) | "mu1r+" → M (L_K1_R (-2))
| "tauk1r-" → M (L_K1_R 3) | "tauk1r+" → M (L_K1_R (-3))
| "ek2l-" → M (L_K2_L 1) | "ek2l+" → M (L_K2_L (-1))
| "muk2l-" → M (L_K2_L 2) | "mu2l+" → M (L_K2_L (-2))
| "tauk2l-" → M (L_K2_L 3) | "tauk2l+" → M (L_K2_L (-3))
| "ek2r-" → M (L_K2_R 1) | "ek2r+" → M (L_K2_R (-1))
| "muk2r-" → M (L_K2_R 2) | "mu2r+" → M (L_K2_R (-2))
| "tauk2r-" → M (L_K2_R 3) | "tauk2r+" → M (L_K2_R (-3))
| "nuek1" → M (N_K1 1) | "nuek1bar" → M (N_K1 (-1))
| "numuk1" → M (N_K1 2) | "numuk1bar" → M (N_K1 (-2))
| "nutauk1" → M (N_K1 3) | "nutauk1bar" → M (N_K1 (-3))
| "nuek2" → M (N_K2 1) | "nuek2bar" → M (N_K2 (-1))
| "numuk2" → M (N_K2 2) | "numuk2bar" → M (N_K2 (-2))
| "nutauk2" → M (N_K2 3) | "nutauk2bar" → M (N_K2 (-3))
| _ → invalid_arg "Modellib_BSM.UED.flavor_of_string"

```

```

let flavor_to_string = function
| M f →

```

```

begin match f with
| L 1 → "e-" | L (-1) → "e+"
| L 2 → "mu-" | L (-2) → "mu+"
| L 3 → "tau-" | L (-3) → "tau+"
| L _ → invalid_arg
      "Modellib_BSM.UED.flavor_to_string:␣invalid␣lepton"
| N 1 → "nue" | N (-1) → "nuebar"
| N 2 → "numu" | N (-2) → "numubar"
| N 3 → "nutau" | N (-3) → "nutaubar"
| N _ → invalid_arg
      "Modellib_BSM.UED.flavor_to_string:␣invalid␣neutrino"
| U 1 → "u" | U (-1) → "ubar"
| U 2 → "c" | U (-2) → "cbar"
| U 3 → "t" | U (-3) → "tbar"
| U _ → invalid_arg
      "Modellib_BSM.UED.flavor_to_string:␣invalid␣up␣type␣quark"
| D 1 → "d" | D (-1) → "dbar"
| D 2 → "s" | D (-2) → "sbar"
| D 3 → "b" | D (-3) → "bbar"
| D _ → invalid_arg
      "Modellib_BSM.UED.flavor_to_string:␣invalid␣down␣type␣quark"
| U_K1_L 1 → "uk1l" | U_K1_L (-1) → "uk1lbar"
| U_K1_L 2 → "ck1l" | U_K1_L (-2) → "ck1lbar"
| U_K1_L 3 → "tk1l" | U_K1_L (-3) → "tk1lbar"
| U_K1_L _ → invalid_arg
      "Modellib_BSM.UED.flavor_to_string:␣invalid␣up␣type␣quark"
| D_K1_L 1 → "dk1l" | D_K1_L (-1) → "dk1lbar"
| D_K1_L 2 → "sk1l" | D_K1_L (-2) → "sk1lbar"
| D_K1_L 3 → "bk1l" | D_K1_L (-3) → "bk1lbar"
| D_K1_L _ → invalid_arg
      "Modellib_BSM.UED.flavor_to_string:␣invalid␣down␣type␣quark"
| U_K1_R 1 → "uk1r" | U_K1_R (-1) → "uk1rbar"
| U_K1_R 2 → "ck1r" | U_K1_R (-2) → "ck1rbar"
| U_K1_R 3 → "tk1r" | U_K1_R (-3) → "tk1rbar"
| U_K1_R _ → invalid_arg
      "Modellib_BSM.UED.flavor_to_string:␣invalid␣up␣type␣quark"
| D_K1_R 1 → "dk1r" | D_K1_R (-1) → "dk1rbar"
| D_K1_R 2 → "sk1r" | D_K1_R (-2) → "sk1rbar"
| D_K1_R 3 → "bk1r" | D_K1_R (-3) → "bk1rbar"
| D_K1_R _ → invalid_arg
      "Modellib_BSM.UED.flavor_to_string:␣invalid␣down␣type␣quark"
| U_K2_L 1 → "uk2l" | U_K2_L (-1) → "uk2lbar"
| U_K2_L 2 → "ck2l" | U_K2_L (-2) → "ck2lbar"
| U_K2_L 3 → "tk2l" | U_K2_L (-3) → "tk2lbar"
| U_K2_L _ → invalid_arg
      "Modellib_BSM.UED.flavor_to_string:␣invalid␣up␣type␣quark"
| D_K2_L 1 → "dk2l" | D_K2_L (-1) → "dk2lbar"
| D_K2_L 2 → "sk2l" | D_K2_L (-2) → "sk2lbar"
| D_K2_L 3 → "bk2l" | D_K2_L (-3) → "bk2lbar"
| D_K2_L _ → invalid_arg

```

```

        "Modellib_BSM.UED.flavor_to_string:_invalid_down_type_quark"
    | U_K2_R 1 → "uk2r" | U_K2_R (-1) → "uk2rbar"
    | U_K2_R 2 → "ck2r" | U_K2_R (-2) → "ck2rbar"
    | U_K2_R 3 → "tk2r" | U_K2_R (-3) → "tk2rbar"
    | U_K2_R _ → invalid_arg
        "Modellib_BSM.UED.flavor_to_string:_invalid_up_type_quark"
    | D_K2_R 1 → "dk2r" | D_K2_R (-1) → "dk2rbar"
    | D_K2_R 2 → "sk2r" | D_K2_R (-2) → "sk2rbar"
    | D_K2_R 3 → "bk2r" | D_K2_R (-3) → "bk2rbar"
    | D_K2_R _ → invalid_arg
        "Modellib_BSM.UED.flavor_to_string:_invalid_down_type_quark"
    | L_K1_L 1 → "ek1l-" | L_K1_L (-1) → "ek1l+"
    | L_K1_L 2 → "muk1l-" | L_K1_L (-2) → "muk1l+"
    | L_K1_L 3 → "tau1l-" | L_K1_L (-3) → "tau1l+"
    | L_K1_L _ → invalid_arg
        "Modellib_BSM.UED.flavor_to_string:_invalid_lepton"
    | L_K1_R 1 → "ek1r-" | L_K1_R (-1) → "ek1r+"
    | L_K1_R 2 → "muk1r-" | L_K1_R (-2) → "muk1r+"
    | L_K1_R 3 → "tau1r-" | L_K1_R (-3) → "tau1r+"
    | L_K1_R _ → invalid_arg
        "Modellib_BSM.UED.flavor_to_string:_invalid_lepton"
    | L_K2_L 1 → "ek2l-" | L_K2_L (-1) → "ek2l+"
    | L_K2_L 2 → "muk2l-" | L_K2_L (-2) → "muk2l+"
    | L_K2_L 3 → "tau2l-" | L_K2_L (-3) → "tau2l+"
    | L_K2_L _ → invalid_arg
        "Modellib_BSM.UED.flavor_to_string:_invalid_lepton"
    | L_K2_R 1 → "ek2r-" | L_K2_R (-1) → "ek2r+"
    | L_K2_R 2 → "muk2r-" | L_K2_R (-2) → "muk2r+"
    | L_K2_R 3 → "tau2r-" | L_K2_R (-3) → "tau2r+"
    | L_K2_R _ → invalid_arg
        "Modellib_BSM.UED.flavor_to_string:_invalid_lepton"
    | N_K1 1 → "nuek1" | N_K1 (-1) → "nuek1bar"
    | N_K1 2 → "numuk1" | N_K1 (-2) → "numuk1bar"
    | N_K1 3 → "nutauk1" | N_K1 (-3) → "nutauk1bar"
    | N_K1 _ → invalid_arg
        "Modellib_BSM.UED.flavor_to_string:_invalid_neutrino"
    | N_K2 1 → "nuek2" | N_K2 (-1) → "nuek2bar"
    | N_K2 2 → "numuk2" | N_K2 (-2) → "numuk2bar"
    | N_K2 3 → "nutauk2" | N_K2 (-3) → "nutauk2bar"
    | N_K2 _ → invalid_arg
        "Modellib_BSM.UED.flavor_to_string:_invalid_neutrino"
end
| G f →
begin match f with
| Gl → "g"
| Ga → "A" | Z → "Z"
| Wp → "W+" | Wm → "W-"
| Gl_K1 → "gk1" | Gl_K2 → "gk2"
| B1 → "b1" | B2 → "b2" | Z1 → "z1" | Z2 → "z2"
| Wp1 → "W1+" | Wm1 → "W1-"

```

```

| Wp2 → "W2+" | Wm2 → "W2-"
end
| Of →
begin match f with
| Phip → "phi+" | Phim → "phi-" | Phi0 → "phi0"
| H → "H" | H1up → "H1u+" | H1um → "H1u-"
| H1dp → "H1d+" | H1dm → "H1d-"
| H2up → "H2u+" | H2um → "H2u-"
| H2dp → "H2d+" | H2dm → "H2d-"
| Grav → "GG"
end
let flavor_to_TeX = function
| Mf →
begin match f with
| L1 → "e^-" | L(-1) → "e^+"
| L2 → "\\mu^-" | L(-2) → "\\mu^+"
| L3 → "\\tau^-" | L(-3) → "\\tau^+"
| L_ → invalid_arg
"Modellib_BSM.UED.flavor_to_TeX:␣invalid␣lepton"
| N1 → "\\nu_e" | N(-1) → "\\bar{\\nu}_e"
| N2 → "\\nu_\\mu" | N(-2) → "\\bar{\\nu}_\\mu"
| N3 → "\\nu_\\tau" | N(-3) → "\\bar{\\nu}_\\tau"
| N_ → invalid_arg
"Modellib_BSM.UED.flavor_to_TeX:␣invalid␣neutrino"
| U1 → "u" | U(-1) → "\\bar{u}"
| U2 → "c" | U(-2) → "\\bar{c}"
| U3 → "t" | U(-3) → "\\bar{t}"
| U_ → invalid_arg
"Modellib_BSM.UED.flavor_to_TeX:␣invalid␣up␣type␣quark"
| D1 → "d" | D(-1) → "dbar"
| D2 → "s" | D(-2) → "sbar"
| D3 → "b" | D(-3) → "bbar"
| D_ → invalid_arg
"Modellib_BSM.UED.flavor_to_TeX:␣invalid␣down␣type␣quark"
| U_K1_L1 → "u^\\prime_L" | U_K1_L(-1) → "\\bar{u}^\\prime_L"
| U_K1_L2 → "c^\\prime_L" | U_K1_L(-2) → "\\bar{c}^\\prime_L"
| U_K1_L3 → "t^\\prime_L" | U_K1_L(-3) → "\\bar{t}^\\prime_L"
| U_K1_L_ → invalid_arg
"Modellib_BSM.UED.flavor_to_TeX:␣invalid␣up␣type␣quark"
| D_K1_L1 → "d^\\prime_L" | D_K1_L(-1) → "\\bar{d}^\\prime_L"
| D_K1_L2 → "s^\\prime_L" | D_K1_L(-2) → "\\bar{s}^\\prime_L"
| D_K1_L3 → "b^\\prime_L" | D_K1_L(-3) → "\\bar{b}^\\prime_L"
| D_K1_L_ → invalid_arg
"Modellib_BSM.UED.flavor_to_TeX:␣invalid␣down␣type␣quark"
| U_K1_R1 → "u^\\prime_R" | U_K1_R(-1) → "\\bar{u}^\\prime_R"
| U_K1_R2 → "c^\\prime_R" | U_K1_R(-2) → "\\bar{c}^\\prime_R"
| U_K1_R3 → "t^\\prime_R" | U_K1_R(-3) → "\\bar{t}^\\prime_R"
| U_K1_R_ → invalid_arg
"Modellib_BSM.UED.flavor_to_TeX:␣invalid␣up␣type␣quark"

```



---

```

| D_K1_R 1 → "d^{\prime_R}" | D_K1_R (-1) → "\bar{d}^{\prime_R}"
| D_K1_R 2 → "s^{\prime_R}" | D_K1_R (-2) → "\bar{s}^{\prime_R}"
| D_K1_R 3 → "b^{\prime_R}" | D_K1_R (-3) → "\bar{b}^{\prime_R}"
| D_K1_R _ → invalid_arg
      "Modellib_BSM.UED.flavor_to_TeX:\invalid_down_type_quark"
| U_K2_L 1 → "u^{\prime\prime_L}" | U_K2_L (-1) →
"\bar{u}^{\prime\prime_L}"
| U_K2_L 2 → "c^{\prime\prime_L}" | U_K2_L (-2) →
"\bar{c}^{\prime\prime_L}"
| U_K2_L 3 → "t^{\prime\prime_L}" | U_K2_L (-3) →
"\bar{t}^{\prime\prime_L}"
| U_K2_L _ → invalid_arg
      "Modellib_BSM.UED.flavor_to_TeX:\invalid_up_type_quark"
| D_K2_L 1 → "d^{\prime\prime_L}" | D_K2_L (-1) →
"\bar{d}^{\prime\prime_L}"
| D_K2_L 2 → "s^{\prime\prime_L}" | D_K2_L (-2) →
"\bar{s}^{\prime\prime_L}"
| D_K2_L 3 → "b^{\prime\prime_L}" | D_K2_L (-3) →
"\bar{b}^{\prime\prime_L}"
| D_K2_L _ → invalid_arg
      "Modellib_BSM.UED.flavor_to_TeX:\invalid_down_type_quark"
| U_K2_R 1 → "u^{\prime\prime_R}" | U_K2_R (-1) →
"\bar{u}^{\prime\prime_R}"
| U_K2_R 2 → "c^{\prime\prime_R}" | U_K2_R (-2) →
"\bar{c}^{\prime\prime_R}"
| U_K2_R 3 → "t^{\prime\prime_R}" | U_K2_R (-3) →
"\bar{t}^{\prime\prime_R}"
| U_K2_R _ → invalid_arg
      "Modellib_BSM.UED.flavor_to_TeX:\invalid_up_type_quark"
| D_K2_R 1 → "d^{\prime\prime_R}" | D_K2_R (-1) → "\bar{d}^{\prime\prime_R}"
| D_K2_R 2 → "s^{\prime\prime_R}" | D_K2_R (-2) → "\bar{s}^{\prime\prime_R}"
| D_K2_R 3 → "b^{\prime\prime_R}" | D_K2_R (-3) → "\bar{b}^{\prime\prime_R}"
| D_K2_R _ → invalid_arg
      "Modellib_BSM.UED.flavor_to_TeX:\invalid_down_type_quark"
| L_K1_L 1 → "e_L^{\prime,-}" | L_K1_L (-1) → "\bar{e}_L^{\prime,+}"
| L_K1_L 2 → "\mu_L^{\prime,-}" | L_K1_L (-2) →
"\bar{\mu}_L^{\prime,+}"
| L_K1_L 3 → "\tau_L^{\prime,-}" | L_K1_L (-3) →
"\bar{\tau}_L^{\prime,+}"
| L_K1_L _ → invalid_arg
      "Modellib_BSM.UED.flavor_to_TeX:\invalid_lepton"
| L_K1_R 1 → "e_R^{\prime,-}" | L_K1_R (-1) →
"\bar{e}_R^{\prime,+}"
| L_K1_R 2 → "\mu_R^{\prime,-}" | L_K1_R (-2) →
"\bar{\mu}_R^{\prime,+}"
| L_K1_R 3 → "\tau_R^{\prime,-}" | L_K1_R (-3) →
"\bar{\tau}_R^{\prime,+}"
| L_K1_R _ → invalid_arg
      "Modellib_BSM.UED.flavor_to_TeX:\invalid_lepton"
| L_K2_L 1 → "e^{\prime\prime,-}_L" | L_K2_L (-1) →

```

```

"\bar{e}_L^{\prime\prime}"
| L_K2_L2 → "\mu_L^{\prime\prime}" | L_K2_L(-2) →
"\bar{\mu}_L^{\prime\prime}"
| L_K2_L3 → "\tau_L^{\prime\prime}" | L_K2_L(-3) →
"\bar{\tau}_L^{\prime\prime}"
| L_K2_L_ → invalid_arg
"Modellib_BSM.UED.flavor_to_TeX:\invalid_\lepton"
| L_K2_R1 → "e_R^{\prime\prime}" | L_K2_R(-1) →
"\bar{e}_R^{\prime\prime}"
| L_K2_R2 → "\mu_R^{\prime\prime}" | L_K2_R(-2) →
"\bar{\mu}_R^{\prime\prime}"
| L_K2_R3 → "\tau_R^{\prime\prime}" | L_K2_R(-3) →
"\bar{\tau}_R^{\prime\prime}"
| L_K2_R_ → invalid_arg
"Modellib_BSM.UED.flavor_to_TeX:\invalid_\lepton"
| N_K1_1 → "\nu_e^{\prime\prime}" | N_K1(-1) → "\bar{\nu}_e^{\prime\prime}"
| N_K1_2 → "\nu_\mu^{\prime\prime}" | N_K1(-2) → "\bar{\nu}_\mu^{\prime\prime}"
| N_K1_3 → "\nu_\tau^{\prime\prime}" | N_K1(-3) → "\bar{\nu}_\tau^{\prime\prime}"
| N_K1_ → invalid_arg
"Modellib_BSM.UED.flavor_to_TeX:\invalid_\neutrino"
| N_K2_1 → "\nu_e^{\prime\prime\prime}" | N_K2(-1) →
"\bar{\nu}_e^{\prime\prime\prime}"
| N_K2_2 → "\nu_\mu^{\prime\prime\prime}" | N_K2(-2) →
"\bar{\nu}_\mu^{\prime\prime\prime}"
| N_K2_3 → "\nu_\tau^{\prime\prime\prime}" | N_K2(-3) →
"\bar{\nu}_\tau^{\prime\prime\prime}"
| N_K2_ → invalid_arg
"Modellib_BSM.UED.flavor_to_TeX:\invalid_\neutrino"
end
| G f →
begin match f with
| Gl → "g"
| Ga → "\gamma" | Z → "Z"
| Wp → "W^+" | Wm → "W^- "
| Gl_K1 → "g^{\prime\prime}" | Gl_K2 → "g^{\prime\prime\prime}"
| B1 → "B^{\prime\prime}" | B2 → "B^{\prime\prime\prime}"
| Z1 → "Z^{\prime\prime}" | Z2 → "Z^{\prime\prime\prime}"
| Wp1 → "W^{\prime\prime,+}" | Wm1 → "W^{\prime\prime,-}"
| Wp2 → "W^{\prime\prime\prime,+}" | Wm2 → "W^{\prime\prime\prime,-}"
end
| O f →
begin match f with
| Phip → "\phi^+" | Phim → "\phi^- " | Phi0 →
"\phi^0"
| H → "H" | H1up → "H1u+" | H1um → "H1u-"
| H1dp → "H1d+" | H1dm → "H1d-"
| H2up → "H2u+" | H2um → "H2u-"
| H2dp → "H2d+" | H2dm → "H2d-"
| Grav → "G^{\prime\prime}"
end

```

```

let flavor_symbol = function
| M f →
  begin match f with
  | L n when n > 0 → "l" ^ string_of_int n
  | L n → "l" ^ string_of_int (abs n) ^ "b"
  | N n when n > 0 → "n" ^ string_of_int n
  | N n → "n" ^ string_of_int (abs n) ^ "b"
  | U n when n > 0 → "u" ^ string_of_int n
  | U n → "u" ^ string_of_int (abs n) ^ "b"
  | D n when n > 0 → "d" ^ string_of_int n
  | D n → "d" ^ string_of_int (abs n) ^ "b"
  | L_K1_L n when n > 0 → "lk1l" ^ string_of_int n
  | L_K1_L n → "lk1l" ^ string_of_int (abs n) ^ "b"
  | L_K1_R n when n > 0 → "lk1r" ^ string_of_int n
  | L_K1_R n → "lk1r" ^ string_of_int (abs n) ^ "b"
  | L_K2_L n when n > 0 → "lk2l" ^ string_of_int n
  | L_K2_L n → "lk2l" ^ string_of_int (abs n) ^ "b"
  | L_K2_R n when n > 0 → "lk2r" ^ string_of_int n
  | L_K2_R n → "lk2r" ^ string_of_int (abs n) ^ "b"
  | U_K1_L n when n > 0 → "uk1l" ^ string_of_int n
  | U_K1_L n → "uk1l" ^ string_of_int (abs n) ^ "b"
  | U_K1_R n when n > 0 → "uk1r" ^ string_of_int n
  | U_K1_R n → "uk1r" ^ string_of_int (abs n) ^ "b"
  | U_K2_L n when n > 0 → "uk2l" ^ string_of_int n
  | U_K2_L n → "uk2l" ^ string_of_int (abs n) ^ "b"
  | U_K2_R n when n > 0 → "uk2r" ^ string_of_int n
  | U_K2_R n → "uk2r" ^ string_of_int (abs n) ^ "b"
  | D_K1_L n when n > 0 → "dk1l" ^ string_of_int n
  | D_K1_L n → "dk1l" ^ string_of_int (abs n) ^ "b"
  | D_K1_R n when n > 0 → "dk1r" ^ string_of_int n
  | D_K1_R n → "dk1r" ^ string_of_int (abs n) ^ "b"
  | D_K2_L n when n > 0 → "dk2l" ^ string_of_int n
  | D_K2_L n → "dk2l" ^ string_of_int (abs n) ^ "b"
  | D_K2_R n when n > 0 → "dk2r" ^ string_of_int n
  | D_K2_R n → "dk2r" ^ string_of_int (abs n) ^ "b"
  | N_K1 n when n > 0 → "nk1" ^ string_of_int n
  | N_K1 n → "nk1" ^ string_of_int (abs n) ^ "b"
  | N_K2 n when n > 0 → "nk2" ^ string_of_int n
  | N_K2 n → "nk2" ^ string_of_int (abs n) ^ "b"
  end
| G f →
  begin match f with
  | Gl → "g1"
  | Ga → "a" | Z → "z"
  | Wp → "wp" | Wm → "wm"
  | Gl_K1 → "gk1" | Gl_K2 → "gk2"
  | B1 → "b1" | B2 → "b2" | Z1 → "z1" | Z2 → "z2"
  | Wp1 → "wp1" | Wm1 → "wm1"
  | Wp2 → "wp2" | Wm2 → "wm2"
  end

```

```

|  $O f \rightarrow$ 
  begin match  $f$  with
  |  $Phip \rightarrow "pp"$  |  $Phim \rightarrow "pm"$  |  $Phi0 \rightarrow "p0"$ 
  |  $H \rightarrow "h"$  |  $H1up \rightarrow "h1up"$  |  $H1um \rightarrow "h1um"$ 
  |  $H1dp \rightarrow "h1dp"$  |  $H1dm \rightarrow "h1dm"$ 
  |  $H2up \rightarrow "h2up"$  |  $H2um \rightarrow "h2um"$ 
  |  $H2dp \rightarrow "h2dp"$  |  $H2dm \rightarrow "h2dm"$ 
  |  $Grav \rightarrow "gv"$ 
  end

let  $pdg =$  function
|  $M f \rightarrow$ 
  begin match  $f$  with
  |  $L n$  when  $n > 0 \rightarrow 9 + 2 \times n$ 
  |  $L n \rightarrow -9 + 2 \times n$ 
  |  $N n$  when  $n > 0 \rightarrow 10 + 2 \times n$ 
  |  $N n \rightarrow -10 + 2 \times n$ 
  |  $U n$  when  $n > 0 \rightarrow 2 \times n$ 
  |  $U n \rightarrow 2 \times n$ 
  |  $D n$  when  $n > 0 \rightarrow -1 + 2 \times n$ 
  |  $D n \rightarrow 1 + 2 \times n$ 
  |  $U\_K1\_L n$  when  $n > 0 \rightarrow 4000000 + 2 \times n$ 
  |  $U\_K1\_L n \rightarrow -4000000 + 2 \times n$ 
  |  $D\_K1\_L n$  when  $n > 0 \rightarrow 3999999 + 2 \times n$ 
  |  $D\_K1\_L n \rightarrow -3999999 + 2 \times n$ 
  |  $U\_K1\_R n$  when  $n > 0 \rightarrow 5000000 + 2 \times n$ 
  |  $U\_K1\_R n \rightarrow -5000000 + 2 \times n$ 
  |  $D\_K1\_R n$  when  $n > 0 \rightarrow 4999999 + 2 \times n$ 
  |  $D\_K1\_R n \rightarrow -4999999 + 2 \times n$ 
  |  $U\_K2\_L n$  when  $n > 0 \rightarrow 6000000 + 2 \times n$ 
  |  $U\_K2\_L n \rightarrow -6000000 + 2 \times n$ 
  |  $D\_K2\_L n$  when  $n > 0 \rightarrow 5999999 + 2 \times n$ 
  |  $D\_K2\_L n \rightarrow -5999999 + 2 \times n$ 
  |  $U\_K2\_R n$  when  $n > 7000000 \rightarrow 2 \times n$ 
  |  $U\_K2\_R n \rightarrow -7000000 + 2 \times n$ 
  |  $D\_K2\_R n$  when  $n > 0 \rightarrow 6999999 + 2 \times n$ 
  |  $D\_K2\_R n \rightarrow -6999999 + 2 \times n$ 
  |  $L\_K1\_L n$  when  $n > 0 \rightarrow 4000009 + 2 \times n$ 
  |  $L\_K1\_L n \rightarrow -4000009 + 2 \times n$ 
  |  $L\_K1\_R n$  when  $n > 0 \rightarrow 5000009 + 2 \times n$ 
  |  $L\_K1\_R n \rightarrow -5000009 + 2 \times n$ 
  |  $L\_K2\_L n$  when  $n > 0 \rightarrow 6000009 + 2 \times n$ 
  |  $L\_K2\_L n \rightarrow -6000009 + 2 \times n$ 
  |  $L\_K2\_R n$  when  $n > 0 \rightarrow 7000009 + 2 \times n$ 
  |  $L\_K2\_R n \rightarrow -7000009 + 2 \times n$ 
  |  $N\_K1 n$  when  $n > 0 \rightarrow 4000010 + 2 \times n$ 
  |  $N\_K1 n \rightarrow -4000010 + 2 \times n$ 
  |  $N\_K2 n$  when  $n > 0 \rightarrow 6000010 + 2 \times n$ 
  |  $N\_K2 n \rightarrow -6000010 + 2 \times n$ 
  end

```

```

| G f →
  begin match f with
  | Gl → 21
  | Ga → 22 | Z → 23
  | Wp → 24 | Wm → (-24)
  | Gl_K1 → 4000021 | Gl_K2 → 6000021
  | B1 → 4000022 | B2 → 6000022
  | Z1 → 4000023 | Z2 → 6000024
  | Wp1 → 4000024 | Wm1 → (-4000024)
  | Wp2 → 6000024 | Wm2 → (-6000024)
  end
| O f →
  begin match f with
  | Phip | Phim → 27 | Phi0 → 26
  | H → 25 | H1up → 4000036 | H1um → (-4000036)
  | H1dp → 4000037 | H1dm → (-4000037)
  | H2up → 6000036 | H2um → (-6000036)
  | H2dp → 6000037 | H2dm → (-6000037)
  | Grav → 39
  end

let mass_symbol f =
  "mass(" ^ string_of_int (abs (pdg f)) ^ ")"

let width_symbol f =
  "width(" ^ string_of_int (abs (pdg f)) ^ ")"

let constant_symbol = function
| Unit → "unit" | Pi → "PI"
| Alpha_QED → "alpha" | E → "e" | G_weak → "g" | Vev →
"vev"
| Sin2thw → "sin2thw" | Sinthw → "sinthw" | Costhw →
"costhw"
| Q_lepton → "qllep" | Q_up → "qup" | Q_down → "qdown"
| G_NC_lepton → "gnclep" | G_NC_neutrino → "gncneu"
| G_NC_up → "gncup" | G_NC_down → "gncdown"
| G_CC → "gcc"
| G_CCQ (n1, n2) → "gccq" ^ string_of_int n1 ^ string_of_int n2
| I_Q_W → "iqw" | I_G_ZWW → "igzww"
| I_Q_W_K → "iqwk" | I_G_ZWW_K1 → "igzwwk1"
| I_G_ZWW_K2 → "igzwwk2" | I_G_ZWW_K3 → "igzwwk3"
| G_WWWW → "gw4" | G_ZZWW → "gzzww"
| G_AZWW → "gazww" | G_AAWW → "gaaww"
| G_HWW → "ghww" | G_HZZ → "ghzz"
| G_HHWW → "ghhww" | G_HHZZ → "ghhzz"
| G_Htt → "ghtt" | G_Hbb → "ghbb"
| G_Htautau → "ghtautau" | G_Hcc → "ghcc"
| G_HGaZ → "ghgaz" | G_HGaGa → "ghgaga" | G_Hgg →
"ghgg"
| G_H3 → "gh3" | G_H4 → "gh4"
| G2 → "gs**2" | Gs → "gs" | I_Gs → "igs" | I_GsRt2 →
"igs/sqrt(2.0-default)"

```

```

|  $G_{22} \rightarrow "gs**2/2.0\_default"$ 
|  $G\_Grav \rightarrow "ggrav"$ 
|  $Mass\ f \rightarrow "mass" \wedge flavor\_symbol\ f$ 
|  $Width\ f \rightarrow "width" \wedge flavor\_symbol\ f$ 
end

module GravTest (Flags : BSM_flags) =
struct
  let rcs = RCS.rename rcs_file "Modellib_BSM.GravTest"
    [ "Testing_of_Gravitinos" ]

  open Coupling

  let default_width = ref Timelike
  let use_fudged_width = ref false

  let options = Options.create
    [ "constant_width", Arg.Unit (fun ()  $\rightarrow$  default_width := Constant),
      "use_constant_width(also_in_t-channel)";
      "fudged_width", Arg.Set use_fudged_width,
      "use_fudge_factor_for_charge_particle_width";
      "custom_width", Arg.String (fun f  $\rightarrow$  default_width := Custom f),
      "use_custom_width";
      "cancel_widths", Arg.Unit (fun ()  $\rightarrow$  default_width := Vanishing),
      "use_vanishing_width" ]

  type matter_field = L of int | N of int | U of int | D of int | SL of int
  type gauge_boson = Ga | Wp | Wm | Z | Gl | Phino
  type other = Phip | Phim | Phi0 | H | Grino
  type flavor = M of matter_field | G of gauge_boson | O of other

  let matter_field f = M f
  let gauge_boson f = G f
  let other f = O f

  type field =
  | Matter of matter_field
  | Gauge of gauge_boson
  | Other of other

  let field = function
  | M f  $\rightarrow$  Matter f
  | G f  $\rightarrow$  Gauge f
  | O f  $\rightarrow$  Other f

  type gauge = unit

  let gauge_symbol () =
    failwith "Modellib_BSM.SM.gauge_symbol: internal error"

  let family n = List.map matter_field [ L n; SL n; N n; U n; D n ]

  let external_flavors () =
    [ "1st_Generation", ThoList.flatmap family [1; -1];
      "2nd_Generation", ThoList.flatmap family [2; -2];
      "3rd_Generation", ThoList.flatmap family [3; -3];

```

```

    "Gauge_Bosons", List.map gauge_boson [Ga; Z; Wp; Wm; Gl; Phino];
    "Higgs", List.map other [H];
    "Gravitino", List.map other [Grino];
    "Goldstone_Bosons", List.map other [Phip; Phim; Phi0] ]

let flavors () = ThoList.flatmap snd (external_flavors ())

let spinor n =
  if n ≥ 0 then
    Spinor
  else
    ConjSpinor

let lorentz = function
| M f →
  begin match f with
  | L n → spinor n | N n → spinor n
  | U n → spinor n | D n → spinor n
  | SL _ → Scalar
  end
| G f →
  begin match f with
  | Ga | Gl → Vector
  | Wp | Wm | Z → Massive_Vector
  | Phino → Majorana
  end
| O f →
  begin match f with
  | Grino → Vectorspinor
  | _ → Scalar
  end

let color = function
| M (U n) → Color.SUN (if n > 0 then 3 else -3)
| M (D n) → Color.SUN (if n > 0 then 3 else -3)
| G Gl → Color.AdjSUN 3
| _ → Color.Singlet

let prop_spinor n =
  if n ≥ 0 then
    Prop_Spinor
  else
    Prop_ConjSpinor

let propagator = function
| M f →
  begin match f with
  | L n → prop_spinor n | N n → prop_spinor n
  | U n → prop_spinor n | D n → prop_spinor n
  | SL n → Prop_Scalar
  end
| G f →
  begin match f with

```

```

| Ga | Gl → Prop_Feynman
| Wp | Wm | Z → Prop_Unitarity
| Phino → Prop_Majorana
end
| O f →
  begin match f with
  | Phip | Phim | Phi0 → Only_Insertion
  | H → Prop_Scalar
  | Grino → Prop_Vectorspinor
  end

```

Optionally, ask for the fudge factor treatment for the widths of charged particles. Currently, this only applies to  $W^\pm$  and top.

```

let width f =
  if !use_fudged_width then
    match f with
    | G Wp | G Wm | M (U 3) | M (U (-3)) | O Grino → Fudged
    | _ → !default_width
  else
    !default_width
let goldstone = function
| G f →
  begin match f with
  | Wp → Some (O Phip, Coupling.Const 1)
  | Wm → Some (O Phim, Coupling.Const 1)
  | Z → Some (O Phi0, Coupling.Const 1)
  | _ → None
  end
| _ → None
let conjugate = function
| M f →
  M (begin match f with
  | L n → L (-n) | N n → N (-n)
  | U n → U (-n) | D n → D (-n)
  | SL n → SL (-n)
  end)
| G f →
  G (begin match f with
  | Gl → Gl | Ga → Ga | Z → Z
  | Wp → Wm | Wm → Wp | Phino → Phino
  end)
| O f →
  O (begin match f with
  | Phip → Phim | Phim → Phip | Phi0 → Phi0
  | H → H | Grino → Grino
  end)
let fermion = function
| M f →
  begin match f with

```



```

|  $L\ n \rightarrow \text{if } n > 0 \text{ then } 1 \text{ else } -1$ 
|  $N\ n \rightarrow \text{if } n > 0 \text{ then } 1 \text{ else } -1$ 
|  $U\ n \rightarrow \text{if } n > 0 \text{ then } 1 \text{ else } -1$ 
|  $D\ n \rightarrow \text{if } n > 0 \text{ then } 1 \text{ else } -1$ 
|  $SL\ - \rightarrow 0$ 
end
|  $G\ f \rightarrow$ 
  begin match  $f$  with
  |  $Gl\ |\ Ga\ |\ Z\ |\ Wp\ |\ Wm \rightarrow 0$ 
  |  $Phino \rightarrow 2$ 
  end
|  $O\ f \rightarrow$ 
  begin match  $f$  with
  |  $Grino \rightarrow 2$ 
  |  $- \rightarrow 0$ 
  end

module  $Ch = Charges.QQ$ 
let (  $//$  ) = Algebra.Small-Rational.make

let  $generation'$  = function
| 1  $\rightarrow [1//1; 0//1; 0//1]$ 
| 2  $\rightarrow [0//1; 1//1; 0//1]$ 
| 3  $\rightarrow [0//1; 0//1; 1//1]$ 
| -1  $\rightarrow [-1//1; 0//1; 0//1]$ 
| -2  $\rightarrow [0//1; -1//1; 0//1]$ 
| -3  $\rightarrow [0//1; 0//1; -1//1]$ 
|  $n \rightarrow \text{invalid\_arg } ("SM3.generation':\square" ^ \text{string\_of\_int } n)$ 

let  $generation\ f =$ 
  match  $f$  with
  |  $M\ (L\ n\ |\ N\ n\ |\ U\ n\ |\ D\ n\ |\ SL\ n) \rightarrow generation'\ n$ 
  |  $G\ -\ |\ O\ - \rightarrow [0//1; 0//1; 0//1]$ 

let  $charge =$  function
|  $M\ f \rightarrow$ 
  begin match  $f$  with
  |  $L\ n \rightarrow \text{if } n > 0 \text{ then } -1//1 \text{ else } 1//1$ 
  |  $SL\ n \rightarrow \text{if } n > 0 \text{ then } -1//1 \text{ else } 1//1$ 
  |  $N\ n \rightarrow 0//1$ 
  |  $U\ n \rightarrow \text{if } n > 0 \text{ then } 2//3 \text{ else } -2//3$ 
  |  $D\ n \rightarrow \text{if } n > 0 \text{ then } -1//3 \text{ else } 1//3$ 
  end
|  $G\ f \rightarrow$ 
  begin match  $f$  with
  |  $Gl\ |\ Ga\ |\ Z\ |\ Phino \rightarrow 0//1$ 
  |  $Wp \rightarrow 1//1$ 
  |  $Wm \rightarrow -1//1$ 
  end
|  $O\ f \rightarrow$ 
  begin match  $f$  with
  |  $H\ |\ Phi0\ |\ Grino \rightarrow 0//1$ 

```

```

    | Phip → 1//1
    | Phim → -1//1
  end

let lepton = function
  | M f →
    begin match f with
      | L n | N n | SL n → if n > 0 then 1//1 else -1//1
      | U - | D - → 0//1
    end
  | G - | O - → 0//1

let baryon = function
  | M f →
    begin match f with
      | L - | N - | SL - → 0//1
      | U n | D n → if n > 0 then 1//1 else -1//1
    end
  | G - | O - → 0//1

let charges f =
  [ charge f; lepton f; baryon f ] @ generation f

type constant =
  | Unit | Pi | Alpha_QED | Sin2thw
  | Sinthw | Costhw | E | G_weak | Vev
  | Q_lepton | Q_up | Q_down | G_CC | G_CCQ of int × int
  | G_NC_neutrino | G_NC_lepton | G_NC_up | G_NC_down
  | I_Q_W | I_G_ZWW
  | G_WWWW | G_ZZWW | G_AZWW | G_AAWW
  | G_HWW | G_HHWW | G_HZZ | G_HHZZ
  | G_Htt | G_Hbb | G_Hcc | G_Htautau | G_H3 | G_H4
  | G_HGaZ | G_HGaGa | G_Hgg
  | G_strong | G_Grav
  | Mass of flavor | Width of flavor

```

Two integer counters for the QCD and EW order of the couplings.

```

type orders = int × int

let orders = function
  | - → (0,0)

let input_parameters =
  []

let derived_parameters =
  []

let g_over_2_costh =
  Quot (Neg (Atom G_weak), Prod [Const 2; Atom Costhw])

let nc_coupling c t3 q =
  (Real_Array c,
   [Prod [g_over_2_costh; Diff (t3, Prod [Const 2; q; Atom Sin2thw])];
    Prod [g_over_2_costh; t3]])

```

```

let half = Quot (Const 1, Const 2)

let derived_parameter_arrays =
  [ nc_coupling G_NC_neutrino half (Const 0);
    nc_coupling G_NC_lepton (Neg half) (Const (-1));
    nc_coupling G_NC_up half (Quot (Const 2, Const 3));
    nc_coupling G_NC_down (Neg half) (Quot (Const (-1), Const 3)) ]

let parameters () =
  { input = input_parameters;
    derived = derived_parameters;
    derived_arrays = derived_parameter_arrays }

module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)

let mgm ((m1, g, m2), fbf, c) = ((M m1, G g, M m2), fbf, c)
let mom ((m1, o, m2), fbf, c) = ((M m1, O o, M m2), fbf, c)

let electromagnetic_currents n =
  List.map mgm
    [ ((L (-n), Ga, L n), FBF (1, Psibar, V, Psi), Q_lepton);
      ((U (-n), Ga, U n), FBF (1, Psibar, V, Psi), Q_up);
      ((D (-n), Ga, D n), FBF (1, Psibar, V, Psi), Q_down) ]

let neutral_currents n =
  List.map mgm
    [ ((L (-n), Z, L n), FBF (1, Psibar, VA, Psi), G_NC_lepton);
      ((N (-n), Z, N n), FBF (1, Psibar, VA, Psi), G_NC_neutrino);
      ((U (-n), Z, U n), FBF (1, Psibar, VA, Psi), G_NC_up);
      ((D (-n), Z, D n), FBF (1, Psibar, VA, Psi), G_NC_down) ]

let charged_currents n =
  List.map mgm
    [ ((L (-n), Wm, N n), FBF (1, Psibar, VL, Psi), G_CC);
      ((N (-n), Wp, L n), FBF (1, Psibar, VL, Psi), G_CC);
      ((D (-n), Wm, U n), FBF (1, Psibar, VL, Psi), G_CC);
      ((U (-n), Wp, D n), FBF (1, Psibar, VL, Psi), G_CC) ]

let yukawa =
  List.map mom
    [ ((U (-3), H, U 3), FBF (1, Psibar, S, Psi), G_Htt);
      ((D (-3), H, D 3), FBF (1, Psibar, S, Psi), G_Hbb);
      ((U (-2), H, U 2), FBF (1, Psibar, S, Psi), G_Hcc);
      ((L (-3), H, L 3), FBF (1, Psibar, S, Psi), G_Htautau) ]

let tgc ((g1, g2, g3), t, c) = ((G g1, G g2, G g3), t, c)

let standard_triple_gauge =
  List.map tgc
    [ ((Ga, Wm, Wp), Gauge_Gauge_Gauge 1, I-Q-W);

```

```

      ((Z, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_ZWW) ]
let triple_gauge =
  standard_triple_gauge
let qgc ((g1, g2, g3, g4), t, c) = ((G g1, G g2, G g3, G g4), t, c)
let gauge4 = Vector4 [(2, C_13_42); (-1, C_12_34); (-1, C_14_23)]
let minus_gauge4 = Vector4 [(-2, C_13_42); (1, C_12_34); (1, C_14_23)]
let standard_quartic_gauge =
  List.map qgc
    [ (Wm, Wp, Wm, Wp), gauge4, G_WWWW;
      (Wm, Z, Wp, Z), minus_gauge4, G_ZZWW;
      (Wm, Z, Wp, Ga), minus_gauge4, G_AZWW;
      (Wm, Ga, Wp, Ga), minus_gauge4, G_AAWW ]
let quartic_gauge =
  standard_quartic_gauge
let standard_gauge_higgs =
  [ ((O H, G Wp, G Wm), Scalar_Vector_Vector 1, G_HWW);
    ((O H, G Z, G Z), Scalar_Vector_Vector 1, G_HZZ) ]
let standard_gauge_higgs4 =
  [ (O H, O H, G Wp, G Wm), Scalar2_Vector2 1, G_HHWW;
    (O H, O H, G Z, G Z), Scalar2_Vector2 1, G_HHZZ ]
let standard_higgs =
  [ (O H, O H, O H), Scalar_Scalar_Scalar 1, G_H3 ]
let standard_higgs4 =
  [ (O H, O H, O H, O H), Scalar4 1, G_H4 ]
let anomalous_gauge_higgs =
  []
let anomalous_gauge_higgs4 =
  []
let anomalous_higgs =
  []
let anomaly_higgs =
  [ (O H, G Ga, G Ga), Dim5_Scalar_Gauge2 1, G_HGaGa;
    (O H, G Ga, G Z), Dim5_Scalar_Gauge2 1, G_HGaZ;
    (O H, G Gl, G Gl), Dim5_Scalar_Gauge2 1, G_Hgg ]
let gravitino_coup n =
  [ (O Grino, M (SL (-n)), M (L n)), GBG (1, Gravbar, POT, Psi), G_Grav;
    (M (L (-n)), M (SL n), O Grino), GBG (1, Psibar, POT, Grav), G_Grav ]
let gravitino_gauge =
  [ (O Grino, G Ga, G Phino), GBG (1, Gravbar, V, Chi), G_Grav ]
let anomalous_higgs4 =
  []
let gauge_higgs =

```

```

    standard_gauge_higgs
let gauge_higgs4 =
    standard_gauge_higgs4
let higgs =
    standard_higgs
let higgs4 =
    standard_higgs4
let goldstone_vertices =
[ ((O Phi0, G Wm, G Wp), Scalar_Vector_Vector 1, I-G-ZWW);
  ((O Phip, G Ga, G Wm), Scalar_Vector_Vector 1, I-Q-W);
  ((O Phip, G Z, G Wm), Scalar_Vector_Vector 1, I-G-ZWW);
  ((O Phim, G Wp, G Ga), Scalar_Vector_Vector 1, I-Q-W);
  ((O Phim, G Wp, G Z), Scalar_Vector_Vector 1, I-G-ZWW) ]
let vertices3 =
(ThoList.flatmap electromagnetic_currents [1;2;3] @
 ThoList.flatmap neutral_currents [1;2;3] @
 ThoList.flatmap charged_currents [1;2;3] @
 ThoList.flatmap gravitino_coup [1;2;3] @
 gravitino_gauge @
 yukawa @ triple_gauge @
 gauge_higgs @ higgs @ anomaly_higgs
 @ goldstone_vertices)
let vertices4 =
    quartic_gauge @ gauge_higgs4 @ higgs4
let vertices () = (vertices3, vertices4, [])

```

For efficiency, make sure that *F.of\_vertices vertices* is evaluated only once.

```

let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 4
let flavor_of_string = function
| "e-" → M (L 1) | "e+" → M (L (-1))
| "mu-" → M (L 2) | "mu+" → M (L (-2))
| "tau-" → M (L 3) | "tau+" → M (L (-3))
| "se-" → M (SL 1) | "se+" → M (SL (-1))
| "smu-" → M (SL 2) | "smu+" → M (SL (-2))
| "stau-" → M (SL 3) | "stau+" → M (SL (-3))
| "nue" → M (N 1) | "nuebar" → M (N (-1))
| "numu" → M (N 2) | "numubar" → M (N (-2))
| "nutau" → M (N 3) | "nutaubar" → M (N (-3))
| "u" → M (U 1) | "ubar" → M (U (-1))
| "c" → M (U 2) | "cbar" → M (U (-2))
| "t" → M (U 3) | "tbar" → M (U (-3))
| "d" → M (D 1) | "dbar" → M (D (-1))

```

```

| "s" → M (D 2) | "sbar" → M (D (-2))
| "b" → M (D 3) | "bbar" → M (D (-3))
| "g" | "gl" → G Gl
| "A" → G Ga | "Z" | "Z0" → G Z
| "W+" → G Wp | "W-" → G Wm
| "H" → O H
| "GG" → O Grino
| "phino" | "Phino" → G Phino
| - → invalid_arg "Modellib_BSM.GravTest.flavor_of_string"

let flavor_to_string = function
| M f →
  begin match f with
  | L 1 → "e-" | L (-1) → "e+"
  | L 2 → "mu-" | L (-2) → "mu+"
  | L 3 → "tau-" | L (-3) → "tau+"
  | L _ → invalid_arg
    "Modellib_BSM.GravTest.flavor_to_string:␣invalid␣lepton"
  | SL 1 → "se-" | SL (-1) → "se+"
  | SL 2 → "smu-" | SL (-2) → "smu+"
  | SL 3 → "stau-" | SL (-3) → "stau+"
  | SL _ → invalid_arg
    "Modellib_BSM.GravTest.flavor_to_string:␣invalid␣slepton"
  | N 1 → "nue" | N (-1) → "nuebar"
  | N 2 → "numu" | N (-2) → "numubar"
  | N 3 → "nutau" | N (-3) → "nutaubar"
  | N _ → invalid_arg
    "Modellib_BSM.GravTest.flavor_to_string:␣invalid␣neutrino"
  | U 1 → "u" | U (-1) → "ubar"
  | U 2 → "c" | U (-2) → "cbar"
  | U 3 → "t" | U (-3) → "tbar"
  | U _ → invalid_arg
    "Modellib_BSM.SM.flavor_to_string:␣invalid␣up␣type␣quark"
  | D 1 → "d" | D (-1) → "dbar"
  | D 2 → "s" | D (-2) → "sbar"
  | D 3 → "b" | D (-3) → "bbar"
  | D _ → invalid_arg
    "Modellib_BSM.GravTest.flavor_to_string:␣invalid␣down␣type␣quark"
  end
| G f →
  begin match f with
  | Gl → "g"
  | Ga → "A" | Z → "Z"
  | Wp → "W+" | Wm → "W-"
  | Phino → "phino"
  end
| O f →
  begin match f with
  | Phip → "phi+" | Phim → "phi-" | Phi0 → "phi0"
  | H → "H" | Grino → "GG"

```

```

end

let flavor_to_TeX = function
| M f →
  begin match f with
  | L 1 → "e^-" | L (-1) → "e^+"
  | L 2 → "\\mu^- " | L (-2) → "\\mu^+"
  | L 3 → "\\tau^- " | L (-3) → "\\tau^+"
  | L _ → invalid_arg
    "Modellib_BSM.GravTest.flavor_to_TeX:␣invalid␣lepton"
  | SL 1 → "\\tilde{e}^- " | SL (-1) → "\\tilde{e}^+"
  | SL 2 → "\\tilde{\\mu}^- " | SL (-2) → "\\tilde{\\mu}^+"
  | SL 3 → "\\tilde{\\tau}^- " | SL (-3) → "\\tilde{\\tau}^+"
  | SL _ → invalid_arg
    "Modellib_BSM.GravTest.flavor_to_TeX:␣invalid␣slepton"
  | N 1 → "\\nu_e " | N (-1) → "\\bar{\\nu}_e"
  | N 2 → "\\nu_\\mu " | N (-2) → "\\bar{\\nu}_\\mu"
  | N 3 → "\\nu_\\tau " | N (-3) → "\\bar{\\nu}_\\tau"
  | N _ → invalid_arg
    "Modellib_BSM.GravTest.flavor_to_TeX:␣invalid␣neutrino"
  | U 1 → "u" | U (-1) → "\\bar{u}"
  | U 2 → "c" | U (-2) → "\\bar{c}"
  | U 3 → "t" | U (-3) → "\\bar{t}"
  | U _ → invalid_arg
    "Modellib_BSM.SM.flavor_to_TeX:␣invalid␣up␣type␣quark"
  | D 1 → "d" | D (-1) → "\\bar{d}"
  | D 2 → "s" | D (-2) → "\\bar{s}"
  | D 3 → "b" | D (-3) → "\\bar{b}"
  | D _ → invalid_arg
    "Modellib_BSM.GravTest.flavor_to_TeX:␣invalid␣down␣type␣quark"
  end
| G f →
  begin match f with
  | Gl → "g"
  | Ga → "\\gamma" | Z → "Z"
  | Wp → "W^+" | Wm → "W^- "
  | Phino → "\\tilde{\\phi}"
  end
| O f →
  begin match f with
  | Phip → "\\phi^+" | Phim → "\\phi^- " | Phi0 →
    "\\phi^0"
  | H → "H" | Grino → "\\tilde{G}"
  end
end

let flavor_symbol = function
| M f →
  begin match f with
  | L n when n > 0 → "l" ^ string_of_int n
  | L n → "l" ^ string_of_int (abs n) ^ "b"
  | SL n when n > 0 → "sl" ^ string_of_int n

```

```

|  $SL\ n \rightarrow "s1" \wedge string\_of\_int\ (abs\ n) \wedge "b"$ 
|  $N\ n\ \text{when } n > 0 \rightarrow "n" \wedge string\_of\_int\ n$ 
|  $N\ n \rightarrow "n" \wedge string\_of\_int\ (abs\ n) \wedge "b"$ 
|  $U\ n\ \text{when } n > 0 \rightarrow "u" \wedge string\_of\_int\ n$ 
|  $U\ n \rightarrow "u" \wedge string\_of\_int\ (abs\ n) \wedge "b"$ 
|  $D\ n\ \text{when } n > 0 \rightarrow "d" \wedge string\_of\_int\ n$ 
|  $D\ n \rightarrow "d" \wedge string\_of\_int\ (abs\ n) \wedge "b"$ 
end
|  $G\ f \rightarrow$ 
begin match  $f$  with
|  $Gl \rightarrow "g1"$ 
|  $Ga \rightarrow "a" \mid Z \rightarrow "z"$ 
|  $Wp \rightarrow "wp" \mid Wm \rightarrow "wm"$ 
|  $Phino \rightarrow "phino"$ 
end
|  $O\ f \rightarrow$ 
begin match  $f$  with
|  $Phip \rightarrow "pp" \mid Phim \rightarrow "pm" \mid Phi0 \rightarrow "p0"$ 
|  $H \rightarrow "h" \mid Grino \rightarrow "gv"$ 
end
let  $pdg = \text{function}$ 
|  $M\ f \rightarrow$ 
begin match  $f$  with
|  $L\ n\ \text{when } n > 0 \rightarrow 9 + 2 \times n$ 
|  $L\ n \rightarrow -9 + 2 \times n$ 
|  $SL\ n\ \text{when } n > 0 \rightarrow 39 + 2 \times n$ 
|  $SL\ n \rightarrow -39 + 2 \times n$ 
|  $N\ n\ \text{when } n > 0 \rightarrow 10 + 2 \times n$ 
|  $N\ n \rightarrow -10 + 2 \times n$ 
|  $U\ n\ \text{when } n > 0 \rightarrow 2 \times n$ 
|  $U\ n \rightarrow 2 \times n$ 
|  $D\ n\ \text{when } n > 0 \rightarrow -1 + 2 \times n$ 
|  $D\ n \rightarrow 1 + 2 \times n$ 
end
|  $G\ f \rightarrow$ 
begin match  $f$  with
|  $Gl \rightarrow 21$ 
|  $Ga \rightarrow 22 \mid Z \rightarrow 23$ 
|  $Wp \rightarrow 24 \mid Wm \rightarrow (-24)$ 
|  $Phino \rightarrow 46$ 
end
|  $O\ f \rightarrow$ 
begin match  $f$  with
|  $Phip \mid Phim \rightarrow 27 \mid Phi0 \rightarrow 26$ 
|  $H \rightarrow 25 \mid Grino \rightarrow 39$ 
end
let  $mass\_symbol\ f =$ 
 $"mass(" \wedge string\_of\_int\ (abs\ (pdg\ f)) \wedge ")"$ 

```



```

let width_symbol f =
  "width(" ^ string_of_int (abs (pdg f)) ^ ")"

let constant_symbol = function
| Unit → "unit" | Pi → "PI"
| Alpha_QED → "alpha" | E → "e" | G_weak → "g" | Vev →
"vev"
| Sin2thw → "sin2thw" | Sinthw → "sinthw" | Costhw →
"costhw"
| Q_lepton → "qlep" | Q_up → "qup" | Q_down → "qdown"
| G_NC_lepton → "gnclep" | G_NC_neutrino → "gncneu"
| G_NC_up → "gncup" | G_NC_down → "gncdown"
| G_CC → "gcc"
| G_CCQ (n1, n2) → "gccq" ^ string_of_int n1 ^ string_of_int n2
| I_Q_W → "iqw" | I_G_ZWW → "igzww"
| G_WWWW → "gw4" | G_ZZWW → "gzzww"
| G_AZWW → "gazww" | G_AAWW → "gaaww"
| G_HWW → "ghww" | G_HZZ → "ghzz"
| G_HHWW → "ghhww" | G_HHZZ → "ghhzz"
| G_Htt → "ghtt" | G_Hbb → "ghbb"
| G_Htautau → "ghtautau" | G_Hcc → "ghcc"
| G_HGaZ → "ghgaz" | G_HGaGa → "ghgaga" | G_Hgg →
"ghgg"
| G_H3 → "gh3" | G_H4 → "gh4"
| G_strong → "gs" | G_Grav → "ggrav"
| Mass f → "mass" ^ flavor_symbol f
| Width f → "width" ^ flavor_symbol f

end

module Template (Flags : BSM_flags) =
struct
  let rcs = RCS.rename rcs_file "Modellib_BSM.Template"
    ["Template_for_user-defined_BSM_model"]

  open Coupling

  let default_width = ref Timelike
  let use_fudged_width = ref false

  let options = Options.create
    ["constant_width", Arg.Unit (fun () → default_width := Constant),
      "use_constant_width_(also_in_t-channel)";
      "fudged_width", Arg.Set use_fudged_width,
      "use_fudge_factor_for_charge_particle_width";
      "custom_width", Arg.String (fun f → default_width := Custom f),
      "use_custom_width";
      "cancel_widths", Arg.Unit (fun () → default_width := Vanishing),
      "use_vanishing_width"]

  type matter_field = L of int | N of int | U of int | D of int
  type gauge_boson = Ga | Wp | Wm | Z | Gl
  type other = Phip | Phim | Phi0 | H
  type flavor = M of matter_field | G of gauge_boson | O of other

```

---

```

let matter_field f = M f
let gauge_boson f = G f
let other f = O f

type field =
  | Matter of matter_field
  | Gauge of gauge_boson
  | Other of other

let field = function
  | M f → Matter f
  | G f → Gauge f
  | O f → Other f

type gauge = unit

let gauge_symbol () =
  failwith "Modellib_BSM.Template.gauge_symbol: internal error"

let family n = List.map matter_field [ L n; N n; U n; D n ]

let external_flavors () =
  [ "1st_Generation", ThoList.flatmap family [1; -1];
    "2nd_Generation", ThoList.flatmap family [2; -2];
    "3rd_Generation", ThoList.flatmap family [3; -3];
    "Gauge_Bosons", List.map gauge_boson [Ga; Z; Wp; Wm; Gl];
    "Higgs", List.map other [H];
    "Goldstone_Bosons", List.map other [Phip; Phim; Phi0] ]

let flavors () = ThoList.flatmap snd (external_flavors ())

let spinor n =
  if n ≥ 0 then
    Spinor
  else
    ConjSpinor

let lorentz = function
  | M f →
    begin match f with
    | L n → spinor n | N n → spinor n
    | U n → spinor n | D n → spinor n
    end
  | G f →
    begin match f with
    | Ga | Gl → Vector
    | Wp | Wm | Z → Massive_Vector
    end
  | O f → Scalar

let color = function
  | M (U n) → Color.SUN (if n > 0 then 3 else -3)
  | M (D n) → Color.SUN (if n > 0 then 3 else -3)
  | G Gl → Color.AdjSUN 3
  | - → Color.Singlet

```

```

let prop_spinor n =
  if n ≥ 0 then
    Prop_Spinor
  else
    Prop_ConjSpinor
let propagator = function
| M f →
  begin match f with
  | L n → prop_spinor n | N n → prop_spinor n
  | U n → prop_spinor n | D n → prop_spinor n
  end
| G f →
  begin match f with
  | Ga | Gl → Prop_Feynman
  | Wp | Wm | Z → Prop_Unitarity
  end
| O f →
  begin match f with
  | Phip | Phim | Phi0 → Only_Insertion
  | H → Prop_Scalar
  end

```

Optionally, ask for the fudge factor treatment for the widths of charged particles. Currently, this only applies to  $W^\pm$  and top.

```

let width f =
  if !use_fudged_width then
    match f with
    | G Wp | G Wm | M (U 3) | M (U (-3)) → Fudged
    | _ → !default_width
  else
    !default_width
let goldstone = function
| G f →
  begin match f with
  | Wp → Some (O Phip, Coupling.Const 1)
  | Wm → Some (O Phim, Coupling.Const 1)
  | Z → Some (O Phi0, Coupling.Const 1)
  | _ → None
  end
| _ → None
let conjugate = function
| M f →
  M (begin match f with
  | L n → L (-n) | N n → N (-n)
  | U n → U (-n) | D n → D (-n)
  end)
| G f →
  G (begin match f with
  | Gl → Gl | Ga → Ga | Z → Z

```

```

      |  $Wp \rightarrow Wm \mid Wm \rightarrow Wp$ 
    end)
  |  $O f \rightarrow$ 
     $O$  (begin match  $f$  with
      |  $Phip \rightarrow Phim \mid Phim \rightarrow Phip \mid Phi0 \rightarrow Phi0$ 
      |  $H \rightarrow H$ 
    end)

let fermion = function
  |  $M f \rightarrow$ 
    begin match  $f$  with
      |  $L n \rightarrow$  if  $n > 0$  then 1 else -1
      |  $N n \rightarrow$  if  $n > 0$  then 1 else -1
      |  $U n \rightarrow$  if  $n > 0$  then 1 else -1
      |  $D n \rightarrow$  if  $n > 0$  then 1 else -1
    end
  |  $G f \rightarrow$ 
    begin match  $f$  with
      |  $Gl \mid Ga \mid Z \mid Wp \mid Wm \rightarrow 0$ 
    end
  |  $O _ \rightarrow 0$ 

module Ch = Charges.QQ

let ( // ) = Algebra.Small_Rational.make

let generation' = function
  | 1  $\rightarrow$  [ 1//1; 0//1; 0//1 ]
  | 2  $\rightarrow$  [ 0//1; 1//1; 0//1 ]
  | 3  $\rightarrow$  [ 0//1; 0//1; 1//1 ]
  | -1  $\rightarrow$  [-1//1; 0//1; 0//1 ]
  | -2  $\rightarrow$  [ 0//1; -1//1; 0//1 ]
  | -3  $\rightarrow$  [ 0//1; 0//1; -1//1 ]
  |  $n \rightarrow$  invalid_arg ("Template.generation': $\square$ " ^ string_of_int  $n$ )

let generation f =
  match  $f$  with
  |  $M (L n \mid N n \mid U n \mid D n) \rightarrow$  generation' n
  |  $G _ \mid O _ \rightarrow$  [0//1; 0//1; 0//1]

let charge = function
  |  $M f \rightarrow$ 
    begin match  $f$  with
      |  $L n \rightarrow$  if  $n > 0$  then -1//1 else 1//1
      |  $N n \rightarrow$  0//1
      |  $U n \rightarrow$  if  $n > 0$  then 2//3 else -2//3
      |  $D n \rightarrow$  if  $n > 0$  then -1//3 else 1//3
    end
  |  $G f \rightarrow$ 
    begin match  $f$  with
      |  $Gl \mid Ga \mid Z \rightarrow$  0//1
      |  $Wp \rightarrow$  1//1
      |  $Wm \rightarrow$  -1//1
    end

```

```

    end
  |  $O f \rightarrow$ 
    begin match  $f$  with
    |  $H$  |  $\Phi^0 \rightarrow 0//1$ 
    |  $\Phi^{\pm} \rightarrow 1//1$ 
    |  $\Phi^{\pm\pm} \rightarrow -1//1$ 
    end
let lepton = function
  |  $M f \rightarrow$ 
    begin match  $f$  with
    |  $L n$  |  $N n \rightarrow$  if  $n > 0$  then  $1//1$  else  $-1//1$ 
    |  $U -$  |  $D - \rightarrow 0//1$ 
    end
  |  $G -$  |  $O - \rightarrow 0//1$ 
let baryon = function
  |  $M f \rightarrow$ 
    begin match  $f$  with
    |  $L -$  |  $N - \rightarrow 0//1$ 
    |  $U n$  |  $D n \rightarrow$  if  $n > 0$  then  $1//1$  else  $-1//1$ 
    end
  |  $G -$  |  $O - \rightarrow 0//1$ 
let charges  $f =$ 
  [ charge  $f$ ; lepton  $f$ ; baryon  $f$ ] @ generation  $f$ 
type constant =
  | Unit | Pi | Alpha_QED | Sin2thw
  | Sinhw | Costhw | E | G_weak | Vev
  | Q_lepton | Q_up | Q_down | G_CC
  | G_NC_neutrino | G_NC_lepton | G_NC_up | G_NC_down
  | I_Q_W | I_G_ZWW
  | G_WWWWW | G_ZZWW | G_AZWW | G_AAWW
  | G_HWW | G_HHWW | G_HZZ | G_HHZZ
  | G_Htt | G_Hbb | G_Hcc | G_Hmm | G_Htautau | G_H3 |
G_H4
  | G_HGaZ | G_HGaGa | G_Hgg
  | Gs | I_Gs | G2
  | Mass of flavor | Width of flavor

```

Two integer counters for the QCD and EW order of the couplings.

```

type orders = int  $\times$  int
let orders = function
  | -  $\rightarrow (0, 0)$ 
let input_parameters = []
let derived_parameters = []
let g_over_2_costh =
  Quot (Neg (Atom G_weak), Prod [Const 2; Atom Costhw])

```

```

let nc_coupling c t3 q =
  (Real_Array c,
   [Prod [g-over-2-costh; Diff (t3, Prod [Const 2; q; Atom Sin2thw]);
        Prod [g-over-2-costh; t3]]])

let half = Quot (Const 1, Const 2)

let derived_parameter_arrays =
  [ nc_coupling G_NC_neutrino half (Const 0);
    nc_coupling G_NC_lepton (Neg half) (Const (-1));
    nc_coupling G_NC_up half (Quot (Const 2, Const 3));
    nc_coupling G_NC_down (Neg half) (Quot (Const (-1), Const 3)) ]

let parameters () =
  { input = input_parameters;
    derived = derived_parameters;
    derived_arrays = derived_parameter_arrays }

module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)

let mgm ((m1, g, m2), fbf, c) = ((M m1, G g, M m2), fbf, c)

let electromagnetic_currents n =
  List.map mgm
    [ ((L (-n), Ga, L n), FBF (1, Psibar, V, Psi), Q_lepton);
      ((U (-n), Ga, U n), FBF (1, Psibar, V, Psi), Q_up);
      ((D (-n), Ga, D n), FBF (1, Psibar, V, Psi), Q_down) ]

let color_currents n =
  List.map mgm
    [ ((U (-n), Gl, U n), FBF ((-1), Psibar, V, Psi), Gs);
      ((D (-n), Gl, D n), FBF ((-1), Psibar, V, Psi), Gs) ]

let neutral_currents n =
  List.map mgm
    [ ((L (-n), Z, L n), FBF (1, Psibar, VA, Psi), G_NC_lepton);
      ((N (-n), Z, N n), FBF (1, Psibar, VA, Psi), G_NC_neutrino);
      ((U (-n), Z, U n), FBF (1, Psibar, VA, Psi), G_NC_up);
      ((D (-n), Z, D n), FBF (1, Psibar, VA, Psi), G_NC_down) ]

let charged_currents n =
  List.map mgm
    [ ((L (-n), Wm, N n), FBF (1, Psibar, VL, Psi), G_CC);
      ((N (-n), Wp, L n), FBF (1, Psibar, VL, Psi), G_CC);
      ((D (-n), Wm, U n), FBF (1, Psibar, VL, Psi), G_CC);
      ((U (-n), Wp, D n), FBF (1, Psibar, VL, Psi), G_CC) ]

let yukawa =
  [ ((M (U (-3)), O H, M (U 3)), FBF (1, Psibar, S, Psi), G_Htt);
    ((M (D (-3)), O H, M (D 3)), FBF (1, Psibar, S, Psi), G_Hbb);

```

```

      ((M (U (-2)), O H, M (U 2)), FBF (1, Psibar, S, Psi), G_Hcc);
      ((M (L (-2)), O H, M (L 2)), FBF (1, Psibar, S, Psi), G_Hmm);
      ((M (L (-3)), O H, M (L 3)), FBF (1, Psibar, S, Psi), G_Htautau) ]
let tgc ((g1, g2, g3), t, c) = ((G g1, G g2, G g3), t, c)
let triple_gauge =
  List.map tgc
    [ ((Ga, Wm, Wp), Gauge_Gauge_Gauge 1, I_Q_W);
      ((Z, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_ZWW);
      ((Gl, Gl, Gl), Gauge_Gauge_Gauge 1, I_Gs) ]
let qgc ((g1, g2, g3, g4), t, c) = ((G g1, G g2, G g3, G g4), t, c)
let gauge4 = Vector4 [(2, C_13_42); (-1, C_12_34); (-1, C_14_23)]
let minus_gauge4 = Vector4 [(-2, C_13_42); (1, C_12_34); (1, C_14_23)]
let quartic_gauge =
  List.map qgc
    [ (Wm, Wp, Wm, Wp), gauge4, G_WWWW;
      (Wm, Z, Wp, Z), minus_gauge4, G_ZZWW;
      (Wm, Z, Wp, Ga), minus_gauge4, G_AZWW;
      (Wm, Ga, Wp, Ga), minus_gauge4, G_AAWW;
      (Gl, Gl, Gl, Gl), gauge4, G2]
let gauge_higgs =
  [ ((O H, G Wp, G Wm), Scalar_Vector_Vector 1, G_HWW);
    ((O H, G Z, G Z), Scalar_Vector_Vector 1, G_HZZ) ]
let gauge_higgs4 =
  [ (O H, O H, G Wp, G Wm), Scalar2_Vector2 1, G_HHWW;
    (O H, O H, G Z, G Z), Scalar2_Vector2 1, G_HHZZ ]
let higgs =
  [ (O H, O H, O H), Scalar_Scalar_Scalar 1, G_H3 ]
let higgs4 =
  [ (O H, O H, O H, O H), Scalar4 1, G_H4 ]
let anomaly_higgs =
  []
(* (O H, G Ga, G Ga), Dim5_Scalar_Gauge2 1, G_HGaGa; (O H, G Ga, G Z), Dim5_Scalar_Gauge2 1,
*)
let goldstone_vertices =
  [ ((O Phi0, G Wm, G Wp), Scalar_Vector_Vector 1, I_G_ZWW);
    ((O Phip, G Ga, G Wm), Scalar_Vector_Vector 1, I_Q_W);
    ((O Phip, G Z, G Wm), Scalar_Vector_Vector 1, I_G_ZWW);
    ((O Phim, G Wp, G Ga), Scalar_Vector_Vector 1, I_Q_W);
    ((O Phim, G Wp, G Z), Scalar_Vector_Vector 1, I_G_ZWW) ]
let vertices3 =
  (ThoList.flatmap electromagnetic_currents [1; 2; 3] @
   ThoList.flatmap color_currents [1; 2; 3] @
   ThoList.flatmap neutral_currents [1; 2; 3] @
   ThoList.flatmap charged_currents [1; 2; 3] @
   yukawa @ triple_gauge @ gauge_higgs @ higgs @

```

```

    anomaly_higgs @ goldstone_vertices)

let vertices4 =
    quartic_gauge @ gauge_higgs4 @ higgs4
let vertices () = (vertices3, vertices4, [])
let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 4

let flavor_of_string = function
| "e-" → M (L 1) | "e+" → M (L (-1))
| "mu-" → M (L 2) | "mu+" → M (L (-2))
| "tau-" → M (L 3) | "tau+" → M (L (-3))
| "nue" → M (N 1) | "nuebar" → M (N (-1))
| "numu" → M (N 2) | "numubar" → M (N (-2))
| "nutau" → M (N 3) | "nutaubar" → M (N (-3))
| "u" → M (U 1) | "ubar" → M (U (-1))
| "c" → M (U 2) | "cbar" → M (U (-2))
| "t" → M (U 3) | "tbar" → M (U (-3))
| "d" → M (D 1) | "dbar" → M (D (-1))
| "s" → M (D 2) | "sbar" → M (D (-2))
| "b" → M (D 3) | "bbar" → M (D (-3))
| "g" | "gl" → G Gl
| "A" → G Ga | "Z" | "Z0" → G Z
| "W+" → G Wp | "W-" → G Wm
| "H" → O H
| _ → invalid_arg "Modellib_BSM.Template.flavor_of_string"

let flavor_to_string = function
| M f →
    begin match f with
    | L 1 → "e-" | L (-1) → "e+"
    | L 2 → "mu-" | L (-2) → "mu+"
    | L 3 → "tau-" | L (-3) → "tau+"
    | L _ → invalid_arg
        "Modellib_BSM.Template.flavor_to_string:␣invalid␣lepton"
    | N 1 → "nue" | N (-1) → "nuebar"
    | N 2 → "numu" | N (-2) → "numubar"
    | N 3 → "nutau" | N (-3) → "nutaubar"
    | N _ → invalid_arg
        "Modellib_BSM.Template.flavor_to_string:␣invalid␣neutrino"
    | U 1 → "u" | U (-1) → "ubar"
    | U 2 → "c" | U (-2) → "cbar"
    | U 3 → "t" | U (-3) → "tbar"
    | U _ → invalid_arg
        "Modellib_BSM.Template.flavor_to_string:␣invalid␣up␣type␣quark"
    | D 1 → "d" | D (-1) → "dbar"
    | D 2 → "s" | D (-2) → "sbar"
    | D 3 → "b" | D (-3) → "bbar"

```



---

```

    |  $D_- \rightarrow \text{invalid\_arg}$ 
      "Modellib_BSM.Template.flavor_to_string:␣invalid␣down␣type␣quark"
    end
  |  $G f \rightarrow$ 
    begin match  $f$  with
    |  $Gl \rightarrow "g"$ 
    |  $Ga \rightarrow "A" \mid Z \rightarrow "Z"$ 
    |  $Wp \rightarrow "W^+" \mid Wm \rightarrow "W^-"$ 
    end
  |  $O f \rightarrow$ 
    begin match  $f$  with
    |  $Phip \rightarrow "phi^+" \mid Phim \rightarrow "phi^- \mid Phi0 \rightarrow "phi0"$ 
    |  $H \rightarrow "H"$ 
    end
end

let flavor_to_TeX = function
|  $M f \rightarrow$ 
  begin match  $f$  with
  |  $L 1 \rightarrow "e^- \mid L (-1) \rightarrow "e^+"
  |  $L 2 \rightarrow "\\mu^- \mid L (-2) \rightarrow "\\mu^+"
  |  $L 3 \rightarrow "\\tau^- \mid L (-3) \rightarrow "\\tau^+"
  |  $L_- \rightarrow \text{invalid\_arg}$ 
    "Modellib_BSM.Template.flavor_to_TeX:␣invalid␣lepton"
  |  $N 1 \rightarrow "\\nu_e \mid N (-1) \rightarrow "\\bar{\nu}_e"
  |  $N 2 \rightarrow "\\nu_\mu \mid N (-2) \rightarrow "\\bar{\nu}_\mu"
  |  $N 3 \rightarrow "\\nu_\tau \mid N (-3) \rightarrow "\\bar{\nu}_\tau"
  |  $N_- \rightarrow \text{invalid\_arg}$ 
    "Modellib_BSM.Template.flavor_to_TeX:␣invalid␣neutrino"
  |  $U 1 \rightarrow "u \mid U (-1) \rightarrow "\\bar{u}"
  |  $U 2 \rightarrow "c \mid U (-2) \rightarrow "\\bar{c}"
  |  $U 3 \rightarrow "t \mid U (-3) \rightarrow "\\bar{t}"
  |  $U_- \rightarrow \text{invalid\_arg}$ 
    "Modellib_BSM.Template.flavor_to_TeX:␣invalid␣up␣type␣quark"
  |  $D 1 \rightarrow "d \mid D (-1) \rightarrow "\\bar{d}"
  |  $D 2 \rightarrow "s \mid D (-2) \rightarrow "\\bar{s}"
  |  $D 3 \rightarrow "b \mid D (-3) \rightarrow "\\bar{b}"
  |  $D_- \rightarrow \text{invalid\_arg}$ 
    "Modellib_BSM.Template.flavor_to_TeX:␣invalid␣down␣type␣quark"
  end
|  $G f \rightarrow$ 
  begin match  $f$  with
  |  $Gl \rightarrow "g"$ 
  |  $Ga \rightarrow "\\gamma \mid Z \rightarrow "Z"$ 
  |  $Wp \rightarrow "W^+ \mid Wm \rightarrow "W^-"$ 
  end
|  $O f \rightarrow$ 
  begin match  $f$  with
  |  $Phip \rightarrow "\\phi^+ \mid Phim \rightarrow "\\phi^- \mid Phi0 \rightarrow$ 
    "\\phi^0"
  |  $H \rightarrow "H"$$$$$$$$$$$$$ 
```

```

    end
let flavor_symbol = function
| M f →
    begin match f with
    | L n when n > 0 → "l" ^ string_of_int n
    | L n → "l" ^ string_of_int (abs n) ^ "b"
    | N n when n > 0 → "n" ^ string_of_int n
    | N n → "n" ^ string_of_int (abs n) ^ "b"
    | U n when n > 0 → "u" ^ string_of_int n
    | U n → "u" ^ string_of_int (abs n) ^ "b"
    | D n when n > 0 → "d" ^ string_of_int n
    | D n → "d" ^ string_of_int (abs n) ^ "b"
    end
| G f →
    begin match f with
    | Gl → "gl"
    | Ga → "a" | Z → "z"
    | Wp → "wp" | Wm → "wm"
    end
| O f →
    begin match f with
    | Phip → "pp" | Phim → "pm" | Phi0 → "p0"
    | H → "h"
    end
end
let pdg = function
| M f →
    begin match f with
    | L n when n > 0 → 9 + 2 × n
    | L n → - 9 + 2 × n
    | N n when n > 0 → 10 + 2 × n
    | N n → - 10 + 2 × n
    | U n when n > 0 → 2 × n
    | U n → 2 × n
    | D n when n > 0 → - 1 + 2 × n
    | D n → 1 + 2 × n
    end
| G f →
    begin match f with
    | Gl → 21
    | Ga → 22 | Z → 23
    | Wp → 24 | Wm → (-24)
    end
| O f →
    begin match f with
    | Phip | Phim → 27 | Phi0 → 26
    | H → 25
    end
end
let mass_symbol f =
    "mass(" ^ string_of_int (abs (pdg f)) ^ ")"

```

```

let width_symbol f =
  "width(" ^ string_of_int (abs (pdg f)) ^ ")"

let constant_symbol = function
| Unit → "unit" | Pi → "PI"
| Alpha_QED → "alpha" | E → "e" | G_weak → "g" | Vev →
"vev"
| Sin2thw → "sin2thw" | Sinthw → "sinthw" | Costhw →
"costhw"
| Q_lepton → "qlep" | Q_up → "qup" | Q_down → "qdown"
| G_NC_lepton → "gnclep" | G_NC_neutrino → "gncneu"
| G_NC_up → "gncup" | G_NC_down → "gncdown"
| G_CC → "gcc"
| I_Q_W → "iqw" | I_G_ZWW → "igzww"
| G_WWWW → "gw4" | G_ZZWW → "gzzww"
| G_AZWW → "gazww" | G_AAWW → "gaaww"
| G_HWW → "ghww" | G_HZZ → "ghzz"
| G_HHWW → "ghhww" | G_HHZZ → "ghhzz"
| G_Htt → "ghtt" | G_Hbb → "ghbb"
| G_Htautau → "ghtautau" | G_Hcc → "ghcc" | G_Hmm →
"ghmm"
| G_HGaZ → "ghgaz" | G_HGaGa → "ghgaga" | G_Hgg →
"ghgg"
| G_H3 → "gh3" | G_H4 → "gh4"
| Gs → "gs" | I_Gs → "igs" | G2 → "gs**2"
| Mass f → "mass" ^ flavor_symbol f
| Width f → "width" ^ flavor_symbol f

end

module HSExt (Flags : BSM_flags) =
struct
  let rcs = RCS.rename rcs_file "Modellib_BSM.HSExt"
    [ "Higgs_Singlet_Extension_of_the_SM" ]

  open Coupling

  let default_width = ref Timelike
  let use_fudged_width = ref false

  let options = Options.create
    [ "constant_width", Arg.Unit (fun () → default_width := Constant),
      "use_constant_width(also_in_t-channel);",
      "fudged_width", Arg.Set use_fudged_width,
      "use_fudge_factor_for_charge_particle_width;",
      "custom_width", Arg.String (fun f → default_width := Custom f),
      "use_custom_width;",
      "cancel_widths", Arg.Unit (fun () → default_width := Vanishing),
      "use_vanishing_width" ]

  type matter_field = L of int | N of int | U of int | D of int
  type gauge_boson = Ga | Wp | Wm | Z | Gl
  type other = Phip | Phim | Phi0 | H | S
  type flavor = M of matter_field | G of gauge_boson | O of other

```

```

let matter_field f = M f
let gauge_boson f = G f
let other f = O f

type field =
  | Matter of matter_field
  | Gauge of gauge_boson
  | Other of other

let field = function
  | M f → Matter f
  | G f → Gauge f
  | O f → Other f

type gauge = unit

let gauge_symbol () =
  failwith "Modellib-BSM.HSExt.gauge_symbol: internal error"

let family n = List.map matter_field [ L n; N n; U n; D n ]

let external_flavors () =
  [ "1st_Generation", ThoList.flatmap family [1; -1];
    "2nd_Generation", ThoList.flatmap family [2; -2];
    "3rd_Generation", ThoList.flatmap family [3; -3];
    "Gauge_Bosons", List.map gauge_boson [Ga; Z; Wp; Wm; Gl];
    "Higgs", List.map other [H; S];
    "Goldstone_Bosons", List.map other [Phip; Phim; Phi0] ]

let flavors () = ThoList.flatmap snd (external_flavors ())

let spinor n =
  if n ≥ 0 then
    Spinor
  else
    ConjSpinor

let lorentz = function
  | M f →
    begin match f with
    | L n → spinor n | N n → spinor n
    | U n → spinor n | D n → spinor n
    end
  | G f →
    begin match f with
    | Ga | Gl → Vector
    | Wp | Wm | Z → Massive_Vector
    end
  | O f → Scalar

let color = function
  | M (U n) → Color.SUN (if n > 0 then 3 else -3)
  | M (D n) → Color.SUN (if n > 0 then 3 else -3)
  | G Gl → Color.AdjSUN 3
  | - → Color.Singlet

```

```

let prop_spinor n =
  if n ≥ 0 then
    Prop_Spinor
  else
    Prop_ConjSpinor
let propagator = function
| M f →
  begin match f with
  | L n → prop_spinor n | N n → prop_spinor n
  | U n → prop_spinor n | D n → prop_spinor n
  end
| G f →
  begin match f with
  | Ga | Gl → Prop_Feynman
  | Wp | Wm | Z → Prop_Unitarity
  end
| O f →
  begin match f with
  | Phip | Phim | Phi0 → Only_Insertion
  | H | S → Prop_Scalar
  end

```

Optionally, ask for the fudge factor treatment for the widths of charged particles. Currently, this only applies to  $W^\pm$  and top.

```

let width f =
  if !use_fudged_width then
    match f with
    | G Wp | G Wm | M (U 3) | M (U (-3)) → Fudged
    | _ → !default_width
  else
    !default_width
let goldstone = function
| G f →
  begin match f with
  | Wp → Some (O Phip, Coupling.Const 1)
  | Wm → Some (O Phim, Coupling.Const 1)
  | Z → Some (O Phi0, Coupling.Const 1)
  | _ → None
  end
| _ → None
let conjugate = function
| M f →
  M (begin match f with
  | L n → L (-n) | N n → N (-n)
  | U n → U (-n) | D n → D (-n)
  end)
| G f →
  G (begin match f with
  | Gl → Gl | Ga → Ga | Z → Z

```

```

      |  $Wp \rightarrow Wm \mid Wm \rightarrow Wp$ 
    end)
  |  $O f \rightarrow$ 
     $O$  (begin match  $f$  with
      |  $Phip \rightarrow Phim \mid Phim \rightarrow Phip \mid Phi0 \rightarrow Phi0$ 
      |  $H \rightarrow H \mid S \rightarrow S$ 
    end)

let fermion = function
  |  $M f \rightarrow$ 
    begin match  $f$  with
      |  $L n \rightarrow$  if  $n > 0$  then 1 else -1
      |  $N n \rightarrow$  if  $n > 0$  then 1 else -1
      |  $U n \rightarrow$  if  $n > 0$  then 1 else -1
      |  $D n \rightarrow$  if  $n > 0$  then 1 else -1
    end
  |  $G f \rightarrow$ 
    begin match  $f$  with
      |  $Gl \mid Ga \mid Z \mid Wp \mid Wm \rightarrow 0$ 
    end
  |  $O _ \rightarrow 0$ 

module Ch = Charges.QQ

let ( // ) = Algebra.Small_Rational.make

let generation' = function
  | 1  $\rightarrow$  [ 1//1; 0//1; 0//1]
  | 2  $\rightarrow$  [ 0//1; 1//1; 0//1]
  | 3  $\rightarrow$  [ 0//1; 0//1; 1//1]
  | -1  $\rightarrow$  [-1//1; 0//1; 0//1]
  | -2  $\rightarrow$  [ 0//1; -1//1; 0//1]
  | -3  $\rightarrow$  [ 0//1; 0//1; -1//1]
  |  $n \rightarrow$  invalid_arg ("HSExt.generation':␣" ^ string_of_int  $n$ )

let generation f =
  match  $f$  with
  |  $M (L n \mid N n \mid U n \mid D n) \rightarrow$  generation' n
  |  $G _ \mid O _ \rightarrow$  [0//1; 0//1; 0//1]

let charge = function
  |  $M f \rightarrow$ 
    begin match  $f$  with
      |  $L n \rightarrow$  if  $n > 0$  then -1//1 else 1//1
      |  $N n \rightarrow$  0//1
      |  $U n \rightarrow$  if  $n > 0$  then 2//3 else -2//3
      |  $D n \rightarrow$  if  $n > 0$  then -1//3 else 1//3
    end
  |  $G f \rightarrow$ 
    begin match  $f$  with
      |  $Gl \mid Ga \mid Z \rightarrow$  0//1
      |  $Wp \rightarrow$  1//1
      |  $Wm \rightarrow$  -1//1
    end

```

```

    end
  |  $O f \rightarrow$ 
    begin match  $f$  with
    |  $H$  |  $\Phi^0$  |  $S \rightarrow 0//1$ 
    |  $\Phi^{\pm}$   $\rightarrow 1//1$ 
    |  $\Phi^{\pm}$   $\rightarrow -1//1$ 
    end

let lepton = function
  |  $M f \rightarrow$ 
    begin match  $f$  with
    |  $L n$  |  $N n \rightarrow$  if  $n > 0$  then  $1//1$  else  $-1//1$ 
    |  $U -$  |  $D - \rightarrow 0//1$ 
    end
  |  $G -$  |  $O - \rightarrow 0//1$ 

let baryon = function
  |  $M f \rightarrow$ 
    begin match  $f$  with
    |  $L -$  |  $N - \rightarrow 0//1$ 
    |  $U n$  |  $D n \rightarrow$  if  $n > 0$  then  $1//1$  else  $-1//1$ 
    end
  |  $G -$  |  $O - \rightarrow 0//1$ 

let charges  $f =$ 
  [ charge  $f$ ; lepton  $f$ ; baryon  $f$ ] @ generation  $f$ 

type constant =
  | Unit | Pi | Alpha_QED | Sin2thw
  | Sinhw | Costhw | E | G_weak | Vev
  | Q_lepton | Q_up | Q_down | G_CC
  | G_NC_neutrino | G_NC_lepton | G_NC_up | G_NC_down
  | I_Q_W | I_G_ZWW
  | G_WWWW | G_ZZWW | G_AZWW | G_AAWW
  | G_HWW | G_HHWW | G_HZZ | G_HHZZ
  | G_SWW | G_SSWW | G_SZZ | G_SZZZ | G_HSWW |
  G_HSZZ
  | G_Htt | G_Hbb | G_Hcc | G_Hmm | G_Htautau | G_H3 |
  G_H4-1
  | G_H4-2 | G_H4-3 | G_H4-4 | G_H4-5
  | G_Stt | G_Sbb | G_Scc | G_Smm | G_Stautau | G_HSS |
  G_HHS
  | G_HGaZ | G_HGaGa | G_Hgg | G_SGaZ | G_SGaGa | G_Sgg
  | Gs | I_Gs | G2
  | Mass of flavor | Width of flavor

```

Two integer counters for the QCD and EW order of the couplings.

```

type orders = int  $\times$  int

let orders = function
  | -  $\rightarrow (0, 0)$ 

let input_parameters = []

```

```

let derived_parameters = []
let g_over_2_csth =
  Quot (Neg (Atom G_weak), Prod [Const 2; Atom Costhw])
let nc_coupling c t3 q =
  (Real_Array c,
   [Prod [g_over_2_csth; Diff (t3, Prod [Const 2; q; Atom Sin2thw]);
    Prod [g_over_2_csth; t3]])
let half = Quot (Const 1, Const 2)
let derived_parameter_arrays =
  [ nc_coupling G_NC_neutrino half (Const 0);
    nc_coupling G_NC_lepton (Neg half) (Const (-1));
    nc_coupling G_NC_up half (Quot (Const 2, Const 3));
    nc_coupling G_NC_down (Neg half) (Quot (Const (-1), Const 3)) ]
let parameters () =
  { input = input_parameters;
    derived = derived_parameters;
    derived_arrays = derived_parameter_arrays }
module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)
let mgm ((m1, g, m2), fbf, c) = ((M m1, G g, M m2), fbf, c)
let electromagnetic_currents n =
  List.map mgm
    [ ((L (-n), Ga, L n), FBF (1, Psibar, V, Psi), Q_lepton);
      ((U (-n), Ga, U n), FBF (1, Psibar, V, Psi), Q_up);
      ((D (-n), Ga, D n), FBF (1, Psibar, V, Psi), Q_down) ]
let color_currents n =
  List.map mgm
    [ ((U (-n), Gl, U n), FBF ((-1), Psibar, V, Psi), Gs);
      ((D (-n), Gl, D n), FBF ((-1), Psibar, V, Psi), Gs) ]
let neutral_currents n =
  List.map mgm
    [ ((L (-n), Z, L n), FBF (1, Psibar, VA, Psi), G_NC_lepton);
      ((N (-n), Z, N n), FBF (1, Psibar, VA, Psi), G_NC_neutrino);
      ((U (-n), Z, U n), FBF (1, Psibar, VA, Psi), G_NC_up);
      ((D (-n), Z, D n), FBF (1, Psibar, VA, Psi), G_NC_down) ]
let charged_currents n =
  List.map mgm
    [ ((L (-n), Wm, N n), FBF (1, Psibar, VL, Psi), G_CC);
      ((N (-n), Wp, L n), FBF (1, Psibar, VL, Psi), G_CC);
      ((D (-n), Wm, U n), FBF (1, Psibar, VL, Psi), G_CC);
      ((U (-n), Wp, D n), FBF (1, Psibar, VL, Psi), G_CC) ]

```



```

let yukawa =
  [ ((M (U (-3)), O H, M (U 3)), FBF (1, Psibar, Coupling.S, Psi), G_Htt);
    ((M (D (-3)), O H, M (D 3)), FBF (1, Psibar, Coupling.S, Psi), G_Hbb);
    ((M (U (-2)), O H, M (U 2)), FBF (1, Psibar, Coupling.S, Psi), G_Hcc);
    ((M (L (-2)), O H, M (L 2)), FBF (1, Psibar, Coupling.S, Psi), G_Hmm);
    ((M (L (-3)), O H, M (L 3)),
      FBF (1, Psibar, Coupling.S, Psi), G_Htautau);
    ((M (U (-3)), O S, M (U 3)), FBF (1, Psibar, Coupling.S, Psi), G_Stt);
    ((M (D (-3)), O S, M (D 3)), FBF (1, Psibar, Coupling.S, Psi), G_Sbb);
    ((M (U (-2)), O S, M (U 2)), FBF (1, Psibar, Coupling.S, Psi), G_Scc);
    ((M (L (-2)), O S, M (L 2)), FBF (1, Psibar, Coupling.S, Psi), G_Smm);
    ((M (L (-3)), O S, M (L 3)),
      FBF (1, Psibar, Coupling.S, Psi), G_Stautau) ]

let tgc ((g1, g2, g3), t, c) = ((G g1, G g2, G g3), t, c)

let triple_gauge =
  List.map tgc
    [ ((Ga, Wm, Wp), Gauge_Gauge_Gauge 1, I_Q_W);
      ((Z, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_ZWW);
      ((Gl, Gl, Gl), Gauge_Gauge_Gauge 1, I_Gs) ]

let qgc ((g1, g2, g3, g4), t, c) = ((G g1, G g2, G g3, G g4), t, c)

let gauge4 = Vector4 [(2, C_13_42); (-1, C_12_34); (-1, C_14_23)]
let minus_gauge4 = Vector4 [(-2, C_13_42); (1, C_12_34); (1, C_14_23)]
let quartic_gauge =
  List.map qgc
    [ (Wm, Wp, Wm, Wp), gauge4, G_WWWW;
      (Wm, Z, Wp, Z), minus_gauge4, G_ZZWW;
      (Wm, Z, Wp, Ga), minus_gauge4, G_AZWW;
      (Wm, Ga, Wp, Ga), minus_gauge4, G_AAWW;
      (Gl, Gl, Gl, Gl), gauge4, G2]

let gauge_higgs =
  [ ((O H, G Wp, G Wm), Scalar_Vector_Vector 1, G_HWW);
    ((O H, G Z, G Z), Scalar_Vector_Vector 1, G_HZZ);
    ((O S, G Wp, G Wm), Scalar_Vector_Vector 1, G_SWW);
    ((O S, G Z, G Z), Scalar_Vector_Vector 1, G_SZZ) ]

let gauge_higgs4 =
  [ (O H, O H, G Wp, G Wm), Scalar2_Vector2 1, G_HHWW;
    (O H, O H, G Z, G Z), Scalar2_Vector2 1, G_HHZZ;
    (O H, O S, G Wp, G Wm), Scalar2_Vector2 1, G_HSWW;
    (O H, O S, G Z, G Z), Scalar2_Vector2 1, G_HSZZ;
    (O S, O S, G Wp, G Wm), Scalar2_Vector2 1, G_SSWW;
    (O S, O S, G Z, G Z), Scalar2_Vector2 1, G_SSSZ ]

let higgs =
  [ (O H, O H, O H), Scalar_Scalar_Scalar 1, G_H3;
    (O S, O H, O H), Scalar_Scalar_Scalar 1, G_HHS;
    (O S, O S, O H), Scalar_Scalar_Scalar 1, G_HSS ]

let higgs4 =

```

```

[ (O H, O H, O H, O H), Scalar4 1, G-H4-1;
  (O H, O H, O H, O S), Scalar4 1, G-H4-2;
  (O H, O H, O S, O S), Scalar4 1, G-H4-3;
  (O H, O S, O S, O S), Scalar4 1, G-H4-4;
  (O S, O S, O S, O S), Scalar4 1, G-H4-5 ]

let anomaly_higgs =
[ (O H, G Ga, G Ga), Dim5_Scalar_Gauge2 1, G-HGaGa;
  (O H, G Ga, G Z), Dim5_Scalar_Gauge2 1, G-HGaZ;
  (O H, G Gl, G Gl), Dim5_Scalar_Gauge2 1, G-Hgg;
  (O S, G Ga, G Ga), Dim5_Scalar_Gauge2 1, G-SGaGa;
  (O S, G Ga, G Z), Dim5_Scalar_Gauge2 1, G-SGaZ;
  (O S, G Gl, G Gl), Dim5_Scalar_Gauge2 1, G-Sgg ]

let goldstone_vertices =
[ ((O Phi0, G Wm, G Wp), Scalar_Vector_Vector 1, I-G-ZWW);
  ((O Phip, G Ga, G Wm), Scalar_Vector_Vector 1, I-Q-W);
  ((O Phip, G Z, G Wm), Scalar_Vector_Vector 1, I-G-ZWW);
  ((O Phim, G Wp, G Ga), Scalar_Vector_Vector 1, I-Q-W);
  ((O Phim, G Wp, G Z), Scalar_Vector_Vector 1, I-G-ZWW) ]

let vertices3 =
(ThoList.flatmap electromagnetic_currents [1;2;3] @
 ThoList.flatmap color_currents [1;2;3] @
 ThoList.flatmap neutral_currents [1;2;3] @
 ThoList.flatmap charged_currents [1;2;3] @
 yukawa @ triple_gauge @ gauge_higgs @ higgs @
 anomaly_higgs @ goldstone_vertices)

let vertices4 =
quartic_gauge @ gauge_higgs4 @ higgs4

let vertices () = (vertices3, vertices4, [])

let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 4

let flavor_of_string = function
| "e-" → M (L 1) | "e+" → M (L (-1))
| "mu-" → M (L 2) | "mu+" → M (L (-2))
| "tau-" → M (L 3) | "tau+" → M (L (-3))
| "nue" → M (N 1) | "nuebar" → M (N (-1))
| "numu" → M (N 2) | "numubar" → M (N (-2))
| "nutau" → M (N 3) | "nutaubar" → M (N (-3))
| "u" → M (U 1) | "ubar" → M (U (-1))
| "c" → M (U 2) | "cbar" → M (U (-2))
| "t" → M (U 3) | "tbar" → M (U (-3))
| "d" → M (D 1) | "dbar" → M (D (-1))
| "s" → M (D 2) | "sbar" → M (D (-2))
| "b" → M (D 3) | "bbar" → M (D (-3))
| "g" | "gl" → G Gl

```

```

| "A" → G Ga | "Z" | "Z0" → G Z
| "W+" → G Wp | "W-" → G Wm
| "H" → O H
| "S" → O S
| - → invalid_arg "Modellib_BSM.HSExt.flavor_of_string"

let flavor_to_string = function
| M f →
  begin match f with
  | L 1 → "e-" | L (-1) → "e+"
  | L 2 → "mu-" | L (-2) → "mu+"
  | L 3 → "tau-" | L (-3) → "tau+"
  | L _ → invalid_arg
    "Modellib_BSM.HSExt.flavor_to_string:␣invalid␣lepton"
  | N 1 → "nue" | N (-1) → "nuebar"
  | N 2 → "numu" | N (-2) → "numubar"
  | N 3 → "nutau" | N (-3) → "nutaubar"
  | N _ → invalid_arg
    "Modellib_BSM.HSExt.flavor_to_string:␣invalid␣neutrino"
  | U 1 → "u" | U (-1) → "ubar"
  | U 2 → "c" | U (-2) → "cbar"
  | U 3 → "t" | U (-3) → "tbar"
  | U _ → invalid_arg
    "Modellib_BSM.HSExt.flavor_to_string:␣invalid␣up␣type␣quark"
  | D 1 → "d" | D (-1) → "dbar"
  | D 2 → "s" | D (-2) → "sbar"
  | D 3 → "b" | D (-3) → "bbar"
  | D _ → invalid_arg
    "Modellib_BSM.HSExt.flavor_to_string:␣invalid␣down␣type␣quark"
  end
| G f →
  begin match f with
  | Gl → "g"
  | Ga → "A" | Z → "Z"
  | Wp → "W+" | Wm → "W-"
  end
| O f →
  begin match f with
  | Phip → "phi+" | Phim → "phi-" | Phi0 → "phi0"
  | H → "H" | S → "S"
  end
end

let flavor_to_TeX = function
| M f →
  begin match f with
  | L 1 → "e~-" | L (-1) → "e~+"
  | L 2 → "\\mu~-" | L (-2) → "\\mu~+"
  | L 3 → "\\tau~-" | L (-3) → "\\tau~+"
  | L _ → invalid_arg
    "Modellib_BSM.HSExt.flavor_to_TeX:␣invalid␣lepton"
  | N 1 → "\\nu_e" | N (-1) → "\\bar{\\nu}_e"

```

```

| N 2 → "\\nu_\\mu" | N (-2) → "\\bar{\\nu}_\\mu"
| N 3 → "\\nu_\\tau" | N (-3) → "\\bar{\\nu}_\\tau"
| N _ → invalid_arg
      "Modellib_BSM.HSExt.flavor_to_TeX:␣invalid␣neutrino"
| U 1 → "u" | U (-1) → "\\bar{u}"
| U 2 → "c" | U (-2) → "\\bar{c}"
| U 3 → "t" | U (-3) → "\\bar{t}"
| U _ → invalid_arg
      "Modellib_BSM.HSExt.flavor_to_TeX:␣invalid␣up␣type␣quark"
| D 1 → "d" | D (-1) → "\\bar{d}"
| D 2 → "s" | D (-2) → "\\bar{s}"
| D 3 → "b" | D (-3) → "\\bar{b}"
| D _ → invalid_arg
      "Modellib_BSM.HSExt.flavor_to_TeX:␣invalid␣down␣type␣quark"
end
| G f →
  begin match f with
  | Gl → "g"
  | Ga → "\\gamma" | Z → "Z"
  | Wp → "W^+" | Wm → "W^- "
  end
| O f →
  begin match f with
  | Phip → "\\phi^+" | Phim → "\\phi^-" | Phi0 →
"\\phi^0"
  | H → "H" | S → "S"
  end
let flavor_symbol = function
| M f →
  begin match f with
  | L n when n > 0 → "l" ^ string_of_int n
  | L n → "l" ^ string_of_int (abs n) ^ "b"
  | N n when n > 0 → "n" ^ string_of_int n
  | N n → "n" ^ string_of_int (abs n) ^ "b"
  | U n when n > 0 → "u" ^ string_of_int n
  | U n → "u" ^ string_of_int (abs n) ^ "b"
  | D n when n > 0 → "d" ^ string_of_int n
  | D n → "d" ^ string_of_int (abs n) ^ "b"
  end
| G f →
  begin match f with
  | Gl → "gl"
  | Ga → "a" | Z → "z"
  | Wp → "wp" | Wm → "wm"
  end
| O f →
  begin match f with
  | Phip → "pp" | Phim → "pm" | Phi0 → "p0"
  | H → "h" | S → "s"

```

```

    end

let pdg = function
| M f →
    begin match f with
    | L n when n > 0 → 9 + 2 × n
    | L n → - 9 + 2 × n
    | N n when n > 0 → 10 + 2 × n
    | N n → - 10 + 2 × n
    | U n when n > 0 → 2 × n
    | U n → 2 × n
    | D n when n > 0 → - 1 + 2 × n
    | D n → 1 + 2 × n
    end
| G f →
    begin match f with
    | Gl → 21
    | Ga → 22 | Z → 23
    | Wp → 24 | Wm → (-24)
    end
| O f →
    begin match f with
    | Phip | Phim → 27 | Phi0 → 26
    | H → 25 | S → 35
    end
end

let mass_symbol f =
    "mass(" ^ string_of_int (abs (pdg f)) ^ ")"

let width_symbol f =
    "width(" ^ string_of_int (abs (pdg f)) ^ ")"

let constant_symbol = function
| Unit → "unit" | Pi → "PI"
| Alpha_QED → "alpha" | E → "e" | G_weak → "g" | Vev →
"vev"
| Sin2thw → "sin2thw" | Sinthw → "sinthw" | Costhw →
"costhw"
| Q_lepton → "qllep" | Q_up → "qup" | Q_down → "qdwn"
| G_NC_lepton → "gnclep" | G_NC_neutrino → "gncneu"
| G_NC_up → "gncup" | G_NC_down → "gncdwn"
| G_CC → "gcc"
| I_Q_W → "iqw" | I_G_ZWW → "igzww"
| G_WWWW → "gw4" | G_ZZWW → "gzzww"
| G_AZWW → "gazww" | G_AAWW → "gaaww"
| G_HWW → "ghww" | G_HZZ → "ghzz"
| G_HHWW → "ghhww" | G_HHZZ → "ghhzz"
| G_SWW → "gsww" | G_SZZ → "gszz"
| G_SSWW → "gssww" | G_SSSZ → "gsszz"
| G_HSWW → "ghsww" | G_HSSZ → "ghszz"
| G_Htt → "ghtt" | G_Hbb → "ghbb"

```

```

      |  $G_{H\tau\tau} \rightarrow \text{"gh}\tau\tau\text{"}$  |  $G_{Hcc} \rightarrow \text{"gh}cc\text{"}$  |  $G_{Hmm} \rightarrow$ 
"ghmm"
      |  $G_{Stt} \rightarrow \text{"gstt"}$  |  $G_{Sbb} \rightarrow \text{"gsbb"}$ 
      |  $G_{Stautau} \rightarrow \text{"gstautau"}$  |  $G_{Scc} \rightarrow \text{"gscc"}$  |  $G_{Smm} \rightarrow$ 
"gsmm"
      |  $G_{HGaZ} \rightarrow \text{"ghg}az\text{"}$  |  $G_{HGaGa} \rightarrow \text{"ghg}aga\text{"}$  |  $G_{Hgg} \rightarrow$ 
"ghgg"
      |  $G_{SGaZ} \rightarrow \text{"gsg}az\text{"}$  |  $G_{SGaGa} \rightarrow \text{"gsg}aga\text{"}$  |  $G_{Sgg} \rightarrow \text{"gsgg"}$ 
      |  $G_{H3} \rightarrow \text{"gh3"}$  |  $G_{H4_1} \rightarrow \text{"gh4_1"}$  |  $G_{H4_2} \rightarrow \text{"gh4_2"}$ 
      |  $G_{H4_3} \rightarrow \text{"gh4_3"}$  |  $G_{H4_4} \rightarrow \text{"gh4_4"}$  |  $G_{H4_5} \rightarrow$ 
"gh4_5"
      |  $G_{HHS} \rightarrow \text{"ghhs"}$  |  $G_{HSS} \rightarrow \text{"ghss"}$ 
      |  $G_s \rightarrow \text{"gs"}$  |  $I_{Gs} \rightarrow \text{"igs"}$  |  $G2 \rightarrow \text{"gs**2"}$ 
      |  $Mass\ f \rightarrow \text{"mass"}^{\wedge} flavor\_symbol\ f$ 
      |  $Width\ f \rightarrow \text{"width"}^{\wedge} flavor\_symbol\ f$ 
end

```

### 13.6.2 Three-Site Higgsless Model

```

module type Threeshl_options =
  sig
    val include_ckm : bool
    val include_hf : bool
    val diet : bool
  end

module Threeshl_no_ckm : Threeshl_options =
  struct
    let include_ckm = false
    let include_hf = true
    let diet = false
  end

module Threeshl_ckm : Threeshl_options =
  struct
    let include_ckm = true
    let include_hf = true
    let diet = false
  end

module Threeshl_no_ckm_no_hf : Threeshl_options =
  struct
    let include_ckm = false
    let include_hf = false
    let diet = false
  end

module Threeshl_ckm_no_hf : Threeshl_options =
  struct
    let include_ckm = true
    let include_hf = false
  end

```

```

    let diet = false
  end
module Threeshl_diet_no_hf : Threeshl_options =
  struct
    let include_ckm = false
    let include_hf = false
    let diet = true
  end
module Threeshl_diet : Threeshl_options =
  struct
    let include_ckm = false
    let include_hf = true
    let diet = true
  end
end

```

We use one generic implementation of the model and implement different features via option modules given to a functor

```

module Threeshl (Module_options : Threeshl_options) =
  struct
    open Coupling

    let modname = "Modellib_BSM.Threeshl"

    let rCS =
    let renderbool = function true → "true" | false → "false"
    in RCS.rename rcs_file "Modellib_BSM.Threeshl"
      ["Three-Site_Higgsless_Model," ^
        "flavor_mixing:" ^ (renderbool Module_options.include_ckm) ^
        ",heavy_fermions:" ^ (renderbool Module_options.include_hf) ^
        ",reduced_set_of_couplings:" ^ (renderbool Module_options.diet)
      ]
  end

```

Shamelessly stolen from *Modellib.SM3*, but with no support for fudged width yet

```

let default_width = ref Timelike

```

If this flag is set true, all gauge bosons are assumed to be massless and are assigned feynman gauge propagators. This in conjunction with the unbroken three site model is intended for checking gauge invariance via the ward identities.

```

let all_feynman = ref false
let options = Options.create [
  "constant_width", Arg.Unit (fun _ → default_width := Constant),
    "use_constant_width(also_in_t-channel)";
  "custom_width", Arg.String (fun x → default_width := Custom x),
    "use_custom_width";
  "cancel_widths", Arg.Unit (fun _ → default_width := Vanishing),
    "use_vanishing_width";
  "all_feynman", Arg.Unit (fun _ → all_feynman := true),
    "assign_feynman_gauge_propagators_to_all_gauge_bosons\n"

```

```

^ "\t(for checking the ward identities); use only if you *really* know\n"
^ "\twhat you are doing"]

```

The quantum numbers that are carried by the particles. *csign* is *not* the charge carried by the particle, but differentiates between particles (*Pos*) and antiparticles (*Neg*)

```

type kkmode = Light | Heavy
type generation = Gen0 | Gen1 | Gen2
type csign = Pos | Neg
type isospin = Iso-up | Iso-down

```

Necessary to represent the indices of the couplings defined in FORTRAN

```

type kk2 = Light2 | Heavy2 | Light_Heavy

```

Map the different types to the constants used in the FORTRAN module

```

let fspec_of_kkmode = function Light → "l_mode" | Heavy →
" h_mode"
let fspec_of_kk2 = function
  Light2 → "l_mode" | Heavy2 → "h_mode" | Light_Heavy →
"lh_mode"
let fspec_of_gen = function Gen0 → "gen_0" | Gen1 → "gen_1" |
Gen2 → "gen_2"
let fspec_of_iso = function Iso-up → "iso-up" | Iso-down →
"iso-down"

```

Covert the “charge sign” into a numeric sign (used e.g. in the determination of the MCID codes)

```

let int_of_csign = function Pos → 1 | Neg → -1

```

Convert the generation into an integer (dito)

```

let int_of_gen = function Gen0 → 1 | Gen1 → 2 | Gen2 → 3

```

The type *flavor* is implemented as a variant. Fermions are implemented as a variant differentiating between leptons and quarks (seemed the most natural way as this is also the way in which the FORTRAN code is structured). Bosons are implemented as a variant the differentiates between *W*, *Z* and *A*. All other quantum numbers that are required for identifying the particles are carried by the variant constructors.

```

type fermion =
  | Lepton of (kkmode × csign × generation × isospin)
  | Quark of (kkmode × csign × generation × isospin)

type boson =
  | W of (kkmode × csign)
  | Z of kkmode
  | A
  | G

type flavor = Fermion of fermion | Boson of boson

```

Helpers to construct particles from quantum numbers



```

let lepton kk cs gen iso = Lepton (kk, cs, gen, iso)
let quark kk cs gen iso = Quark (kk, cs, gen, iso)
let w kk cs = W (kk, cs)
let z kk = Z kk
let flavor_of_f x = Fermion x
let flavor_of_b x = Boson x

```

Map a list of functions to the list (partially) applied to a value

```
let revmap funs v = List.map (fun x → x v) funs
```

The same for a list of values; the result is flattened

```
let revmap2 funs vals = ThoList.flatmap (revmap funs) vals
```

Functions to loop the constructors over quantum numbers for list creation purposes

```

let loop_kk flist = revmap2 flist [Light; Heavy]
let loop_cs flist = revmap2 flist [Pos; Neg]
let loop_gen flist = revmap2 flist [Gen0; Gen1; Gen2]
let loop_iso flist = revmap2 flist [Iso_up; Iso_down]
let loop_kk2 flist = revmap2 flist [Light2; Heavy2; Light_Heavy]

```

Conditional looping over kk modes depending on whether to include heavy fermions

```

let cloop_kk flist = match Module_options.include_hf with
| true → loop_kk flist
| false → revmap flist Light
let cloop_kk2 flist = match Module_options.include_hf with
| true → loop_kk2 flist
| false → revmap flist Light2

```

Having defined the necessary helpers, the magic of currying makes building lists of particles as easy as nesting the loop functions in the correct order...

```

let all_leptons = loop_iso (loop_gen (loop_cs (cloop_kk [lepton] )))
let all_quarks = loop_iso (loop_gen (loop_cs (cloop_kk [quark] )))
let all_bosons = (loop_cs (loop_kk [w] )) @ [Z Light; Z Heavy; A; G]

```

Converts a flavor spec to the BCD identifier defined in the FORTRAN module. Splitting the function into two parts **prefix** and **rump** removes a lot of redundancy.

```

let bcdi_of_flavor =
let prefix = function
| Fermion (Lepton (Heavy, -, -, -)) | Fermion (Quark (Heavy, -, -, -))
| Boson (W (Heavy, -)) | Boson (Z Heavy) → "h"
| _ → ""
in let rump = function
| Fermion (Lepton spec) → (match spec with
| (-, -, Gen0, Iso_up) → "nue"
| (-, -, Gen0, Iso_down) → "e"
| (-, -, Gen1, Iso_up) → "numu"
| (-, -, Gen1, Iso_down) → "mu"

```

```

      | (-, -, Gen2, Iso-up) → "nutau"
      | (-, -, Gen2, Iso-down) → "tau"
    | Fermion (Quark spec) → (match spec with
      | (-, -, Gen0, Iso-up) → "u"
      | (-, -, Gen0, Iso-down) → "d"
      | (-, -, Gen1, Iso-up) → "c"
      | (-, -, Gen1, Iso-down) → "s"
      | (-, -, Gen2, Iso-up) → "t"
      | (-, -, Gen2, Iso-down) → "b")
    | Boson (W _) → "w" | Boson (Z _) → "z"
    | Boson A → invalid_arg (modname ^ ".bcd_of_flavor:_no_bcd_for_photon!")
    | Boson G → invalid_arg (modname ^ ".bcd_of_flavor:_no_bcd_for_gluon!")
  in function x → (prefix x) ^ (rump x) ^ "_bcd"

```

The function defined in the model signature which returns the colour representation of a particle

```

let color =
let quarkrep = function
  | (-, Pos, -, -) → Color.SUN 3
  | (-, Neg, -, -) → Color.SUN (-3)
in function
  | Fermion (Quark x) → quarkrep x
  | Boson G → Color.AdjSUN 3
  | _ → Color.Singlet

```

Function for calculating the MCID code of a particle. Conventions have been chosen such that the heavy modes are identified by the same numbers as the light ones, prefixed with 99. This is supposedly in accord with the conventions for adding new particles to the list of MCID codes. This function is required by the signature.

```

let pdg =
let iso_delta = function Iso-down → 0 | Iso-up → 1
in let gen_delta = function Gen0 → 0 | Gen1 → 2 | Gen2 → 4
in let kk_delta = function Light → 0 | Heavy → 9900
in function
  | Fermion (Lepton (kk, cs, gen, iso)) →
    (int_of_csign cs) × (11 + (gen_delta gen) + (iso_delta iso) + (kk_delta kk))
  | Fermion (Quark (kk, cs, gen, iso)) →
    (int_of_csign cs) × (1 + (gen_delta gen) + (iso_delta iso) + (kk_delta kk))
  | Boson (W (kk, cs)) → (int_of_csign cs) × (24 + (kk_delta kk))
  | Boson (Z kk) → 23 + (kk_delta kk)
  | Boson A → 22
  | Boson G → 21

```

Returns the lorentz representation of a particle; required by the signature.

```

let lorentz =
let spinor = function
  | (-, Pos, -, -) → Spinor
  | (-, Neg, -, -) → ConjSpinor
in function

```

```

| Fermion (Lepton x) | Fermion (Quark x) → spinor x
| Boson (W _) | Boson (Z _) → Massive_Vector
| Boson A → Vector
| Boson G → Vector

```

O'Mega supports models that allow different gauges; however, we only implement unitary gauge and therefore stub this (SM3 does the same thing). The `gauge` type as well as `gauge_symbol` are required by the signature.

```

type gauge = unit

let gauge_symbol () =
  failwith (modname ^ ".gauge_symbol: internal error")

```

Returns the propagator for a given particle type. Required by signature.

```

let propagator =
let spinorprop = function
  | (_, Pos, _, _) → Prop_Spinor
  | (_, Neg, _, _) → Prop_ConjSpinor
in function
  | Fermion (Lepton x) | Fermion (Quark x) → spinorprop x
  | Boson (W _) | Boson (Z _) →
    (match !all_feynman with false → Prop_Unitarity | true →
Prop_Feynman)
  | Boson A → Prop_Feynman
  | Boson G → Prop_Feynman

```

Return the width of a particle, required by signature.

*TODO:* Refine such that stable particles always are treade via vanishing width, as this might speed up the generated code a bit.

```

let width _ = !default_width

```

Returns the conjugate particle; required by signature.

```

let conjugate =
let conj_csign = function
  | Pos → Neg
  | Neg → Pos
in function
  | Fermion (Lepton (kk, cs, gen, iso)) → Fermion (Lepton (kk, conj_csign cs, gen, iso))
  | Fermion (Quark (kk, cs, gen, iso)) → Fermion (Quark (kk, conj_csign cs, gen, iso))
  | Boson (W (kk, cs)) → Boson (W (kk, conj_csign cs))
  | x → x

```

Tells the diagram generator whether a particle is a fermion, a conjugate fermion or a boson. Required by signature

```

let fermion = function
  | Fermion (Lepton (_, cs, _, _)) | Fermion (Quark (_, cs, _, _)) →
int_of_csign cs
  | Boson _ → 0

```

Charges are: charge, lepton number, baryon number, generation. Required by signature

```

module Ch = Charges.QQ
let ( // ) = Algebra.Small_Rational.make

let qn_charge = function
| Boson b → (match b with
| W (_, c) → (int_of_csign (c)) // 1
| _ → 0//1)
| Fermion f → (match f with
| Lepton (_, c, -, Iso_up) → 0//1
| Lepton (_, c, -, Iso_down) → (-1 × int_of_csign (c)) // 1
| Quark (_, c, -, Iso_up) → (2 × int_of_csign (c)) // 3
| Quark (_, c, -, Iso_down) → (-1 × int_of_csign (c)) // 3)

let qn_lepton = function
| Fermion (Lepton (_, c, -, -)) → int_of_csign (c) // 1
| _ → 0//1

let qn_baryon = function
| Fermion (Quark (_, c, -, -)) → int_of_csign (c) // 1
| _ → 0//1

```

Generation is conditional: if we enable the nontrivial CKM matrix, all particles carry generation 0; 0; 0

```

let qn_generation x =
let qn_cs gen =
let c = int_of_csign (cs) in
match gen with
| Gen0 → [c//1; 0//1; 0//1]
| Gen1 → [0//1; c//1; 0//1]
| Gen2 → [0//1; 0//1; c//1]
in
if Module_options.include_ckm then
[0//1; 0//1; 0//1]
else
match x with
| Fermion (Lepton (_, c, g, -)) → qn c g
| Fermion (Quark (_, c, g, -)) → qn c g
| _ → [0//1; 0//1; 0//1]

let charges x =
[qn_charge x; qn_lepton x; qn_baryon x] @ (qn_generation x)

```

A variant to represent the different coupling constants, choosen to mimic the FORTRAN part. Required by signature.

```

type constant =
| G_a_lep | G_a_quark of isospin
| G_auw | G_aaww
| G_w_lep of (kkmode × kkmode × generation × kkmode ×
generation)
| G_w_quark of (kkmode × kkmode × generation × kkmode ×
generation)
| G_z_lep of (kkmode × kk2 × generation × isospin)

```

```

| G_z_quark of (kkmode × kk2 × generation × isospin)
| G_wwz of (kk2 × kkmode)
| G_wwzz of (kk2 × kk2)
| G_wwza of (kk2 × kkmode)
| G_www of int
| G_s
| IG_s
| G_s2

```

Two integer counters for the QCD and EW order of the couplings.

```

type orders = int × int

let orders = function
| _ → (0,0)

```

Functions for the construction of constants from indices

```

let g_a_quark x = G_a_quark x
let g_w_lep kk1 kk2 gen1 kk3 gen2 = G_w_lep (kk1, kk2, gen1, kk3, gen2)
let g_w_quark kk1 kk2 gen1 kk3 gen2 = G_w_quark (kk1, kk2, gen1, kk3, gen2)
let g_z_lep kk1 kk2 gen iso = G_z_lep (kk1, kk2, gen, iso)
let g_z_quark kk1 kk2 gen iso = G_z_quark (kk1, kk2, gen, iso)
let g_wwz kk1 kk2 = G_wwz (kk1, kk2)
let g_wwzz kk1 kk2 = G_wwzz (kk1, kk2)
let g_wwza kk1 kk2 = G_wwza (kk1, kk2)
let g_www nhw = if (nhw ≥ 0) ∧ (nhw ≤ 4) then G_www nhw
                  else failwith (modname ^ ".g_www: invalid integer, very bad")

```

Build a list of the different constants

```

let clist = [G_a_lep; G_ww; G_wwz] @ (loop_iso [g_a_quark]) @
  (loop_gen (cloop_kk (loop_gen (cloop_kk (loop_kk [g_w_lep] )))) @
    (loop_gen (cloop_kk (loop_gen (cloop_kk (loop_kk [g_w_quark] )))) @
      (loop_iso (loop_gen (cloop_kk2 (loop_kk [g_z_lep] )))) @
        (loop_iso (loop_gen (cloop_kk2 (loop_kk [g_z_quark] )))) @
          (loop_kk (loop_kk2 [g_wwz] )) @ (loop_kk2 (loop_kk2 [g_wwzz] )) @
            (loop_kk (loop_kk2 [g_wwza] )) @ (List.map g_www [0; 1; 2; 3; 4])

```

Maximum number of lines meeting at a vertex, required by signature.

```

let max_degree () = 4

```

Transform a pair of kk identifiers into a kk2 identifier

```

let get_kk2 = function (Light, Light) → Light2 | (Heavy, Heavy) →
Heavy2
| (Light, Heavy) | (Heavy, Light) → Light_Heavy

```

Flip isospin

```

let conj_iso = function Iso_up → Iso_down | Iso_down → Iso_up

```

Below, lists of couplings are generated which ultimately are joined into a list of all couplings in the model. The generated lists can be viewed using the `dump.ml` script in the O'Mega toplevel directory.

The individual couplings are defined as 5-tuples resp. 6-tuples consisting in this

order of the particles meeting at the vertex, the coupling type (see `couplings.ml`) and the coupling constant.

List of *llA* type vertices

```
let vertices_all =
let vgen kk gen =
  ((Fermion (Lepton (kk, Neg, gen, Iso_down)), Boson A, Fermion (Lepton (kk, Pos, gen,
    Iso_down))), FBF(1, Psibar, V, Psi), G_a_lep)
in loop_gen (cloop_kk [vgen])
```

List of *qqA* type vertices

```
let vertices_aqq =
let vgen kk gen iso =
  ((Fermion (Quark (kk, Neg, gen, iso)), Boson A, Fermion (Quark (kk, Pos, gen,
    iso))), FBF(1, Psibar, V, Psi), G_a_quark iso)
in loop_iso (loop_gen (cloop_kk [vgen]))
```

List of  $\nu W$  type vertices

```
let vertices_wll =
let vgen kkw kk_f kk_fbar iso_f gen =
  ((Fermion (Lepton (kk_fbar, Neg, gen, conj_iso iso_f)),
    Boson (W (kkw, (match iso_f with Iso_up → Neg | _ →
Pos))),
    Fermion (Lepton (kk_f, Pos, gen, iso_f))),
    FBF (1, Psibar, VA2, Psi),
    G_w_lep (kkw, (match iso_f with Iso_up → kk_f | _ →
kk_fbar), gen,
    (match iso_f with Iso_up → kk_fbar | _ → kk_f), gen) )
in loop_gen (loop_iso (cloop_kk (cloop_kk (loop_kk [vgen] ))))
```

The same list, but without couplings between the  $W'$  and light fermions

```
let vertices_wll_diet =
let filter = function
  | ((Fermion (Lepton (Light, -, -, -)), Boson (W (Heavy, -)),
    Fermion (Lepton (Light, -, -, -))), -, -) → false
  | _ → true
in List.filter filter vertices_wll
```

List of *udW* type vertices, flavor-diagonal

```
let vertices_wqq_no_ckm =
let vgen kkw kk_f kk_fbar iso_f gen =
  ((Fermion (Quark (kk_fbar, Neg, gen, conj_iso iso_f)),
    Boson (W (kkw, (match iso_f with Iso_up → Neg | _ →
Pos))),
    Fermion (Quark (kk_f, Pos, gen, iso_f))),
    FBF (1, Psibar, VA2, Psi),
    G_w_quark (kkw, (match iso_f with Iso_up → kk_f | _ →
kk_fbar), gen,
    (match iso_f with Iso_up → kk_fbar | _ → kk_f), gen) )
in loop_gen (loop_iso (cloop_kk (cloop_kk (loop_kk [vgen] ))))
```

The same list, but without couplings between the  $W'$  and the first two generations of quarks

```
let vertices_wqq_no_ckm_diet =
let filter = function
  | ((Fermion (Quark (Light, -, gen, -)), Boson (W (Heavy, -))),
    Fermion (Quark (Light, -, -, -))), -, -) →
    (match gen with Gen2 → true | - → false)
  | - → true
in List.filter filter vertices_wqq_no_ckm
```

List of  $udW$  type vertices, including non flavor-diagonal couplings

```
let vertices_wqq =
let vgen kkw kk_f gen_f kk_fbar gen_fbar iso_f =
  ((Fermion (Quark (kk_fbar, Neg, gen_fbar, conj_iso iso_f)),
    Boson (W (kkw, (match iso_f with Iso_up → Neg | - →
Pos))),
    Fermion (Quark (kk_f, Pos, gen_f, iso_f))),
  FBF (1, Psibar, VA2, Psi),
  G_w_quark (match iso_f with
    | Iso_up → (kkw, kk_f, gen_f, kk_fbar, gen_fbar)
    | Iso_down → (kkw, kk_fbar, gen_fbar, kk_f, gen_f)))
in loop_iso (loop_gen (cloop_kk (loop_gen (cloop_kk (loop_kk [vgen] )))))
```

List of  $llZ$  /  $\nu\nu Z$  type vertices

```
let vertices_zll =
let vgen kkz kk_f kk_fbar gen iso =
  ((Fermion (Lepton (kk_fbar, Neg, gen, iso)), Boson (Z kkz),
    Fermion (Lepton (kk_f, Pos, gen, iso))),
  FBF (1, Psibar, VA2, Psi),
  G_z_lep (kkz, get_kk2 (kk_f, kk_fbar), gen, iso))
in loop_iso (loop_gen (cloop_kk (cloop_kk (loop_kk [vgen] )))))
```

List of  $qqZ$  type vertices

```
let vertices_zqq =
let vgen kkz kk_f kk_fbar gen iso =
  ((Fermion (Quark (kk_fbar, Neg, gen, iso)), Boson (Z kkz),
    Fermion (Quark (kk_f, Pos, gen, iso))),
  FBF (1, Psibar, VA2, Psi),
  G_z_quark (kkz, get_kk2 (kk_f, kk_fbar), gen, iso))
in loop_iso (loop_gen (cloop_kk (cloop_kk (loop_kk [vgen] )))))
```

$gq\bar{q}$

```
let vertices_gqq =
let vgen kk gen iso =
  ((Fermion (Quark (kk, Neg, gen, iso)), Boson G, Fermion (Quark (kk, Pos, gen, iso))),
  FBF (1, Psibar, V, Psi), G_s)
in loop_iso (loop_gen (cloop_kk [vgen]))
```

AWW

```
let vertices_aww =
```

```

let vgen kk =
  ((Boson A, Boson (W (kk, Pos)), Boson (W (kk, Neg))), Gauge_Gauge_Gauge 1, G_aww)
in loop_kk [vgen]

```

ZWW

```

let vertices_zww =
let vgen kkz kkwp kkwm =
  ((Boson (Z kkz), Boson (W (kkwp, Pos)), Boson (W (kkwm, Neg))), Gauge_Gauge_Gauge 1,
    G_wwz (get_kk2 (kkwp, kkwm), kkz))
in loop_kk (loop_kk (loop_kk [vgen]))

```

ggg

```

let vertices_ggg = [(Boson G, Boson G, Boson G), Gauge_Gauge_Gauge (-1), IG_s]

```

Stolen from Modellib.SM; the signs seem to be OK. See `couplings.ml` for more docs.

```

let gauge4 = Vector4 [(2, C_13_42); (-1, C_12_34); (-1, C_14_23)]
let minus_gauge4 = Vector4 [(-2, C_13_42); (1, C_12_34); (1, C_14_23)]

```

AAWW

```

let vertices_aaww =
let vgen kk =
  ((Boson A, Boson (W (kk, Pos)), Boson A, Boson (W (kk, Neg))), minus_gauge4, G_aaww)
in loop_kk [vgen]

```

WWZZ

```

let vertices_wwzz =
let vgen kkwp kkwm kk2z =
  ((Boson (Z (match kk2z with Heavy2 → Heavy | Light2 |
    Light_Heavy → Light)),
    Boson (W (kkwp, Pos)),
    Boson (Z (match kk2z with Heavy2 | Light_Heavy → Heavy |
    Light2 → Light)),
    Boson (W (kkwm, Neg))), minus_gauge4, G_wwzz (get_kk2 (kkwp, kkwm), kk2z))
in loop_kk2 (loop_kk (loop_kk [vgen]))

```

WWZA

```

let vertices_wwza =
let vgen kkwp kkwm kkz =
  ((Boson A, Boson (W (kkwp, Pos)), Boson (Z kkz), Boson (W (kkwm, Neg))),
    minus_gauge4, G_wwza (get_kk2 (kkwp, kkwm), kkz))
in loop_kk (loop_kk (loop_kk [vgen]))

```

WWWW

```

let vertices_wwww =
let count = function Light2 → 0 | Light_Heavy → 1 | Heavy2 → 2
in let vgen kk2wp kk2wm =
  ((Boson (W ((match kk2wp with Heavy2 → Heavy | Light2 |
    Light_Heavy → Light), Pos)),
    Boson (W ((match kk2wm with Heavy2 → Heavy | Light2 |
    Light_Heavy → Light), Neg))),

```



```

      Boson (W ((match kk2wp with Heavy2 | Light_Heavy → Heavy |
Light2 → Light), Pos)),
      Boson (W ((match kk2wm with Heavy2 | Light_Heavy →
Heavy | Light2 → Light), Neg))),
      gauge4, G_www ((count kk2wp) + (count kk2wm)))
in loop_kk2 (loop_kk2 [vgen])
gggg
let vertices_gggg = [(Boson G, Boson G, Boson G, Boson G), gauge4, G_s2]

```

The list of couplings is transformed into the fusion lists required by the generator by the `Model.Fusions` functor.

This is copy& paste from the other models; check again with Thorsten if it is correct

```

module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end )

```

Not sure yet whether `F.fusex` also creates the conjugate vertices; by looking at the implementation of the other models, I assume it doesn't. Still, better ask Thorsten to be sure!!!

*Update:* Still didn't get to ask, but since the results are consistent, I suspect my assertion is correct.

The stuff below is required by the signature.

```

let vertices () = (vertices_all @ vertices_aqq @
  (match Module_options.diet with
    | false → vertices_wll
    | true → vertices_wll_diet) @
  (match (Module_options.include_ckm, Module_options.diet) with
    | (true, false) → vertices_wqq
    | (false, false) → vertices_wqq_no_ckm
    | (false, true) → vertices_wqq_no_ckm_diet
    | (true, true) → raise (Failure
      ("Modules4.Threeshl.vertices:_CKM_matrix_together_with_option_diet_is_not" ^
        "_implemented_yet!")))) @
  vertices_zll @ vertices_zqq @ vertices_auw @ vertices_zww @ vertices_gqq @ vertices_ggg,
  vertices_aaww @ vertices_wuzz @ vertices_wuza @ vertices_www @ vertices_gggg
, [])
let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table

```

A function that returns a list of a flavours known to the model, required by the signature.

```

let flavors () = (List.map flavor_of_f (all_leptons @ all_quarks)) @
  (List.map flavor_of_b all_bosons)

```

dito, external flavours, also required.

```
let external_flavors () = [
  "light_leptons", List.map flavor_of_f (loop_iso (loop_gen (loop_cs [lepton Light])));
  "light_quarks", List.map flavor_of_f (loop_iso (loop_gen (loop_cs [quark Light])));
  "light_gauge_bosons", List.map flavor_of_b [W (Light, Pos); W (Light, Neg); Z Light; A];
  "heavy_gauge_bosons", List.map flavor_of_b [W (Heavy, Pos); W (Heavy, Neg); Z Heavy] @
  (match Module_options.include_hf with
  | true → [
    "heavy_leptons", List.map flavor_of_f (loop_iso (loop_gen (loop_cs [lepton Heavy])));
    "heavy_quarks", List.map flavor_of_f (loop_iso (loop_gen (loop_cs [quark Heavy])))]
  | false → []) @ ["gluons", [Boson G]]
```

Which of the particles are goldstones? → none. Required by the signature.

```
let goldstone x = None
```

This is wrong but handy for debugging the constant identifier generation via -params. Usually, this function would return a record consisting of the parameters as well as expression for the dependent quantities that can be used to generate FORTRAN code for calculating them. However, we have a separate module for the threeshl, so we can abuse this for debugging. Required by signature.

```
let parameters () = {input = List.map (fun x → (x, 0.)) clist;
  derived = []; derived_arrays = []}
```

Convert a flavour into a ID string with which it will be referred by the user interface of the compiled generator. Required by signature

```
let flavor_to_string =
let prefix = function
  | Fermion (Lepton (Heavy, -, -, -)) | Fermion (Quark (Heavy, -, -, -))
  | Boson (W (Heavy, -)) | Boson (Z Heavy) → "H"
  | _ → ""
in let postfix = function
  | Fermion (Lepton (-, cs, -, Iso_down)) → (match cs with Pos →
  "-" | Neg → "+")
  | Fermion (Quark (-, Neg, -, -)) | Fermion (Lepton (-, Neg, -, Iso_up)) →
  "bar"
  | Boson (W (-, cs)) → (match cs with Pos → "+" | Neg → "-")
  | _ → ""
in let rump = function
  | Fermion (Lepton desc) → (match desc with
  | (-, -, Gen0, Iso_up) → "nue"
  | (-, -, Gen0, Iso_down) → "e"
  | (-, -, Gen1, Iso_up) → "numu"
  | (-, -, Gen1, Iso_down) → "mu"
  | (-, -, Gen2, Iso_up) → "nutau"
  | (-, -, Gen2, Iso_down) → "tau")
  | Fermion (Quark desc) → (match desc with
  | (-, -, Gen0, Iso_up) → "u"
  | (-, -, Gen0, Iso_down) → "d"
  | (-, -, Gen1, Iso_up) → "c"
```

```

      | (-, -, Gen1, Iso_down) → "s"
      | (-, -, Gen2, Iso_up) → "t"
      | (-, -, Gen2, Iso_down) → "b")
    | Boson (W _) → "W" | Boson (Z _) → "Z" | Boson A → "A" |
    Boson G → "g1"
    in function x → (prefix x) ^ (rump x) ^ (postfix x)

```

Conversion of the ID string into a particle flavor. Instead of going through all cases again, we generate a “dictionary” of flavor / ID pairs which we use to identify the correct flavor. Required by signature.

```

let flavor_of_string x =
let dict = List.map (fun x → (x, flavor_to_string x)) (flavors ())
in let get_ident = function (x, _) → x
in try
  get_ident (List.find (fun (_, y) → (x = y)) dict)
with
  Not_found → (match x with
    | "g" → Boson G
    | _ → invalid_arg (modname ^ ".flavor_of_string")
  )

```

Converts a flavor into a symbol used as identification in the generated FORTRAN code (has to comply to the conventions of valid FORTRAN identifiers therefore). We stick to the same conventions as SM3, prefixing heavy modes with a H. Required by signature.

```

let flavor_symbol =
let prefix = function
  | Fermion (Lepton (Heavy, -, -, -)) | Fermion (Quark (Heavy, -, -, -))
  | Boson (W (Heavy, -)) | Boson (Z Heavy) → "H"
  | _ → ""
in let postfix = function
  | Fermion (Lepton (_, Neg, -, -)) | Fermion (Quark (_, Neg, -, -)) →
  "b"
  | _ → ""
in let rump = function
  | Fermion spec → (match spec with
    | Lepton (_, -, gen, Iso_up) → "n" ^ (string_of_int (int_of_gen gen))
    | Lepton (_, -, gen, Iso_down) → "l" ^ (string_of_int (int_of_gen gen))
    | Quark (_, -, gen, Iso_up) → "u" ^ (string_of_int (int_of_gen gen))
    | Quark (_, -, gen, Iso_down) → "d" ^ (string_of_int (int_of_gen gen)))
  | Boson spec → (match spec with
    | W (_, Pos) → "wp" | W (_, Neg) → "wm"
    | Z _ → "z" | A → "a" | G → "g1" )
in function
  x → (prefix x) ^ (rump x) ^ (postfix x)

```

Generate TeX for a flavor

```

let flavor_to_TeX =
let bar x y = match x with Neg → "\\overline{" ^ y ^ "}" | Pos →
y

```

```

in let pm x y = match x with Neg → "{" ^ y ^ "}^+" | Pos →
"{" ^ y ^ "}^~"
in let prime x y = match x with Light → y | Heavy → "{" ^ y ^ "}^\\prime"
in function
  | Fermion (Lepton desc) → (match desc with
    | (kk, cs, gen, Iso_up) → prime kk (bar cs (match gen with
      | Gen0 → "\\nu-e"
      | Gen1 → "\\nu-\\mu"
      | Gen2 → "\\nu-\\tau"))
    | (kk, cs, gen, Iso_down) → prime kk (pm cs (match gen with
      | Gen0 → "e" | Gen1 → "\\mu" | Gen2 → "\\tau"))))
  | Fermion (Quark (kk, cs, gen, iso)) → prime kk (bar cs (match (gen, iso) with
    | (Gen0, Iso_up) → "u"
    | (Gen0, Iso_down) → "d"
    | (Gen1, Iso_up) → "c"
    | (Gen1, Iso_down) → "s"
    | (Gen2, Iso_up) → "t"
    | (Gen2, Iso_down) → "b"))
  | Boson spec → (match spec with
    | W (kk, cs) → prime kk (pm (match cs with Pos → Neg |
Neg → Pos) "W")
    | Z kk → prime kk "Z"
    | A → "A" | G → "g")

```

Returns the string referring to the particle mass in the generated FORTRAN code. Required by signature.

```

let mass_symbol = function
  | Boson A | Boson G → "0._default"
  | x → "mass_array(" ^ (bcdi_of_flavor x) ^ ")"

```

Dito, for width. Required by signature.

```

let width_symbol = function
  | Boson A | Boson G → "0._default"
  | x → "width_array(" ^ (bcdi_of_flavor x) ^ ")"

```

Determines the string referring to a coupling constant in the generated FORTRAN code. Required by signature.

```

let constant_symbol =
let c = ",_□"
in let g_w_ferm = function
  (kk1, kk2, gen1, kk3, gen2) →
    ":",_□" ^ (fspec_of_kkmode kk1) ^ c ^ (fspec_of_kkmode kk2) ^ c ^ (fspec_of_gen gen1) ^ c ^
    (fspec_of_kkmode kk3) ^ c ^ (fspec_of_gen gen2)
in let g_z_ferm = function
  (kk1, kk2, gen, iso) →
    ":",_□" ^ (fspec_of_kkmode kk1) ^ c ^ (fspec_of_kk2 kk2) ^ c ^ (fspec_of_gen gen) ^ c ^
    (fspec_of_iso iso)
in function
  | G_a_lep → "g_a_lep"
  | G_s → "g_s_norm"

```

```

| IG_s → "ig-s-norm"
| G_s2 → "g-s-norm2"
| G_a-quark iso → "g-a-quark(" ^ (fspec_of_iso iso) ^ ")"
| G_auw → "ig-aww"
| G_aauw → "g-aauw"
| G_w-lep spec → "g-w-lep-va(" ^ (g_w-ferm spec) ^ ")"
| G_w-quark spec → "g-w-quark-va(" ^ (g_w-ferm spec) ^ ")"
| G_z-lep spec → "g-z-lep-va(" ^ (g_z-ferm spec) ^ ")"
| G_z-quark spec → "g-z-quark-va(" ^ (g_z-ferm spec) ^ ")"
| G_wwz (kk1, kk2) → "ig-wwz(" ^ (fspec_of_kk2 kk1) ^ c ^
  (fspec_of_kkmode kk2) ^ ")"
| G_wwzz (kk1, kk2) → "g-wwzz(" ^ (fspec_of_kk2 kk1) ^ c ^
  (fspec_of_kkmode kk2) ^ ")"
| G_wwza (kk1, kk2) → "g-wwza(" ^ (fspec_of_kk2 kk1) ^ c ^
  (fspec_of_kkmode kk2) ^ ")"
| G_www nhw → if (0 ≤ nhw) ∧ (nhw ≤ 4) then
  "g_www(" ^ (string_of_int nhw) ^ ")"
  else failwith "Modules4.Thresh1.constant_symbol: invalid int for G_www; very bad"
end

```

### 13.6.3 2HDM with and without non-trivial flavor structure

```

module type THDM_flags =
sig
  val ckm_present : bool
end

module THDM : THDM_flags =
struct
  let ckm_present = false
end

module THDM_CKM : THDM_flags =
struct
  let ckm_present = true
end

module TwoHiggsDoublet (Flags : THDM_flags) =
struct
  let rcs = rcs_file

  open Coupling

  let default_width = ref Timelike
  let use_fudged_width = ref false

  let options = Options.create
  [ "constant_width", Arg.Unit (fun () → default_width := Constant),
    "use_constant_width(also_in_t-channel)";
    "fudged_width", Arg.Set use_fudged_width,
    "use_fudge_factor_for_charge_particle_width";
    "custom_width", Arg.String (fun f → default_width := Custom f),

```

```

    "use_custom_width";
    "cancel_widths", Arg.Unit (fun () → default_width := Vanishing),
    "use_vanishing_width" ]

type matter_field = L of int | N of int | U of int | D of int
type gauge_boson = Ga | Wp | Wm | Z | Gl
type other = Phip | Phim | Phi0 | Hh | HA | HH | Hp | Hm
type flavor = M of matter_field | G of gauge_boson | O of other

let matter_field f = M f
let gauge_boson f = G f
let other f = O f

type field =
| Matter of matter_field
| Gauge of gauge_boson
| Other of other

let field = function
| M f → Matter f
| G f → Gauge f
| O f → Other f

type gauge = unit

let gauge_symbol () =
    failwith "Modellib_BSM.TwoHiggsDoublet.gauge_symbol: internal_error"

let family n = List.map matter_field [ L n; N n; U n; D n ]

let external_flavors () =
[ "1st_Generation", ThoList.flatmap family [1; -1];
  "2nd_Generation", ThoList.flatmap family [2; -2];
  "3rd_Generation", ThoList.flatmap family [3; -3];
  "Gauge_Bosons", List.map gauge_boson [Ga; Z; Wp; Wm; Gl];
  "Higgs", List.map other [Hh; HH; HA; Hp; Hm];
  "Goldstone_Bosons", List.map other [Phip; Phim; Phi0] ]

let flavors () = ThoList.flatmap snd (external_flavors ())

let spinor n =
    if n ≥ 0 then
        Spinor
    else
        ConjSpinor

let lorentz = function
| M f →
    begin match f with
    | L n → spinor n | N n → spinor n
    | U n → spinor n | D n → spinor n
    end
| G f →
    begin match f with
    | Ga | Gl → Vector
    | Wp | Wm | Z → Massive_Vector

```

```

    end
  |  $O f \rightarrow \text{Scalar}$ 

let color = function
  |  $M (U n) \rightarrow \text{Color.SUN (if } n > 0 \text{ then } 3 \text{ else } -3)$ 
  |  $M (D n) \rightarrow \text{Color.SUN (if } n > 0 \text{ then } 3 \text{ else } -3)$ 
  |  $G Gl \rightarrow \text{Color.AdjSUN } 3$ 
  |  $- \rightarrow \text{Color.Singlet}$ 

let prop_spinor n =
  if  $n \geq 0$  then
    Prop_Spinor
  else
    Prop_ConjSpinor

let propagator = function
  |  $M f \rightarrow$ 
    begin match f with
    |  $L n \rightarrow \text{prop\_spinor } n$  |  $N n \rightarrow \text{prop\_spinor } n$ 
    |  $U n \rightarrow \text{prop\_spinor } n$  |  $D n \rightarrow \text{prop\_spinor } n$ 
    end
  |  $G f \rightarrow$ 
    begin match f with
    | Ga | Gl  $\rightarrow \text{Prop\_Feynman}$ 
    | Wp | Wm | Z  $\rightarrow \text{Prop\_Unitarity}$ 
    end
  |  $O f \rightarrow$ 
    begin match f with
    | Phip | Phim | Phi0  $\rightarrow \text{Only\_Insertion}$ 
    | Hh | HH | HA | Hp | Hm  $\rightarrow \text{Prop\_Scalar}$ 
    end

```

Optionally, ask for the fudge factor treatment for the widths of charged particles. Currently, this only applies to  $W^\pm$  and top.

```

let width f =
  if !use_fudged_width then
    match f with
    |  $G Wp$  |  $G Wm$  |  $M (U 3)$  |  $M (U (-3)) \rightarrow \text{Fudged}$ 
    |  $- \rightarrow \text{!default\_width}$ 
  else
    !default_width

let goldstone = function
  |  $G f \rightarrow$ 
    begin match f with
    | Wp  $\rightarrow \text{Some (O Phip, Coupling.Const 1)}$ 
    | Wm  $\rightarrow \text{Some (O Phim, Coupling.Const 1)}$ 
    | Z  $\rightarrow \text{Some (O Phi0, Coupling.Const 1)}$ 
    |  $- \rightarrow \text{None}$ 
    end
  |  $- \rightarrow \text{None}$ 

```

```

let conjugate = function
| M f →
  M (begin match f with
    | L n → L (-n) | N n → N (-n)
    | U n → U (-n) | D n → D (-n)
  end)
| G f →
  G (begin match f with
    | Gl → Gl | Ga → Ga | Z → Z
    | Wp → Wm | Wm → Wp
  end)
| O f →
  O (begin match f with
    | Phip → Phim | Phim → Phip | Phi0 → Phi0
    | Hh → Hh | HH → HH | HA → HA
    | Hp → Hm | Hm → Hp
  end)

let fermion = function
| M f →
  begin match f with
    | L n → if n > 0 then 1 else -1
    | N n → if n > 0 then 1 else -1
    | U n → if n > 0 then 1 else -1
    | D n → if n > 0 then 1 else -1
  end
| G f →
  begin match f with
    | Gl | Ga | Z | Wp | Wm → 0
  end
| O _ → 0

```

Electrical charge, lepton number, baryon number. We could avoid the rationals altogether by multiplying the first and last by 3 ...

```

module Ch = Charges.QQ
let ( // ) = Algebra.Small_Rational.make

let generation' = function
| 1 → [ 1//1; 0//1; 0//1]
| 2 → [ 0//1; 1//1; 0//1]
| 3 → [ 0//1; 0//1; 1//1]
| -1 → [-1//1; 0//1; 0//1]
| -2 → [ 0//1; -1//1; 0//1]
| -3 → [ 0//1; 0//1; -1//1]
| n → invalid_arg ("Modellib_BSM.TwoHiggsDoublet.generation':_" ^ string_of_int n)

let generation f =
  if Flags.ckm_present then
    []
  else
    match f with
    | M (L n | N n | U n | D n) → generation' n

```



```

|  $G_-$  |  $O_-$   $\rightarrow$  [ 0//1; 0//1; 0//1]

let charge = function
|  $M f$   $\rightarrow$ 
  begin match  $f$  with
  |  $L n$   $\rightarrow$  if  $n > 0$  then -1//1 else 1//1
  |  $N n$   $\rightarrow$  0//1
  |  $U n$   $\rightarrow$  if  $n > 0$  then 2//3 else -2//3
  |  $D n$   $\rightarrow$  if  $n > 0$  then -1//3 else 1//3
  end
|  $G f$   $\rightarrow$ 
  begin match  $f$  with
  |  $Gl$  |  $Ga$  |  $Z$   $\rightarrow$  0//1
  |  $Wp$   $\rightarrow$  1//1
  |  $Wm$   $\rightarrow$  -1//1
  end
|  $O f$   $\rightarrow$ 
  begin match  $f$  with
  |  $Hh$  |  $HH$  |  $HA$  |  $Phi0$   $\rightarrow$  0//1
  |  $Hp$  |  $Phi p$   $\rightarrow$  1//1
  |  $Hm$  |  $Phi m$   $\rightarrow$  -1//1
  end

let lepton = function
|  $M f$   $\rightarrow$ 
  begin match  $f$  with
  |  $L n$  |  $N n$   $\rightarrow$  if  $n > 0$  then 1//1 else -1//1
  |  $U_-$  |  $D_-$   $\rightarrow$  0//1
  end
|  $G_-$  |  $O_-$   $\rightarrow$  0//1

let baryon = function
|  $M f$   $\rightarrow$ 
  begin match  $f$  with
  |  $L_-$  |  $N_-$   $\rightarrow$  0//1
  |  $U n$  |  $D n$   $\rightarrow$  if  $n > 0$  then 1//1 else -1//1
  end
|  $G_-$  |  $O_-$   $\rightarrow$  0//1

let charges  $f$  =
[ charge  $f$ ; lepton  $f$ ; baryon  $f$ ] @ generation  $f$ 

type constant =
| Unit | Pi | Alpha_QED | Sin2thw
| Sinhw | Costhw | E | G_weak | Vev
| Q_lepton | Q_up | Q_down | G_CC
| G_NC_neutrino | G_NC_lepton | G_NC_up | G_NC_down
| I_Q_W | I_G_ZWW | I_G_WWW
| G_WWWW | G_ZZWW | G_AZWW | G_AAWW
| G_htt | G_hbb | G_hcc | G_hatautau | G_hmumu
| G_Htt | G_Hbb | G_Hcc | G_Hatautau | G_Hmumu
| I_G_Att | I_G_Abb | I_G_Acc | I_G_Atautau | I_G_Amumu
| G_Htb | G_Hcs | G_Htaunu | G_Hmunu

```

---

		$G_s$		$I_{-G_s}$		$G_2$									
		$G_{-AHpHm}$		$G_{-ZHpHm}$		$G_{-Zh1h2}$		$G_{-Zh1h3}$		$G_{-Zh2h3}$					
		$G_{-WpHmh1}$		$G_{-WpHmh2}$		$G_{-WpHmh3}$		$G_{-WmHph1}$							
$G_{-WmHph2}$															
		$G_{-WmHph3}$		$G_{-h1ZZ}$		$G_{-h2ZZ}$		$G_{-h3ZZ}$		$G_{-h1WpWm}$					
$G_{-h2WpWm}$															
		$G_{-h3WpWm}$		$G_{-hhWpWm}$		$G_{-hhZZ}$		$G_{-HpHmAA}$							
$G_{-HpHmZZ}$		$G_{-HpHmAZ}$													
		$G_{-HpHmWpWm}$		$G_{-h1HpAWm}$		$G_{-h2HpAWm}$		$G_{-h3HpAWm}$							
$G_{-h1HpZWm}$															
		$G_{-h2HpZWm}$		$G_{-h3HpZWm}$		$G_{-h1HpAWmC}$		$G_{-h2HpAWmC}$							
$G_{-h3HpAWmC}$															
		$G_{-h1HpZWmC}$		$G_{-h2HpZWmC}$		$G_{-h3HpZWmC}$		$G_{-h1HpHm}$							
$G_{-h2HpHm}$		$G_{-h3HpHm}$													
		$G_{-h111}$		$G_{-h112}$		$G_{-h113}$		$G_{-h221}$		$G_{-h222}$		$G_{-h223}$			
$G_{-h331}$		$G_{-h332}$													
		$G_{-h333}$		$G_{-h123}$		$G_{-HpHmHpHm}$		$G_{-HpHm11}$		$G_{-HpHm12}$					
$G_{-HpHm13}$															
		$G_{-HpHm22}$		$G_{-HpHm23}$		$G_{-HpHm33}$		$G_{-h1111}$		$G_{-h1112}$					
$G_{-h1113}$															
		$G_{-h1122}$		$G_{-h1123}$		$G_{-h1133}$		$G_{-h1222}$		$G_{-h1223}$					
$G_{-h1233}$		$G_{-h1333}$													
		$G_{-h2222}$		$G_{-h2223}$		$G_{-h2233}$		$G_{-h2333}$		$G_{-h3333}$					
		$G_{-h1uu}$		$G_{-h2uu}$		$G_{-h3uu}$		$G_{-h1uc}$		$G_{-h2uc}$		$G_{-h3uc}$			
$G_{-h1ut}$															
		$G_{-h2ut}$		$G_{-h3ut}$		$G_{-h1cu}$		$G_{-h2cu}$		$G_{-h3cu}$		$G_{-h1cc}$			
$G_{-h2cc}$															
		$G_{-h3cc}$		$G_{-h1ct}$		$G_{-h2ct}$		$G_{-h3ct}$		$G_{-h1tu}$		$G_{-h2tu}$			
$G_{-h3tu}$															
		$G_{-h1tc}$		$G_{-h2tc}$		$G_{-h3tc}$		$G_{-h1tt}$		$G_{-h2tt}$		$G_{-h3tt}$			
		$G_{-h1dd}$		$G_{-h2dd}$		$G_{-h3dd}$		$G_{-h1ds}$		$G_{-h2ds}$		$G_{-h3ds}$			
$G_{-h1db}$															
		$G_{-h2db}$		$G_{-h3db}$		$G_{-h1sd}$		$G_{-h2sd}$		$G_{-h3sd}$		$G_{-h1ss}$			
$G_{-h2ss}$															
		$G_{-h3ss}$		$G_{-h1sb}$		$G_{-h2sb}$		$G_{-h3sb}$		$G_{-h1bd}$		$G_{-h2bd}$			
$G_{-h3bd}$															
		$G_{-h1bs}$		$G_{-h2bs}$		$G_{-h3bs}$		$G_{-h1bb}$		$G_{-h2bb}$		$G_{-h3bb}$			
		$G_{-hud}$		$G_{-hus}$		$G_{-hub}$		$G_{-hcd}$		$G_{-hcs}$		$G_{-hcb}$		$G_{-htd}$	
$G_{-hts}$		$G_{-htb}$													
		$G_{-hdu}$		$G_{-hdc}$		$G_{-hdt}$		$G_{-hsu}$		$G_{-hsc}$		$G_{-hst}$		$G_{-hbu}$	
$G_{-hbc}$		$G_{-hbt}$													
		$G_{-he1n1}$		$G_{-he1n2}$		$G_{-he1n3}$		$G_{-he2n1}$		$G_{-he2n2}$					
$G_{-he2n3}$		$G_{-he3n1}$													
		$G_{-he3n2}$		$G_{-he3n3}$		$G_{-hn1e1}$		$G_{-hn1e2}$		$G_{-hn1e3}$					
$G_{-hn2e1}$		$G_{-hn2e2}$													
		$G_{-hn2e3}$		$G_{-hn3e1}$		$G_{-hn3e2}$		$G_{-hn3e3}$							
		$G_{-h1e1e1}$		$G_{-h2e1e1}$		$G_{-h3e1e1}$		$G_{-h1e1e2}$		$G_{-h2e1e2}$					
$G_{-h3e1e2}$															
		$G_{-h1e1e3}$		$G_{-h2e1e3}$		$G_{-h3e1e3}$		$G_{-h1e2e1}$		$G_{-h2e2e1}$					
$G_{-h3e2e1}$															

```

      | G_h1e2e2 | G_h2e2e2 | G_h3e2e2 | G_h1e2e3 | G_h2e2e3 |
G_h3e2e3
      | G_h1e3e1 | G_h2e3e1 | G_h3e3e1 | G_h1e3e2 | G_h2e3e2 |
G_h3e3e2
      | G_h1e3e3 | G_h2e3e3 | G_h3e3e3
      | Mass of flavor | Width of flavor

```

Two integer counters for the QCD and EW order of the couplings.

```

type orders = int × int

let orders = function
  | - → (0,0)

let g_over_2_csth =
  Quot (Neg (Atom G_weak), Prod [Const 2; Atom Costhw])

let nc_coupling c t3 q =
  (Real_Array c,
   [Prod [g_over_2_csth; Diff (t3, Prod [Const 2; q; Atom Sin2thw]);
    Prod [g_over_2_csth; t3]])

let half = Quot (Const 1, Const 2)

let array_list = [G_h1uu; G_h2uu; G_h3uu; G_h1uc; G_h2uc; G_h3uc; G_h1ut;
  G_h2ut; G_h3ut; G_h1cu; G_h2cu; G_h3cu; G_h1cc; G_h2cc;
  G_h3cc; G_h1ct; G_h2ct; G_h3ct; G_h1tu; G_h2tu; G_h3tu;
  G_h1tc; G_h2tc; G_h3tc; G_h1tt; G_h2tt; G_h3tt;
  G_h1dd; G_h2dd; G_h3dd; G_h1ds; G_h2ds; G_h3ds; G_h1db;
  G_h2db; G_h3db; G_h1sd; G_h2sd; G_h3sd; G_h1ss; G_h2ss;
  G_h3ss; G_h1sb; G_h2sb; G_h3sb; G_h1bd; G_h2bd; G_h3bd;
  G_h1bs; G_h2bs; G_h3bs; G_h1bb; G_h2bb; G_h3bb;
  G_hud; G_hus; G_hub; G_hcd; G_hcs; G_hcb; G_htd; G_hts; G_htb;
  G_hdu; G_hdc; G_hdt; G_hsu; G_hsc; G_hst; G_hbu; G_hbc; G_hbt;
  G_he1n1; G_he1n2; G_he1n3; G_he2n1; G_he2n2; G_he2n3; G_he3n1;
  G_he3n2; G_he3n3; G_hn1e1; G_hn1e2; G_hn1e3; G_hn2e1; G_hn2e2;
  G_hn2e3; G_hn3e1; G_hn3e2; G_hn3e3;
  G_h1e1e1; G_h2e1e1; G_h3e1e1; G_h1e1e2; G_h2e1e2; G_h3e1e2;
  G_h1e1e3; G_h2e1e3; G_h3e1e3; G_h1e2e1; G_h2e2e1; G_h3e2e1;
  G_h1e2e2; G_h2e2e2; G_h3e2e2; G_h1e2e3; G_h2e2e3; G_h3e2e3;
  G_h1e3e1; G_h2e3e1; G_h3e3e1; G_h1e3e2; G_h2e3e2; G_h3e3e2;
  G_h1e3e3; G_h2e3e3; G_h3e3e3]

let add_complex_array_tag c = (Complex_Array c, [Const 0; Const 0])

let derived_parameter_arrays =
  [ nc_coupling G_NC_neutrino half (Const 0);
    nc_coupling G_NC_lepton (Neg half) (Const (-1));
    nc_coupling G_NC_up half (Quot (Const 2, Const 3));
    nc_coupling G_NC_down (Neg half) (Quot (Const (-1), Const 3));
  ] @ (List.map add_complex_array_tag array_list)

let parameters () =
  { input = []; derived = []; derived_arrays = derived_parameter_arrays }

```

```

module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)

```

$$\mathcal{L}_{\text{EM}} = -e \sum_i q_i \bar{\psi}_i \not{A} \psi_i \quad (13.46)$$

```

let mgm ((m1, g, m2), fbf, c) = ((M m1, G g, M m2), fbf, c)

```

```

let electromagnetic_currents n =
  List.map mgm
    [ ((L (-n), Ga, L n), FBF (1, Psibar, V, Psi), Q_lepton);
      ((U (-n), Ga, U n), FBF (1, Psibar, V, Psi), Q_up);
      ((D (-n), Ga, D n), FBF (1, Psibar, V, Psi), Q_down) ]

```

```

let color_currents n =
  List.map mgm
    [ ((U (-n), Gl, U n), FBF (1, Psibar, V, Psi), Gs);
      ((D (-n), Gl, D n), FBF (1, Psibar, V, Psi), Gs) ]

```

$$\mathcal{L}_{\text{NC}} = -\frac{g}{2 \cos \theta_W} \sum_i \bar{\psi}_i \not{Z} (g_V^i - g_A^i \gamma_5) \psi_i \quad (13.47)$$

```

let neutral_currents n =
  List.map mgm
    [ ((L (-n), Z, L n), FBF (1, Psibar, VA, Psi), G_NC_lepton);
      ((N (-n), Z, N n), FBF (1, Psibar, VA, Psi), G_NC_neutrino);
      ((U (-n), Z, U n), FBF (1, Psibar, VA, Psi), G_NC_up);
      ((D (-n), Z, D n), FBF (1, Psibar, VA, Psi), G_NC_down) ]

```

$$\mathcal{L}_{\text{CC}} = -\frac{g}{2\sqrt{2}} \sum_i \bar{\psi}_i (T^+ \not{W}^+ + T^- \not{W}^-) (1 - \gamma_5) \psi_i \quad (13.48)$$

```

let charged_currents n =
  List.map mgm
    [ ((L (-n), Wm, N n), FBF (1, Psibar, VL, Psi), G_CC);
      ((N (-n), Wp, L n), FBF (1, Psibar, VL, Psi), G_CC);
      ((D (-n), Wm, U n), FBF (1, Psibar, VL, Psi), G_CC);
      ((U (-n), Wp, D n), FBF (1, Psibar, VL, Psi), G_CC) ]

```

```

let yukawa =
  [ ((M (U (-1)), O Hh, M (U 1)), FBF (1, Psibar, SP, Psi), G_h1uu);
    ((M (U (-1)), O HH, M (U 1)), FBF (1, Psibar, SP, Psi), G_h2uu);
    ((M (U (-1)), O HA, M (U 1)), FBF (1, Psibar, SP, Psi), G_h3uu);
    ((M (U (-2)), O Hh, M (U 2)), FBF (1, Psibar, SP, Psi), G_h1cc);
    ((M (U (-2)), O HH, M (U 2)), FBF (1, Psibar, SP, Psi), G_h2cc);
    ((M (U (-2)), O HA, M (U 2)), FBF (1, Psibar, SP, Psi), G_h3cc);
    ((M (U (-3)), O Hh, M (U 3)), FBF (1, Psibar, SP, Psi), G_h1tt);

```

```

((M (U (-3)), O HH, M (U 3)), FBF (1, Psibar, SP, Psi), G_h2tt);
((M (U (-3)), O HA, M (U 3)), FBF (1, Psibar, SP, Psi), G_h3tt);

((M (D (-1)), O Hh, M (D 1)), FBF (1, Psibar, SP, Psi), G_h1dd);
((M (D (-1)), O HH, M (D 1)), FBF (1, Psibar, SP, Psi), G_h2dd);
((M (D (-1)), O HA, M (D 1)), FBF (1, Psibar, SP, Psi), G_h3dd);
((M (D (-2)), O Hh, M (D 2)), FBF (1, Psibar, SP, Psi), G_h1ss);
((M (D (-2)), O HH, M (D 2)), FBF (1, Psibar, SP, Psi), G_h2ss);
((M (D (-2)), O HA, M (D 2)), FBF (1, Psibar, SP, Psi), G_h3ss);
((M (D (-3)), O Hh, M (D 3)), FBF (1, Psibar, SP, Psi), G_h1bb);
((M (D (-3)), O HH, M (D 3)), FBF (1, Psibar, SP, Psi), G_h2bb);
((M (D (-3)), O HA, M (D 3)), FBF (1, Psibar, SP, Psi), G_h3bb);

((M (U (-1)), O Hp, M (D 1)), FBF (1, Psibar, SP, Psi), G_hud);
((M (U (-2)), O Hp, M (D 2)), FBF (1, Psibar, SP, Psi), G_hcs);
((M (U (-3)), O Hp, M (D 3)), FBF (1, Psibar, SP, Psi), G_htb);

((M (D (-1)), O Hm, M (U 1)), FBF (1, Psibar, SP, Psi), G_hdu);
((M (D (-2)), O Hm, M (U 2)), FBF (1, Psibar, SP, Psi), G_hsc);
((M (D (-3)), O Hm, M (U 3)), FBF (1, Psibar, SP, Psi), G_hbt);

((M (L (-1)), O Hh, M (L 1)), FBF (1, Psibar, SP, Psi), G_h1e1e1);
((M (L (-1)), O HH, M (L 1)), FBF (1, Psibar, SP, Psi), G_h2e1e1);
((M (L (-1)), O HA, M (L 1)), FBF (1, Psibar, SP, Psi), G_h3e1e1);
((M (L (-2)), O Hh, M (L 2)), FBF (1, Psibar, SP, Psi), G_h1e2e2);
((M (L (-2)), O HH, M (L 2)), FBF (1, Psibar, SP, Psi), G_h2e2e2);
((M (L (-2)), O HA, M (L 2)), FBF (1, Psibar, SP, Psi), G_h3e2e2);
((M (L (-3)), O Hh, M (L 3)), FBF (1, Psibar, SP, Psi), G_h1e3e3);
((M (L (-3)), O HH, M (L 3)), FBF (1, Psibar, SP, Psi), G_h2e3e3);
((M (L (-3)), O HA, M (L 3)), FBF (1, Psibar, SP, Psi), G_h3e3e3)

```

] @

if *Flags.ckm\_present* then

```

[ ((M (U (-1)), O Hh, M (U 2)), FBF (1, Psibar, SP, Psi), G_h1uc);
  ((M (U (-1)), O Hh, M (U 3)), FBF (1, Psibar, SP, Psi), G_h1ut);
  ((M (U (-2)), O Hh, M (U 1)), FBF (1, Psibar, SP, Psi), G_h1cu);
  ((M (U (-2)), O Hh, M (U 3)), FBF (1, Psibar, SP, Psi), G_h1ct);
  ((M (U (-1)), O HH, M (U 2)), FBF (1, Psibar, SP, Psi), G_h2uc);
  ((M (U (-1)), O HH, M (U 3)), FBF (1, Psibar, SP, Psi), G_h2ut);
  ((M (U (-1)), O HA, M (U 2)), FBF (1, Psibar, SP, Psi), G_h3uc);
  ((M (U (-1)), O HA, M (U 3)), FBF (1, Psibar, SP, Psi), G_h3ut);
  ((M (U (-2)), O HH, M (U 1)), FBF (1, Psibar, SP, Psi), G_h2cu);
  ((M (U (-2)), O HH, M (U 3)), FBF (1, Psibar, SP, Psi), G_h2ct);
  ((M (U (-2)), O HA, M (U 1)), FBF (1, Psibar, SP, Psi), G_h3cu);
  ((M (U (-2)), O HA, M (U 3)), FBF (1, Psibar, SP, Psi), G_h3ct);
  ((M (U (-3)), O Hh, M (U 1)), FBF (1, Psibar, SP, Psi), G_h1tu);
  ((M (U (-3)), O Hh, M (U 2)), FBF (1, Psibar, SP, Psi), G_h1tc);
  ((M (U (-3)), O HH, M (U 1)), FBF (1, Psibar, SP, Psi), G_h2tu);
  ((M (U (-3)), O HH, M (U 2)), FBF (1, Psibar, SP, Psi), G_h2tc);
  ((M (U (-3)), O HA, M (U 1)), FBF (1, Psibar, SP, Psi), G_h3tu);
  ((M (U (-3)), O HA, M (U 2)), FBF (1, Psibar, SP, Psi), G_h3tc);

  ((M (D (-1)), O Hh, M (D 2)), FBF (1, Psibar, SP, Psi), G_h1ds);

```

```

((M (D (-1)), O Hh, M (D 3)), FBF (1, Psibar, SP, Psi), G_h1db);
((M (D (-1)), O HH, M (D 2)), FBF (1, Psibar, SP, Psi), G_h2ds);
((M (D (-1)), O HH, M (D 3)), FBF (1, Psibar, SP, Psi), G_h2db);
((M (D (-1)), O HA, M (D 2)), FBF (1, Psibar, SP, Psi), G_h3ds);
((M (D (-1)), O HA, M (D 3)), FBF (1, Psibar, SP, Psi), G_h3db);
((M (D (-2)), O Hh, M (D 1)), FBF (1, Psibar, SP, Psi), G_h1sd);
((M (D (-2)), O Hh, M (D 3)), FBF (1, Psibar, SP, Psi), G_h1sb);
((M (D (-2)), O HH, M (D 1)), FBF (1, Psibar, SP, Psi), G_h2sd);
((M (D (-2)), O HH, M (D 3)), FBF (1, Psibar, SP, Psi), G_h2sb);
((M (D (-2)), O HA, M (D 1)), FBF (1, Psibar, SP, Psi), G_h3sd);

((M (L (-1)), O Hh, M (L 2)), FBF (1, Psibar, SP, Psi), G_h1e1e2);
((M (L (-1)), O Hh, M (L 3)), FBF (1, Psibar, SP, Psi), G_h1e1e3);
((M (L (-1)), O HH, M (L 2)), FBF (1, Psibar, SP, Psi), G_h2e1e2);
((M (L (-1)), O HH, M (L 3)), FBF (1, Psibar, SP, Psi), G_h2e1e3);
((M (L (-1)), O HA, M (L 2)), FBF (1, Psibar, SP, Psi), G_h3e1e2);
((M (L (-1)), O HA, M (L 3)), FBF (1, Psibar, SP, Psi), G_h3e1e3);
((M (L (-2)), O Hh, M (L 1)), FBF (1, Psibar, SP, Psi), G_h1e2e1);
((M (L (-2)), O Hh, M (L 3)), FBF (1, Psibar, SP, Psi), G_h1e2e3);
((M (L (-2)), O HH, M (L 1)), FBF (1, Psibar, SP, Psi), G_h2e2e1);
((M (L (-2)), O HH, M (L 3)), FBF (1, Psibar, SP, Psi), G_h2e2e3);
((M (L (-2)), O HA, M (L 1)), FBF (1, Psibar, SP, Psi), G_h3e2e1);
((M (L (-2)), O HA, M (L 3)), FBF (1, Psibar, SP, Psi), G_h3e2e3);
((M (L (-3)), O Hh, M (L 1)), FBF (1, Psibar, SP, Psi), G_h1e3e1);
((M (L (-3)), O Hh, M (L 2)), FBF (1, Psibar, SP, Psi), G_h1e3e2);
((M (L (-3)), O HH, M (L 1)), FBF (1, Psibar, SP, Psi), G_h2e3e1);
((M (L (-3)), O HH, M (L 2)), FBF (1, Psibar, SP, Psi), G_h2e3e2);
((M (L (-3)), O HA, M (L 1)), FBF (1, Psibar, SP, Psi), G_h3e3e1);
((M (L (-3)), O HA, M (L 2)), FBF (1, Psibar, SP, Psi), G_h3e3e2) ]
else
[]

```

$$\mathcal{L}_{\text{TGC}} = -e\partial_\mu A_\nu W_+^\mu W_-^\nu + \dots - e\cot\theta_w\partial_\mu Z_\nu W_+^\mu W_-^\nu + \dots \quad (13.49)$$

let *tgc* ((*g1*, *g2*, *g3*), *t*, *c*) = ((*G g1*, *G g2*, *G g3*), *t*, *c*)

let *triple\_gauge* =

*List.map tgc*

```

[ ((Ga, Wm, Wp), Gauge_Gauge_Gauge 1, I_Q_W);
  ((Z, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_ZWW);
  ((Gl, Gl, Gl), Gauge_Gauge_Gauge 1, I_Gs) ]

```

$$\mathcal{L}_{\text{QGC}} = -g^2 W_{+,\mu} W_{-,\nu} W_+^\mu W_-^\nu + \dots \quad (13.50)$$

Actually, quartic gauge couplings are a little bit more straightforward using auxiliary fields. Here we have to impose the antisymmetry manually:

$$\begin{aligned}
& (W_1^{+,\mu} W_2^{-,\nu} - W_1^{+,\nu} W_2^{-,\mu})(W_{3,\mu}^+ W_{4,\nu}^- - W_{3,\nu}^+ W_{4,\mu}^-) \\
& = 2(W_1^+ W_3^+)(W_2^- W_4^-) - 2(W_1^+ W_4^-)(W_2^- W_3^+) \quad (13.51a)
\end{aligned}$$

also ( $V$  can be  $A$  or  $Z$ )

$$\begin{aligned} (W_1^{+,\mu} V_2^\nu - W_1^{+,\nu} V_2^\mu)(W_{3,\mu}^- V_{4,\nu} - W_{3,\nu}^- V_{4,\mu}) \\ = 2(W_1^+ W_3^-)(V_2 V_4) - 2(W_1^+ V_4)(V_2 W_3^-) \end{aligned} \quad (13.51b)$$

$$W^{+,\mu} W^{-,\nu} W_\mu^+ W_\nu^- \quad (13.52a)$$

```

let qgc ((g1, g2, g3, g4), t, c) = ((G g1, G g2, G g3, G g4), t, c)
let gauge4 = Vector4 [(2, C_13_42); (-1, C_12_34); (-1, C_14_23)]
let minus_gauge4 = Vector4 [(-2, C_13_42); (1, C_12_34); (1, C_14_23)]
let quartic_gauge =
  List.map qgc
    [ (Wm, Wp, Wm, Wp), gauge4, G_WWWW;
      (Wm, Z, Wp, Z), minus_gauge4, G_ZZWW;
      (Wm, Z, Wp, Ga), minus_gauge4, G_AZWW;
      (Wm, Ga, Wp, Ga), minus_gauge4, G_AAWW;
      (Gl, Gl, Gl, Gl), gauge4, G2]

let gauge_higgs =
  [ (G Ga, O Hp, O Hm), Vector_Scalar_Scalar 1, G_AHpHm;
    (G Z, O Hp, O Hm), Vector_Scalar_Scalar 1, G_ZHpHm;
    (G Z, O Hh, O HH), Vector_Scalar_Scalar 1, G_Zh1h2;
    (G Z, O Hh, O HA), Vector_Scalar_Scalar 1, G_Zh1h3;
    (G Z, O HH, O HA), Vector_Scalar_Scalar 1, G_Zh2h3;
    (G Wp, O Hm, O Hh), Vector_Scalar_Scalar 1, G_WpHmh1;
    (G Wp, O Hm, O HH), Vector_Scalar_Scalar 1, G_WpHmh2;
    (G Wp, O Hm, O HA), Vector_Scalar_Scalar 1, G_WpHmh3;
    (G Wm, O Hp, O Hh), Vector_Scalar_Scalar 1, G_WmHph1;
    (G Wm, O Hp, O HH), Vector_Scalar_Scalar 1, G_WmHph2;
    (G Wm, O Hp, O HA), Vector_Scalar_Scalar 1, G_WmHph3;
    (O Hh, G Z, G Z), Scalar_Vector_Vector 1, G_h1ZZ;
    (O HH, G Z, G Z), Scalar_Vector_Vector 1, G_h2ZZ;
    (O HA, G Z, G Z), Scalar_Vector_Vector 1, G_h3ZZ;
    (O Hh, G Wp, G Wm), Scalar_Vector_Vector 1, G_h1WpWm;
    (O HH, G Wp, G Wm), Scalar_Vector_Vector 1, G_h2WpWm;
    (O HA, G Wp, G Wm), Scalar_Vector_Vector 1, G_h3WpWm ]

let gauge_higgs4 =
  [ (O Hh, O Hh, G Wp, G Wm), Scalar2_Vector2 1, G_hhWpWm;
    (O HH, O HH, G Wp, G Wm), Scalar2_Vector2 1, G_hhWpWm;
    (O HA, O HA, G Wp, G Wm), Scalar2_Vector2 1, G_hhWpWm;
    (O Hh, O Hh, G Z, G Z), Scalar2_Vector2 1, G_hhZZ;
    (O HH, O HH, G Z, G Z), Scalar2_Vector2 1, G_hhZZ;
    (O HA, O HA, G Z, G Z), Scalar2_Vector2 1, G_hhZZ;
    (O Hp, O Hm, G Ga, G Ga), Scalar2_Vector2 1, G_HpHmAA;
    (O Hp, O Hm, G Z, G Z), Scalar2_Vector2 1, G_HpHmZZ;
    (O Hp, O Hm, G Ga, G Z), Scalar2_Vector2 1, G_HpHmAZ;
    (O Hp, O Hm, G Wp, G Wm), Scalar2_Vector2 1, G_HpHmWpWm;
  ]

```

```

(O Hh, O Hp, G Ga, G Wm), Scalar2_Vector2 1, G_h1HpAWm;
(O HH, O Hp, G Ga, G Wm), Scalar2_Vector2 1, G_h2HpAWm;
(O HA, O Hp, G Ga, G Wm), Scalar2_Vector2 1, G_h3HpAWm;
(O Hh, O Hp, G Z, G Wm), Scalar2_Vector2 1, G_h1HpZWm;
(O HH, O Hp, G Z, G Wm), Scalar2_Vector2 1, G_h2HpZWm;
(O HA, O Hp, G Z, G Wm), Scalar2_Vector2 1, G_h3HpZWm;
(O Hh, O Hm, G Ga, G Wp), Scalar2_Vector2 1, G_h1HpAWmC;
(O HH, O Hm, G Ga, G Wp), Scalar2_Vector2 1, G_h2HpAWmC;
(O HA, O Hm, G Ga, G Wp), Scalar2_Vector2 1, G_h3HpAWmC;
(O Hh, O Hm, G Z, G Wp), Scalar2_Vector2 1, G_h1HpZWmC;
(O HH, O Hm, G Z, G Wp), Scalar2_Vector2 1, G_h2HpZWmC;
(O HA, O Hm, G Z, G Wp), Scalar2_Vector2 1, G_h3HpZWmC ]

let higgs =
[ (O Hh, O Hp, O Hm), Scalar_Scalar_Scalar 1, G_h1HpHm;
  (O HH, O Hp, O Hm), Scalar_Scalar_Scalar 1, G_h2HpHm;
  (O HA, O Hp, O Hm), Scalar_Scalar_Scalar 1, G_h3HpHm;
  (O Hh, O Hh, O Hh), Scalar_Scalar_Scalar 1, G_h111;
  (O Hh, O Hh, O HH), Scalar_Scalar_Scalar 1, G_h112;
  (O Hh, O Hh, O HA), Scalar_Scalar_Scalar 1, G_h113;
  (O HH, O HH, O Hh), Scalar_Scalar_Scalar 1, G_h221;
  (O HH, O HH, O HH), Scalar_Scalar_Scalar 1, G_h222;
  (O HH, O HH, O HA), Scalar_Scalar_Scalar 1, G_h223;
  (O HA, O HA, O Hh), Scalar_Scalar_Scalar 1, G_h331;
  (O HA, O HA, O HH), Scalar_Scalar_Scalar 1, G_h332;
  (O HA, O HA, O HA), Scalar_Scalar_Scalar 1, G_h333;
  (O Hh, O HH, O HA), Scalar_Scalar_Scalar 1, G_h123 ]

let higgs4 =
[ (O Hp, O Hm, O Hp, O Hm), Scalar4 1, G_HpHmHpHm;
  (O Hp, O Hm, O Hh, O Hh), Scalar4 1, G_HpHm11;
  (O Hp, O Hm, O Hh, O HH), Scalar4 1, G_HpHm12;
  (O Hp, O Hm, O Hh, O HA), Scalar4 1, G_HpHm13;
  (O Hp, O Hm, O HH, O HH), Scalar4 1, G_HpHm22;
  (O Hp, O Hm, O HH, O HA), Scalar4 1, G_HpHm23;
  (O Hp, O Hm, O HA, O HA), Scalar4 1, G_HpHm33;
  (O Hh, O Hh, O Hh, O Hh), Scalar4 1, G_h1111;
  (O Hh, O Hh, O Hh, O HH), Scalar4 1, G_h1112;
  (O Hh, O Hh, O Hh, O HA), Scalar4 1, G_h1113;
  (O Hh, O Hh, O HH, O HH), Scalar4 1, G_h1122;
  (O Hh, O Hh, O HH, O HA), Scalar4 1, G_h1123;
  (O Hh, O Hh, O HA, O HA), Scalar4 1, G_h1133;
  (O Hh, O HH, O HH, O HH), Scalar4 1, G_h1222;
  (O Hh, O HH, O HH, O HA), Scalar4 1, G_h1223;
  (O Hh, O HH, O HA, O HA), Scalar4 1, G_h1233;
  (O Hh, O HA, O HA, O HA), Scalar4 1, G_h1333;
  (O HH, O HH, O HH, O HH), Scalar4 1, G_h2222;
  (O HH, O HH, O HH, O HA), Scalar4 1, G_h2223;
  (O HH, O HH, O HA, O HA), Scalar4 1, G_h2233;
  (O HH, O HA, O HA, O HA), Scalar4 1, G_h2333;
  (O HA, O HA, O HA, O HA), Scalar4 1, G_h3333 ]

```



```

let goldstone_vertices =
  [ ((O Phi0, G Wm, G Wp), Scalar_Vector_Vector 1, I-G-ZWW);
    ((O Phip, G Ga, G Wm), Scalar_Vector_Vector 1, I-Q-W);
    ((O Phip, G Z, G Wm), Scalar_Vector_Vector 1, I-G-ZWW);
    ((O Phim, G Wp, G Ga), Scalar_Vector_Vector 1, I-Q-W);
    ((O Phim, G Wp, G Z), Scalar_Vector_Vector 1, I-G-ZWW) ]

let vertices3 =
  (ThoList.flatmap electromagnetic_currents [1;2;3] @
   ThoList.flatmap color_currents [1;2;3] @
   ThoList.flatmap neutral_currents [1;2;3] @
   ThoList.flatmap charged_currents [1;2;3] @
   yukawa @ triple_gauge @
   gauge_higgs @ higgs @ goldstone_vertices)

let vertices4 =
  quartic_gauge @ gauge_higgs4 @ higgs4

let vertices () = (vertices3, vertices4, [])

```

For efficiency, make sure that  $F.of\_vertices$  `vertices` is evaluated only once.

```

let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 4

let flavor_of_string = function
| "e-" → M (L 1) | "e+" → M (L (-1))
| "mu-" → M (L 2) | "mu+" → M (L (-2))
| "tau-" → M (L 3) | "tau+" → M (L (-3))
| "nue" → M (N 1) | "nuebar" → M (N (-1))
| "numu" → M (N 2) | "numubar" → M (N (-2))
| "nutau" → M (N 3) | "nutaubar" → M (N (-3))
| "u" → M (U 1) | "ubar" → M (U (-1))
| "c" → M (U 2) | "cbar" → M (U (-2))
| "t" → M (U 3) | "tbar" → M (U (-3))
| "d" → M (D 1) | "dbar" → M (D (-1))
| "s" → M (D 2) | "sbar" → M (D (-2))
| "b" → M (D 3) | "bbar" → M (D (-3))
| "g" → G Gl
| "A" → G Ga | "Z" | "Z0" → G Z
| "W+" → G Wp | "W-" → G Wm
| "h0" → O Hh
| "H0" → O HH
| "A0" → O HA
| _ → invalid_arg "Modellib-BSM.TwoHiggsDoublet.flavor_of_string"

let flavor_to_string = function
| M f →
  begin match f with
  | L 1 → "e-" | L (-1) → "e+"
  | L 2 → "mu-" | L (-2) → "mu+"

```

```

| L 3 → "tau-" | L (-3) → "tau+"
| L _ → invalid_arg
      "Modellib_BSM.TwoHiggsDoublet.flavor_to_string:_invalid_lepton"
| N 1 → "nue" | N (-1) → "nuebar"
| N 2 → "numu" | N (-2) → "numubar"
| N 3 → "nutau" | N (-3) → "nutaubar"
| N _ → invalid_arg
      "Modellib_BSM.TwoHiggsDoublet.flavor_to_string:_invalid_neutrino"
| U 1 → "u" | U (-1) → "ubar"
| U 2 → "c" | U (-2) → "cbar"
| U 3 → "t" | U (-3) → "tbar"
| U _ → invalid_arg
      "Modellib_BSM.TwoHiggsDoublet.flavor_to_string:_invalid_up_type_quark"
| D 1 → "d" | D (-1) → "dbar"
| D 2 → "s" | D (-2) → "sbar"
| D 3 → "b" | D (-3) → "bbar"
| D _ → invalid_arg
      "Modellib_BSM.TwoHiggsDoublet.flavor_to_string:_invalid_down_type_quark"
end
| G f →
  begin match f with
  | Gl → "g"
  | Ga → "A" | Z → "Z"
  | Wp → "W+" | Wm → "W-"
  end
| O f →
  begin match f with
  | Phip → "phi+" | Phim → "phi-" | Phi0 → "phi0"
  | Hh → "h0" | HH → "H0" | HA → "A0"
  | Hp → "H+" | Hm → "H-"
  end
let flavor_to_TeX = function
| M f →
  begin match f with
  | L 1 → "e~-" | L (-1) → "e~+"
  | L 2 → "\\mu~-" | L (-2) → "\\mu~+"
  | L 3 → "\\tau~-" | L (-3) → "\\tau~+"
  | L _ → invalid_arg
        "Modellib_BSM.TwoHiggsDoublet.flavor_to_TeX:_invalid_lepton"
  | N 1 → "\\nu_e" | N (-1) → "\\bar{\\nu}_e"
  | N 2 → "\\nu_\\mu" | N (-2) → "\\bar{\\nu}_\\mu"
  | N 3 → "\\nu_\\tau" | N (-3) → "\\bar{\\nu}_\\tau"
  | N _ → invalid_arg
        "Modellib_BSM.TwoHiggsDoublet.flavor_to_TeX:_invalid_neutrino"
  | U 1 → "u" | U (-1) → "\\bar{u}"
  | U 2 → "c" | U (-2) → "\\bar{c}"
  | U 3 → "t" | U (-3) → "\\bar{t}"
  | U _ → invalid_arg
        "Modellib_BSM.TwoHiggsDoublet.flavor_to_TeX:_invalid_up_type_quark"

```

```

| D 1 → "d" | D (-1) → "\\bar{d}"
| D 2 → "s" | D (-2) → "\\bar{s}"
| D 3 → "b" | D (-3) → "\\bar{b}"
| D _ → invalid_arg
      "Modellib-BSM.TwoHiggsDoublet.flavor_to_TeX:_invalid_down_type_quark"
end
| G f →
  begin match f with
  | Gl → "g"
  | Ga → "\\gamma" | Z → "Z"
  | Wp → "W^+" | Wm → "W^- "
  end
| O f →
  begin match f with
  | Phip → "\\phi^+" | Phim → "\\phi^- " | Phi0 →
"\\phi^0"
  | Hh → "h^0" | HH → "H^0" | HA → "A^0"
  | Hp → "H^+" | Hm → "H^- "
  end
let flavor_symbol = function
| M f →
  begin match f with
  | L n when n > 0 → "l" ^ string_of_int n
  | L n → "l" ^ string_of_int (abs n) ^ "b"
  | N n when n > 0 → "n" ^ string_of_int n
  | N n → "n" ^ string_of_int (abs n) ^ "b"
  | U n when n > 0 → "u" ^ string_of_int n
  | U n → "u" ^ string_of_int (abs n) ^ "b"
  | D n when n > 0 → "d" ^ string_of_int n
  | D n → "d" ^ string_of_int (abs n) ^ "b"
  end
| G f →
  begin match f with
  | Gl → "gl"
  | Ga → "a" | Z → "z"
  | Wp → "wp" | Wm → "wm"
  end
| O f →
  begin match f with
  | Phip → "pp" | Phim → "pm" | Phi0 → "p0"
  | Hh → "h" | HH → "h0" | HA → "a0"
  | Hp → "hp" | Hm → "hm"
  end
let pdg = function
| M f →
  begin match f with
  | L n when n > 0 → 9 + 2 × n
  | L n → - 9 + 2 × n
  | N n when n > 0 → 10 + 2 × n

```

```

      |  $N\ n \rightarrow -10 + 2 \times n$ 
      |  $U\ n \text{ when } n > 0 \rightarrow 2 \times n$ 
      |  $U\ n \rightarrow 2 \times n$ 
      |  $D\ n \text{ when } n > 0 \rightarrow -1 + 2 \times n$ 
      |  $D\ n \rightarrow 1 + 2 \times n$ 
    end
  |  $G\ f \rightarrow$ 
    begin match  $f$  with
    |  $Gl \rightarrow 21$ 
    |  $Ga \rightarrow 22$  |  $Z \rightarrow 23$ 
    |  $Wp \rightarrow 24$  |  $Wm \rightarrow (-24)$ 
    end
  |  $O\ f \rightarrow$ 
    begin match  $f$  with
    |  $Phip \rightarrow 27$  |  $Phim \rightarrow -27$  |  $Phi0 \rightarrow 26$ 
    |  $Hh \rightarrow 25$ 
    |  $HH \rightarrow 35$ 
    |  $HA \rightarrow 36$ 
    |  $Hp \rightarrow 37$ 
    |  $Hm \rightarrow -37$ 
    end
end

let mass_symbol  $f =$ 
  "mass(" ^ string_of_int (abs (pdg  $f$ )) ^ ")"

let width_symbol  $f =$ 
  "width(" ^ string_of_int (abs (pdg  $f$ )) ^ ")"

let constant_symbol = function
| Unit  $\rightarrow$  "unit" |  $Pi \rightarrow$  "PI"
| Alpha_QED  $\rightarrow$  "alpha" |  $E \rightarrow$  "e" |  $G\_weak \rightarrow$  "g" |  $Vev \rightarrow$ 
"vev"
| Sin2thw  $\rightarrow$  "sin2thw" | Sinthw  $\rightarrow$  "sinthw" | Costhw  $\rightarrow$ 
"costhw"
|  $Q\_lepton \rightarrow$  "qllep" |  $Q\_up \rightarrow$  "qup" |  $Q\_down \rightarrow$  "qdown"
|  $G\_NC\_lepton \rightarrow$  "gnclep" |  $G\_NC\_neutrino \rightarrow$  "gncneu"
|  $G\_NC\_up \rightarrow$  "gncup" |  $G\_NC\_down \rightarrow$  "gncdown"
|  $G\_CC \rightarrow$  "gcc"
|  $I\_Q\_W \rightarrow$  "iqw" |  $I\_G\_ZWW \rightarrow$  "igzww" |  $I\_G\_WWW \rightarrow$ 
"igwww"
|  $G\_WWWW \rightarrow$  "gw4" |  $G\_ZZWW \rightarrow$  "gzzww"
|  $G\_AZWW \rightarrow$  "gazww" |  $G\_AAWW \rightarrow$  "gaaww"
|  $G\_htt \rightarrow$  "ghtt" |  $G\_hbb \rightarrow$  "ghbb" |  $G\_hcc \rightarrow$  "ghcc"
|  $G\_Htt \rightarrow$  "gh0tt" |  $G\_Hbb \rightarrow$  "gh0bb" |  $G\_Hcc \rightarrow$  "gh0cc"
|  $I\_G\_Att \rightarrow$  "iga0tt" |  $I\_G\_Abb \rightarrow$  "iga0bb" |  $I\_G\_Acc \rightarrow$ 
"iga0cc"
|  $G\_htautau \rightarrow$  "ghtautau" |  $G\_hmumu \rightarrow$  "ghmumu"
|  $G\_Htautau \rightarrow$  "gh0tautau" |  $G\_Hmumu \rightarrow$  "gh0mumu"
|  $I\_G\_Atautau \rightarrow$  "iga0tautau" |  $I\_G\_Amumu \rightarrow$  "iga0mumu"
|  $G\_Htb \rightarrow$  "ghptb" |  $G\_Hcs \rightarrow$  "ghpcs"
|  $G\_Htaunu \rightarrow$  "ghptaunu" |  $G\_Hmunu \rightarrow$  "ghpmunu"
|  $Gs \rightarrow$  "gs" |  $I\_Gs \rightarrow$  "igs" |  $G2 \rightarrow$  "gs**2"

```

---

```

| G_AHpHm → "gAHpHm" | G_ZHpHm → "gZHpHm"
| G_Zh1h2 → "gZh1h2" | G_Zh1h3 → "gZh1h3"
| G_Zh2h3 → "gZh2h3" | G_WpHmh1 → "gWpHmh1"
| G_WpHmh2 → "gWpHmh2" | G_WpHmh3 → "gWpHmh3"
| G_WmHph1 → "gWmHph1" | G_WmHph2 → "gWmHph2"
| G_WmHph3 → "gWmHph3" | G_h1ZZ → "gh1ZZ"
| G_h2ZZ → "gh2ZZ" | G_h3ZZ → "gh3ZZ"
| G_h1WpWm → "gh1WpWm" | G_h2WpWm → "gh2WpWm"
| G_h3WpWm → "gh3WpWm" | G_hhWpWm → "ghhWpWm"
| G_hhZZ → "ghhZZ" | G_HpHmAA → "gHpHmAA"
| G_HpHmZZ → "gHpHmZZ" | G_HpHmAZ → "gHpHmAZ"
| G_HpHmWpWm → "gHpHmWpWm" | G_h1HpAWm → "gh1HpAWm"
| G_h2HpAWm → "gh2HpAWm" | G_h3HpAWm → "gh3HpAWm"
| G_h1HpZWm → "gh1HpZWm" | G_h2HpZWm → "gh2HpZWm"
| G_h3HpZWm → "gh3HpZWm" | G_h1HpAWmC → "gh1HpAWmC"
| G_h2HpAWmC → "gh2HpAWmC" | G_h3HpAWmC → "gh3HpAWmC"
| G_h1HpZWmC → "gh1HpZWmC" | G_h2HpZWmC → "gh2HpZWmC"
| G_h3HpZWmC → "gh3HpZWmC" | G_h1HpHm → "gh1HpHm"
| G_h2HpHm → "gh2HpHm" | G_h3HpHm → "gh3HpHm"
| G_h111 → "gh111" | G_h112 → "gh112" | G_h113 → "gh113"
| G_h221 → "gh221" | G_h222 → "gh222" | G_h223 → "gh223"
| G_h331 → "gh331" | G_h332 → "gh332"
| G_h333 → "gh333" | G_h123 → "gh123"
| G_HpHmHpHm → "gHpHmHpHm" | G_HpHm11 → "gHpHm11"
| G_HpHm12 → "gHpHm12" | G_HpHm13 → "gHpHm13"
| G_HpHm22 → "gHpHm22" | G_HpHm23 → "gHpHm23"
| G_HpHm33 → "gHpHm33" | G_h1111 → "gh1111"
| G_h1112 → "gh1112" | G_h1113 → "gh1113"
| G_h1122 → "gh1122" | G_h1123 → "gh1123"
| G_h1133 → "gh1133" | G_h1222 → "gh1222"
| G_h1223 → "gh1223" | G_h1233 → "gh1233"
| G_h1333 → "gh1333" | G_h2222 → "gh2222"
| G_h2223 → "gh2223" | G_h2233 → "gh2233"
| G_h2333 → "gh2333" | G_h3333 → "gh3333"
| G_h1uu → "gh1uu" | G_h2uu → "gh2uu"
| G_h3uu → "gh3uu" | G_h1uc → "gh1uc"
| G_h2uc → "gh2uc" | G_h3uc → "gh3uc"
| G_h1ut → "gh1ut" | G_h2ut → "gh2ut"
| G_h3ut → "gh3ut" | G_h1cu → "gh1cu"
| G_h2cu → "gh2cu" | G_h3cu → "gh3cu"
| G_h1cc → "gh1cc" | G_h2cc → "gh2cc"
| G_h3cc → "gh3cc" | G_h1ct → "gh1ct"
| G_h2ct → "gh2ct" | G_h3ct → "gh3ct"
| G_h1tu → "gh1tu" | G_h2tu → "gh2tu"
| G_h3tu → "gh3tu" | G_h1tc → "gh1tc"
| G_h2tc → "gh2tc" | G_h3tc → "gh3tc"
| G_h1tt → "gh1tt" | G_h2tt → "gh2tt"
| G_h3tt → "gh3tt"
| G_h1dd → "gh1dd" | G_h2dd → "gh2dd"
| G_h3dd → "gh3dd" | G_h1ds → "gh1ds"

```

---

```

| G_h2ds → "gh2ds" | G_h3ds → "gh3ds"
| G_h1db → "gh1db" | G_h2db → "gh2db"
| G_h3db → "gh3db" | G_h1sd → "gh1sd"
| G_h2sd → "gh2sd" | G_h3sd → "gh3sd"
| G_h1ss → "gh1ss" | G_h2ss → "gh2ss"
| G_h3ss → "gh3ss" | G_h1sb → "gh1sb"
| G_h2sb → "gh2sb" | G_h3sb → "gh3sb"
| G_h1bd → "gh1bd" | G_h2bd → "gh2bd"
| G_h3bd → "gh3bd" | G_h1bs → "gh1bs"
| G_h2bs → "gh2bs" | G_h3bs → "gh3bs"
| G_h1bb → "gh1bb" | G_h2bb → "gh2bb"
| G_h3bb → "gh3bb"
| G_hud → "ghud" | G_hus → "ghus"
| G_hub → "ghub" | G_hcd → "ghcd"
| G_hcs → "ghcs" | G_hcb → "ghcb"
| G_htd → "ghtd" | G_hts → "ghts"
| G_htb → "ghtb"
| G_hdu → "ghdu" | G_hdc → "ghdc"
| G_hdt → "ghdt" | G_hsu → "ghsu"
| G_hsc → "ghsc" | G_hst → "ghst"
| G_hbu → "ghbu" | G_hbc → "ghbc"
| G_hbt → "ghbt"
| G_he1n1 → "ghe1n1" | G_he1n2 → "ghe1n2"
| G_he1n3 → "ghe1n3" | G_he2n1 → "ghe2n1"
| G_he2n2 → "ghe2n2" | G_he2n3 → "ghe2n3"
| G_he3n1 → "ghe3n1" | G_he3n2 → "ghe3n2"
| G_he3n3 → "ghe3n3" | G_hn1e1 → "ghn1e1"
| G_hn1e2 → "ghn1e2" | G_hn1e3 → "ghn1e3"
| G_hn2e1 → "ghn2e1" | G_hn2e2 → "ghn2e2"
| G_hn2e3 → "ghn2e3" | G_hn3e1 → "ghn3e1"
| G_hn3e2 → "ghn3e2" | G_hn3e3 → "ghn3e3"
| G_h1e1e1 → "gh1e1e1" | G_h2e1e1 → "gh2e1e1"
| G_h3e1e1 → "gh3e1e1" | G_h1e1e2 → "gh1e1e2"
| G_h2e1e2 → "gh2e1e2" | G_h3e1e2 → "gh3e1e2"
| G_h1e1e3 → "gh1e1e3" | G_h2e1e3 → "gh2e1e3"
| G_h3e1e3 → "gh3e1e3" | G_h1e2e1 → "gh1e2e1"
| G_h2e2e1 → "gh2e2e1" | G_h3e2e1 → "gh3e2e1"
| G_h1e2e2 → "gh1e2e2" | G_h2e2e2 → "gh2e2e2"
| G_h3e2e2 → "gh3e2e2" | G_h1e2e3 → "gh1e2e3"
| G_h2e2e3 → "gh2e2e3" | G_h3e2e3 → "gh3e2e3"
| G_h1e3e1 → "gh1e3e1" | G_h2e3e1 → "gh2e3e1"
| G_h3e3e1 → "gh3e3e1" | G_h1e3e2 → "gh1e3e2"
| G_h2e3e2 → "gh2e3e2" | G_h3e3e2 → "gh3e3e2"
| G_h1e3e3 → "gh1e3e3" | G_h2e3e3 → "gh2e3e3"
| G_h3e3e3 → "gh3e3e3"
| Mass f → "mass" ^ flavor_symbol f
| Width f → "width" ^ flavor_symbol f

```

end

module type *SSC\_flags* =

```

sig
  val higgs_triangle : bool (*  $H\gamma\gamma$ ,  $Hg\gamma$  and  $Hgg$  couplings *)
  val higgs_hmm : bool
  val triple_anom : bool
  val quartic_anom : bool
  val higgs_anom : bool
  val k_matrix : bool
  val ckm_present : bool
  val top_anom : bool
  val top_anom_4f : bool
end

module SSC_kmatrix : SSC_flags =
  struct
    let higgs_triangle = false
    let higgs_hmm = false
    let triple_anom = false
    let quartic_anom = true
    let higgs_anom = false
    let k_matrix = true
    let ckm_present = false
    let top_anom = false
    let top_anom_4f = false
  end

```

#### 13.6.4 Complete Minimal Standard Model including additional Resonances

```

module SSC (Flags : SSC_flags) =
  struct
    let rcs = RCS.rename rcs_file "Modellib_BSM.SSC"
    [ "minimal_electroweak_standard_model_in_unitarity_gauge_with_additional_Vectorboson"

    open Coupling

    let default_width = ref Timelike
    let use_fudged_width = ref false

    let options = Options.create
    [ "constant_width", Arg.Unit (fun () → default_width := Constant),
      "use_constant_width_(also_in_t-channel)";
      "fudged_width", Arg.Set use_fudged_width,
      "use_fudge_factor_for_charge_particle_width";
      "custom_width", Arg.String (fun f → default_width := Custom f),
      "use_custom_width";
      "cancel_widths", Arg.Unit (fun () → default_width := Vanishing),
      "use_vanishing_width"]

    type f_aux_top = TTGG | TBWA | TBWZ | TTWW | BBWW |
    let quartic_gauge =
      standard_quartic_gauge @ anomalous_quartic_gauge @ k_matrix_quartic_gauge

```

```

let standard_gauge_higgs =
  [ ((O H, G Wp, G Wm), Scalar_Vector_Vector 1, G_HWW);
    ((O H, G Z, G Z), Scalar_Vector_Vector 1, G_HZZ) ]

let standard_gauge_higgs4 =
  [ (O H, O H, G Wp, G Wm), Scalar2_Vector2 1, G_HHWW;
    (O H, O H, G Z, G Z), Scalar2_Vector2 1, G_HHZZ ]

let standard_higgs =
  [ (O H, O H, O H), Scalar_Scalar_Scalar 1, G_H3 ]

let standard_higgs4 =
  [ (O H, O H, O H, O H), Scalar4 1, G_H4 ]

```

WK's couplings (apparently, he still intends to divide by  $\Lambda_{\text{EWSB}}^2 = 16\pi^2 v_F^2$ ):

$$\mathcal{L}_4^\tau = \left[ (\partial_\mu H)(\partial^\mu H) + \frac{g^2 v_F^2}{4} V_\mu V^\mu \right]^2 \quad (13.53a)$$

$$\mathcal{L}_5^\tau = \left[ (\partial_\mu H)(\partial_\nu H) + \frac{g^2 v_F^2}{4} V_\mu V_\nu \right]^2 \quad (13.53b)$$

with

$$V_\mu V_\nu = \frac{1}{2} (W_\mu^+ W_\nu^- + W_\nu^+ W_\mu^-) + \frac{1}{2 \cos^2 \theta_w} Z_\mu Z_\nu \quad (13.54)$$

(note the symmetrization!), i. e.

$$\mathcal{L}_4 = \alpha_4 \frac{g^4 v_F^4}{16} (V_\mu V_\nu)^2 \quad (13.55a)$$

$$\mathcal{L}_5 = \alpha_5 \frac{g^4 v_F^4}{16} (V_\mu V^\mu)^2 \quad (13.55b)$$

Breaking thinks up

$$\mathcal{L}_4^{\tau, H^4} = [(\partial_\mu H)(\partial^\mu H)]^2 \quad (13.56a)$$

$$\mathcal{L}_5^{\tau, H^4} = [(\partial_\mu H)(\partial^\mu H)]^2 \quad (13.56b)$$

and

$$\mathcal{L}_4^{\tau, H^2 V^2} = \frac{g^2 v_F^2}{2} (\partial_\mu H)(\partial^\mu H) V_\mu V^\mu \quad (13.57a)$$

$$\mathcal{L}_5^{\tau, H^2 V^2} = \frac{g^2 v_F^2}{2} (\partial_\mu H)(\partial_\nu H) V_\mu V_\nu \quad (13.57b)$$

i. e.

$$\mathcal{L}_4^{\tau, H^2 V^2} = \frac{g^2 v_F^2}{2} \left[ (\partial_\mu H)(\partial^\mu H) W_\nu^+ W^{-, \nu} + \frac{1}{2 \cos^2 \theta_w} (\partial_\mu H)(\partial^\mu H) Z_\nu Z^\nu \right] \quad (13.58a)$$

$$\mathcal{L}_5^{\tau, H^2 V^2} = \frac{g^2 v_F^2}{2} \left[ (W^{+, \mu} \partial_\mu H)(W^{-, \nu} \partial_\nu H) + \frac{1}{2 \cos^2 \theta_w} (Z^\mu \partial_\mu H)(Z^\nu \partial_\nu H) \right] \quad (13.58b)$$



$$\begin{aligned}
 & \tau_8^4 \mathcal{L}_4^{\tau, H^2 V^2} + \tau_8^5 \mathcal{L}_5^{\tau, H^2 V^2} = \\
 & -\frac{g^2 v_F^2}{2} \left[ 2\tau_8^4 \frac{1}{2} (i\partial_\mu H)(i\partial^\mu H) W_\nu^+ W^{-,\nu} + \tau_8^5 (W^{+,\mu} i\partial_\mu H)(W^{-,\nu} i\partial_\nu H) \right. \\
 & \left. + \frac{2\tau_8^4}{\cos^2 \theta_w} \frac{1}{4} (i\partial_\mu H)(i\partial^\mu H) Z_\nu Z^\nu + \frac{\tau_8^5}{\cos^2 \theta_w} \frac{1}{2} (Z^\mu i\partial_\mu H)(Z^\nu i\partial_\nu H) \right] \quad (13.59)
 \end{aligned}$$

where the two powers of  $i$  make the sign conveniently negative, i. e.

$$\alpha_{(\partial H)^2 W^2}^2 = \tau_8^4 g^2 v_F^2 \quad (13.60a)$$

$$\alpha_{(\partial HW)^2}^2 = \frac{\tau_8^5 g^2 v_F^2}{2} \quad (13.60b)$$

$$\alpha_{(\partial H)^2 Z^2}^2 = \frac{\tau_8^4 g^2 v_F^2}{\cos^2 \theta_w} \quad (13.60c)$$

$$\alpha_{(\partial HZ)^2}^2 = \frac{\tau_8^5 g^2 v_F^2}{2 \cos^2 \theta_w} \quad (13.60d)$$

```

let anomalous_gauge_higgs =
  [ (O H, G Ga, G Ga), Dim5_Scalar_Gauge2 1, G_HGaGa_anom;
    (O H, G Ga, G Z), Dim5_Scalar_Gauge2 1, G_HGaZ_anom;
    (O H, G Z, G Z), Dim5_Scalar_Gauge2 1, G_HZZ_anom;
    (O H, G Wp, G Wm), Dim5_Scalar_Gauge2 1, G_HWW_anom;
    (O H, G Ga, G Z), Dim5_Scalar_Vector_Vector_U 1, G_HGaZ_u;
    (O H, G Z, G Z), Dim5_Scalar_Vector_Vector_U 1, G_HZZ_u;
    (O H, G Wp, G Wm), Dim5_Scalar_Vector_Vector_U 1, G_HWW_u;
    (O H, G Wm, G Wp), Dim5_Scalar_Vector_Vector_U 1, G_HWW_u
  ]

let anomalous_gauge_higgs4 =
  []

let anomalous_higgs =
  []

let higgs_triangle_vertices =
  if Flags.higgs_triangle then
    [ (O H, G Ga, G Ga), Dim5_Scalar_Gauge2 1, G_HGaGa;
      (O H, G Ga, G Z), Dim5_Scalar_Gauge2 1, G_HGaZ;
      (O H, G Gl, G Gl), Dim5_Scalar_Gauge2 1, G_Hgg ]
  else
    []

let anomalous_higgs4 =
  []

let gauge_higgs =
  if Flags.higgs_anom then
    standard_gauge_higgs @ anomalous_gauge_higgs
  else
    standard_gauge_higgs

let gauge_higgs4 =

```

```

if Flags.higgs_anom then
  standard_gauge_higgs4 @ anomalous_gauge_higgs4
else
  standard_gauge_higgs4

let higgs =
  if Flags.higgs_anom then
    standard_higgs @ anomalous_higgs
  else
    standard_higgs

let higgs4 =
  if Flags.higgs_anom then
    standard_higgs4 @ anomalous_higgs4
  else
    standard_higgs4

let goldstone_vertices =
  [ ((O Phi0, G Wm, G Wp), Scalar_Vector_Vector 1, I-G-ZWW);
    ((O Phip, G Ga, G Wm), Scalar_Vector_Vector 1, I-Q-W);
    ((O Phip, G Z, G Wm), Scalar_Vector_Vector 1, I-G-ZWW);
    ((O Phim, G Wp, G Ga), Scalar_Vector_Vector 1, I-Q-W);
    ((O Phim, G Wp, G Z), Scalar_Vector_Vector 1, I-G-ZWW) ]

```

#### New Resonances



There is an extra minus in the Lagrangian to have the same sign as HWW or HZZ vertex. Effectively this doesn't matter for SSC, because  $(-1)^2 = 1$ . This is only for completeness.

$$\mathbf{V}_\mu = -ig\mathbf{W}_\mu + ig'\mathbf{B}_\mu \quad (13.61a)$$

$$\mathbf{W}_\mu = W_\mu^a \frac{\tau^a}{2} \quad (13.61b)$$

$$\mathbf{B}_\mu = W_\mu^a \frac{\tau^3}{2} \quad (13.61c)$$

$$\tau^{++} = \tau^+ \otimes \tau^+ \quad (13.61d)$$

$$\tau^+ = \frac{1}{2} (\tau^+ \otimes \tau^3 + \tau^3 + \tau^+) \quad (13.61e)$$

$$\tau^0 = \frac{1}{\sqrt{6}} (\tau^3 \otimes \tau^3 - \tau^+ \otimes \tau^- - \tau^- + \tau^+) \quad (13.61f)$$

$$\tau^- = \frac{1}{2} (\tau^- \otimes \tau^3 + \tau^3 + \tau^-) \quad (13.61g)$$

$$\tau^{--} = \tau^- \otimes \tau^- \quad (13.61h)$$

#### Scalar Isoscalar

$$\mathcal{L}_\sigma = -\frac{g_{\sigma v}}{2} \text{tr} [\mathbf{V}_\mu \mathbf{V}^\mu] \sigma \quad (13.62)$$

```

let rsigma3 =
  [ ((O Rsigma, G Wp, G Wm), Scalar_Vector_Vector 1, G-SWW);
    ((O Rsigma, G Z, G Z), Scalar_Vector_Vector 1, G-SZZ) ]

```

```

let rsigma3t =
  [ ((O Rsigma, G Wp, G Wm), Scalar_Vector_Vector_t 1, G_SWW_T);
    ((O Rsigma, G Z, G Z), Scalar_Vector_Vector_t 1, G_SZZ_T) ]

let rsigma4 =
  [ (O Rsigma, O Rsigma, G Wp, G Wm), Scalar2_Vector2 1, G_SSWW;
    (O Rsigma, O Rsigma, G Z, G Z), Scalar2_Vector2 1, G_SZZZ ]

```

Scalar Isotensor

$$\mathcal{L}_\phi = \frac{g_\phi v}{4} \text{Tr} \left[ \left( \mathbf{V}_\mu \otimes \mathbf{V}^\mu - \frac{\tau^{aa}}{6} \text{Tr} [\mathbf{V}_\mu \mathbf{V}^\mu] \right) \phi \right] \quad (13.63a)$$

$$\phi = \sqrt{2} (\phi^{++} \tau^{++} + \phi^+ \tau^+ + \phi^0 \tau^0 + \phi^- \tau^- + \phi^{--} \tau^{--}) \quad (13.63b)$$

```

let rphi3 =
  [ ((O Rphin, G Wp, G Wm), Scalar_Vector_Vector 1, G_PNWW);
    ((O Rphin, G Z, G Z), Scalar_Vector_Vector 1, G_PNZZ);
    ((O Rhip, G Z, G Wm), Scalar_Vector_Vector 1, G_PWZ);
    ((O Rhipp, G Wm, G Wm), Scalar_Vector_Vector 1, G_PWW);
    ((O Rphim, G Wp, G Z), Scalar_Vector_Vector 1, G_PWZ);
    ((O Rphimm, G Wp, G Wp), Scalar_Vector_Vector 1, G_PWW) ]

```

Tensor IsoScalar

```

let rf3 =
  [ ((O Rf, G Wp, G Wm), Tensor_2_Vector_Vector_1 1, G_FWW);
    ((O Rf, G Z, G Z), Tensor_2_Vector_Vector_1 1, G_FZZ) ]

let rf3t =
  [ ((O Rf, G Wp, G Wm), Tensor_2_Vector_Vector_t 1, G_FWW_T);
    ((O Rf, G Z, G Z), Tensor_2_Vector_Vector_t 1, G_FZZ_T) ]

```

Tensor Isotensor

$$\mathcal{L}_t \quad (13.64a)$$

```

let rt3 =
  [ ((O Rtn, G Wp, G Wm), Tensor_2_Vector_Vector_1 1, G_TNWW);
    ((O Rtn, G Z, G Z), Tensor_2_Vector_Vector_1 1, G_TNZZ);
    ((O Rtp, G Z, G Wm), Tensor_2_Vector_Vector_1 1, G_TWZ);
    ((O Rtp, G Wm, G Wm), Tensor_2_Vector_Vector_1 1, G_TWW);
    ((O Rtm, G Wp, G Z), Tensor_2_Vector_Vector_1 1, G_TWZ);
    ((O Rtm, G Wp, G Wp), Tensor_2_Vector_Vector_1 1, G_TWW) ]

```

Anomalous trilinear interactions  $f_i f_j V$  and  $ttH$ :

$$\Delta \mathcal{L}_{tt\gamma} = -e \frac{v}{\Lambda^2} \bar{t} i \sigma^{\mu\nu} k_\nu (d_V(k^2) + i d_A(k^2) \gamma_5) t A_\mu \quad (13.65)$$

```

let anomalous_ttA =
  if Flags.top_anom then
    [ ((M (U (-3)), G Ga, M (U 3)), FBF (1, Psibar, TVAM, Psi), G_TVA_ttA) ]
  else
    []

```

$$\Delta\mathcal{L}_{bb\gamma} = -e\frac{v}{\Lambda^2}\bar{b}i\sigma^{\mu\nu}k_\nu(d_V(k^2) + id_A(k^2)\gamma_5)bA_\mu \quad (13.66)$$

```

let anomalous_bbA =
  if Flags.top_anom then
    [ ((M (D (-3))), G Ga, M (D 3)), FBF (1, Psibar, TVAM, Psi), G_TVA_bbA ]
  else
    []

```

$$\Delta\mathcal{L}_{ttg} = -g_s\frac{v}{\Lambda^2}\bar{t}\lambda^a i\sigma^{\mu\nu}k_\nu(d_V(k^2) + id_A(k^2)\gamma_5)tG_\mu^a \quad (13.67)$$

```

let anomalous_ttG =
  if Flags.top_anom then
    [ ((M (U (-3))), G Gl, M (U 3)), FBF (1, Psibar, TVAM, Psi), G_TVA_ttG ]
  else
    []

```

$$\Delta\mathcal{L}_{ttZ} = -\frac{g}{2c_W}\frac{v^2}{\Lambda^2}\left[\bar{t}\not{Z}(X_L(k^2)P_L + X_R(k^2)P_R)t + \bar{t}\frac{i\sigma^{\mu\nu}k_\nu}{m_Z}(d_V(k^2) + id_A(k^2)\gamma_5)tZ_\mu\right] \quad (13.68)$$

```

let anomalous_ttZ =
  if Flags.top_anom then
    [ ((M (U (-3))), G Z, M (U 3)), FBF (1, Psibar, VLRM, Psi), G_VLR_ttZ;
      ((M (U (-3))), G Z, M (U 3)), FBF (1, Psibar, TVAM, Psi), G_TVA_ttZ ]
  else
    []

```

$$\Delta\mathcal{L}_{bbZ} = -\frac{g}{2c_W}\frac{v^2}{\Lambda^2}\bar{b}\frac{i\sigma^{\mu\nu}k_\nu}{m_Z}(d_V(k^2) + id_A(k^2)\gamma_5)bZ_\mu \quad (13.69)$$

```

let anomalous_bbZ =
  if Flags.top_anom then
    [ ((M (D (-3))), G Z, M (D 3)), FBF (1, Psibar, TVAM, Psi), G_TVA_bbZ ]
  else
    []

```

$$\Delta\mathcal{L}_{tbW} = -\frac{g}{\sqrt{2}}\frac{v^2}{\Lambda^2}\left[\bar{b}\not{W}^-(V_L(k^2)P_L + V_R(k^2)P_R)t + \bar{b}\frac{i\sigma^{\mu\nu}k_\nu}{m_W}(g_L(k^2)P_L + g_R(k^2)P_R)tW_\mu^-\right] + \text{H.c.} \quad (13.70)$$

```

let anomalous_tbW =
  if Flags.top_anom then
    [ ((M (D (-3))), G Wm, M (U 3)), FBF (1, Psibar, VLRM, Psi), G_VLR_btW;
      ((M (U (-3))), G Wp, M (D 3)), FBF (1, Psibar, VLRM, Psi), G_VLR_tbW;
      ((M (D (-3))), G Wm, M (U 3)), FBF (1, Psibar, TLRM, Psi), G_TLR_btW;
      ((M (U (-3))), G Wp, M (D 3)), FBF (1, Psibar, TRLM, Psi), G_TRL_tbW ]
  else
    []

```

[]

$$\Delta\mathcal{L}_{ttH} = -\frac{1}{\sqrt{2}}\bar{t}(Y_V(k^2) + iY_A(k^2)\gamma_5)tH \quad (13.71)$$

```

let anomalous_ttH =
  if Flags.top_anom then
    [ ((M (U (-3)), O H, M (U 3)), FBF (1, Psibar, SPM, Psi), G_SP_ttH) ]
  else
    []

```

quartic fermion-gauge interactions  $f_i f_j V_1 V_2$  emerging from gauge-invariant effective operators:

$$\Delta\mathcal{L}_{ttgg} = -\frac{g_s^2}{2}f_{abc}\frac{v}{\Lambda^2}\bar{t}\lambda^a\sigma^{\mu\nu}(d_V(k^2) + id_A(k^2)\gamma_5)tG_\mu^b G_\nu^c \quad (13.72)$$

```

let anomalous_ttGG =
  if Flags.top_anom then
    [ ((M (U (-3)), O (Aux_top (2, 1, 0, true, TTGG)), M (U 3)), FBF (1, Psibar, TVA, Psi), G_TVA,
      ((O (Aux_top (2, 1, 0, false, TTGG)), G Gl, G Gl), Aux_Gauge_Gauge 1, I_Gs) ]
  else
    []

```

$$\Delta\mathcal{L}_{tbWA} = -i\sin\theta_w\frac{g^2}{2\sqrt{2}}\frac{v^2}{\Lambda^2}\left[\bar{b}\frac{\sigma^{\mu\nu}}{m_W}(g_L(k^2)P_L + g_R(k^2)P_R)tA_\mu W_\nu^-\right] + \text{H.c.} \quad (13.73)$$

```

let anomalous_tbWA =
  if Flags.top_anom then
    [ ((M (D (-3)), O (Aux_top (2, 0, -1, true, TBWA)), M (U 3)), FBF (1, Psibar, TLR, Psi), G_TLR,
      ((O (Aux_top (2, 0, 1, false, TBWA)), G Ga, G Wm), Aux_Gauge_Gauge 1, I_G_weak);
      ((M (U (-3)), O (Aux_top (2, 0, 1, true, TBWA)), M (D 3)), FBF (1, Psibar, TRL, Psi), G_TRL,
      ((O (Aux_top (2, 0, -1, false, TBWA)), G Wp, G Ga), Aux_Gauge_Gauge 1, I_G_weak) ]
  else
    []

```

$$\Delta\mathcal{L}_{tbWZ} = -i\cos\theta_w\frac{g^2}{2\sqrt{2}}\frac{v^2}{\Lambda^2}\left[\bar{b}\frac{\sigma^{\mu\nu}}{m_W}(g_L(k^2)P_L + g_R(k^2)P_R)tZ_\mu W_\nu^-\right] + \text{H.c.} \quad (13.74)$$

```

let anomalous_tbWZ =
  if Flags.top_anom then
    [ ((M (D (-3)), O (Aux_top (2, 0, -1, true, TBWZ)), M (U 3)), FBF (1, Psibar, TLR, Psi), G_TLR,
      ((O (Aux_top (2, 0, 1, false, TBWZ)), G Z, G Wm), Aux_Gauge_Gauge 1, I_G_weak);
      ((M (U (-3)), O (Aux_top (2, 0, 1, true, TBWZ)), M (D 3)), FBF (1, Psibar, TRL, Psi), G_TRL,
      ((O (Aux_top (2, 0, -1, false, TBWZ)), G Wp, G Z), Aux_Gauge_Gauge 1, I_G_weak) ]
  else
    []

```

$$\Delta\mathcal{L}_{ttWW} = -i\frac{g^2}{2}\frac{v^2}{\Lambda^2}\bar{t}\frac{\sigma^{\mu\nu}}{m_W}(d_V(k^2) + id_A(k^2)\gamma_5)tW_\mu^-W_\nu^+ \quad (13.75)$$

```

let anomalous_ttWW =
  if Flags.top_anom then
    [ ((M (U (-3)), O (Aux_top (2,0,0,true,TTWW)), M (U 3)), FBF (1, Psibar, TVA, Psi), G-TV
      ((O (Aux_top (2,0,0,false,TTWW)), G Wm, G Wp), Aux_Gauge_Gauge 1, I-G-weak) ]
  else
    []

```

$$\Delta\mathcal{L}_{bbWW} = -i\frac{g^2}{2}\frac{v^2}{\Lambda^2}\bar{b}\frac{\sigma^{\mu\nu}}{m_W}(d_V(k^2) + id_A(k^2)\gamma_5)bW_\mu^-W_\nu^+ \quad (13.76)$$

```

let anomalous_bbWW =
  if Flags.top_anom then
    [ ((M (D (-3)), O (Aux_top (2,0,0,true,BBWW)), M (D 3)), FBF (1, Psibar, TVA, Psi), G-TV
      ((O (Aux_top (2,0,0,false,BBWW)), G Wm, G Wp), Aux_Gauge_Gauge 1, I-G-weak) ]
  else
    []

```

4-fermion contact terms emerging from operator rewriting:

```

let anomalous_top_qGuG_tt =
  [ ((M (U (-3)), O (Aux_top (1,1,0,true,QGUG)), M (U 3)), FBF (1, Psibar, VLR, Psi), G-VLR-q
let anomalous_top_qGuG_ff n =
  List.map mom
    [ ((U (-n), Aux_top (1,1,0,false,QGUG), U n), FBF (1, Psibar, V, Psi), Unit);
      ((D (-n), Aux_top (1,1,0,false,QGUG), D n), FBF (1, Psibar, V, Psi), Unit) ]
let anomalous_top_qGuG =
  if Flags.top_anom_4f then
    anomalous_top_qGuG_tt @ ThoList.flatmap anomalous_top_qGuG_ff [1;2;3]
  else
    []
let anomalous_top_qBuB_tt =
  [ ((M (U (-3)), O (Aux_top (1,0,0,true,QBUB)), M (U 3)), FBF (1, Psibar, VLR, Psi), G-VLR-q
let anomalous_top_qBuB_ff n =
  List.map mom
    [ ((U (-n), Aux_top (1,0,0,false,QBUB), U n), FBF (1, Psibar, VLR, Psi), G-VLR-qBuB-u);
      ((D (-n), Aux_top (1,0,0,false,QBUB), D n), FBF (1, Psibar, VLR, Psi), G-VLR-qBuB-d);
      ((L (-n), Aux_top (1,0,0,false,QBUB), L n), FBF (1, Psibar, VLR, Psi), G-VLR-qBuB-e);
      ((N (-n), Aux_top (1,0,0,false,QBUB), N n), FBF (1, Psibar, VL, Psi), G-VL-qBuB-n) ]
let anomalous_top_qBuB =
  if Flags.top_anom_4f then
    anomalous_top_qBuB_tt @ ThoList.flatmap anomalous_top_qBuB_ff [1;2;3]
  else
    []
let anomalous_top_qW_tq =

```

```

[ ((M (U (-3)), O (Aux_top (1, 0, 0, true, QW)), M (U 3)), FBF (1, Psibar, VL, Psi), G_VL_qW);
  ((M (D (-3)), O (Aux_top (1, 0, -1, true, QW)), M (U 3)), FBF (1, Psibar, VL, Psi), G_VL_qW);
  ((M (U (-3)), O (Aux_top (1, 0, 1, true, QW)), M (D 3)), FBF (1, Psibar, VL, Psi), G_VL_qW) ]

let anomalous_top_qW_ff n =
  List.map mom
    [ ((U (-n), Aux_top (1, 0, 0, false, QW), U n), FBF (1, Psibar, VL, Psi), G_VL_qW_u);
      ((D (-n), Aux_top (1, 0, 0, false, QW), D n), FBF (1, Psibar, VL, Psi), G_VL_qW_d);
      ((N (-n), Aux_top (1, 0, 0, false, QW), N n), FBF (1, Psibar, VL, Psi), G_VL_qW_u);
      ((L (-n), Aux_top (1, 0, 0, false, QW), L n), FBF (1, Psibar, VL, Psi), G_VL_qW_d);
      ((D (-n), Aux_top (1, 0, -1, false, QW), U n), FBF (1, Psibar, VL, Psi), Half);
      ((U (-n), Aux_top (1, 0, 1, false, QW), D n), FBF (1, Psibar, VL, Psi), Half);
      ((L (-n), Aux_top (1, 0, -1, false, QW), N n), FBF (1, Psibar, VL, Psi), Half);
      ((N (-n), Aux_top (1, 0, 1, false, QW), L n), FBF (1, Psibar, VL, Psi), Half) ]

let anomalous_top_qW =
  if Flags.top_anom_4f then
    anomalous_top_qW_tq @ ThoList.flatmap anomalous_top_qW_ff [1; 2; 3]
  else
    []

let anomalous_top_DuDd =
  if Flags.top_anom_4f then
    [ ((M (U (-3)), O (Aux_top (0, 0, 0, true, DR)), M (U 3)), FBF (1, Psibar, SR, Psi), Half);
      ((M (U (-3)), O (Aux_top (0, 0, 0, false, DR)), M (U 3)), FBF (1, Psibar, SL, Psi), G_SL_DttR);
      ((M (D (-3)), O (Aux_top (0, 0, 0, false, DR)), M (D 3)), FBF (1, Psibar, SR, Psi), G_SR_DttR);
      ((M (U (-3)), O (Aux_top (0, 0, 0, true, DL)), M (U 3)), FBF (1, Psibar, SL, Psi), Half);
      ((M (D (-3)), O (Aux_top (0, 0, 0, false, DL)), M (D 3)), FBF (1, Psibar, SL, Psi), G_SL_DttL);
      ((M (D (-3)), O (Aux_top (0, 0, -1, true, DR)), M (U 3)), FBF (1, Psibar, SR, Psi), Half);
      ((M (U (-3)), O (Aux_top (0, 0, 1, false, DR)), M (D 3)), FBF (1, Psibar, SLR, Psi), G_SLR_D);
      ((M (D (-3)), O (Aux_top (0, 0, -1, true, DL)), M (U 3)), FBF (1, Psibar, SL, Psi), Half);
      ((M (U (-3)), O (Aux_top (0, 0, 1, false, DL)), M (D 3)), FBF (1, Psibar, SL, Psi), G_SL_DbtL)
    ]
  else
    []

let vertices3 =
  (ThoList.flatmap electromagnetic_currents [1; 2; 3] @
   ThoList.flatmap color_currents [1; 2; 3] @
   ThoList.flatmap neutral_currents [1; 2; 3] @
   (if Flags.ckm_present then
     charged_currents_ckm
   else
     charged_currents_triv) @
   yukawa @ triple_gauge @
   gauge_higgs @ higgs @ higgs_triangle_vertices
  @ goldstone_vertices @
  rsigma3 @ rsigma3t @ rphi3 @ rf3 @ rf3t @ rt3 @
  anomalous_ttA @ anomalous_bbA @
  anomalous_ttZ @ anomalous_bbZ @
  anomalous_tbW @ anomalous_tbWA @ anomalous_tbWZ @
  anomalous_ttWW @ anomalous_bbWW @
  anomalous_ttG @ anomalous_ttGG @

```

```

anomalous_ttH @
anomalous_top_qGuG @ anomalous_top_qBuB @
anomalous_top_qW @ anomalous_top_DuDd)

let vertices4 =
  quartic_gauge @ gauge_higgs4 @ higgs4 @ rsigma4
let vertices () = (vertices3, vertices4, [])

```

For efficiency, make sure that *F.of\_vertices* *vertices* is evaluated only once.

```

let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 4

let flavor_of_string = function
| "e-" → M (L 1) | "e+" → M (L (-1))
| "mu-" → M (L 2) | "mu+" → M (L (-2))
| "tau-" → M (L 3) | "tau+" → M (L (-3))
| "nue" → M (N 1) | "nuebar" → M (N (-1))
| "numu" → M (N 2) | "numubar" → M (N (-2))
| "nutau" → M (N 3) | "nutaubar" → M (N (-3))
| "u" → M (U 1) | "ubar" → M (U (-1))
| "c" → M (U 2) | "cbar" → M (U (-2))
| "t" → M (U 3) | "tbar" → M (U (-3))
| "d" → M (D 1) | "dbar" → M (D (-1))
| "s" → M (D 2) | "sbar" → M (D (-2))
| "b" → M (D 3) | "bbar" → M (D (-3))
| "g" | "gl" → G Gl
| "A" → G Ga | "Z" | "Z0" → G Z
| "W+" → G Wp | "W-" → G Wm
| "H" → O H | "Rsigma" → O Rsigma
| "Rphi0" → O Rphin
| "Rphi+" → O Rhip | "Rphi-" → O Rphim
| "Rphi++" → O Rhip | "Rphi--" → O Rphimm
| "Rf" → O Rf
| "Rt0" → O Rtn
| "Rt+" → O Rtp | "Rt-" → O Rtm
| "Rt++" → O Rtp | "Rt--" → O Rtmm
| "Aux_t_ttGG0" → O (Aux_top (2, 1, 0, true, TTGG)) | "Aux_ttGG0" →
O (Aux_top (2, 1, 0, false, TTGG))
| "Aux_t_ttbWA+" → O (Aux_top (2, 0, 1, true, TBWA)) | "Aux_ttbWA+" →
O (Aux_top (2, 0, 1, false, TBWA))
| "Aux_t_ttbWA-" → O (Aux_top (2, 0, -1, true, TBWA)) | "Aux_ttbWA-" →
O (Aux_top (2, 0, -1, false, TBWA))
| "Aux_t_ttbWZ+" → O (Aux_top (2, 0, 1, true, TBWZ)) | "Aux_ttbWZ+" →
O (Aux_top (2, 0, 1, false, TBWZ))
| "Aux_t_ttbWZ-" → O (Aux_top (2, 0, -1, true, TBWZ)) | "Aux_ttbWZ-" →
O (Aux_top (2, 0, -1, false, TBWZ))
| "Aux_t_ttWW0" → O (Aux_top (2, 0, 0, true, TTWW)) | "Aux_ttWW0" →
O (Aux_top (2, 0, 0, false, TTWW))

```



---

```

    | "Aux_t_bbWW0" → O (Aux_top (2, 0, 0, true, BBWW)) | "Aux_bbWW0" →
O (Aux_top (2, 0, 0, false, BBWW))
    | "Aux_t_qGuG0" → O (Aux_top (1, 1, 0, true, QGUG)) | "Aux_qGuG0" →
O (Aux_top (1, 1, 0, false, QGUG))
    | "Aux_t_qBuB0" → O (Aux_top (1, 0, 0, true, QBUB)) | "Aux_qBuB0" →
O (Aux_top (1, 0, 0, false, QBUB))
    | "Aux_t_qW0" → O (Aux_top (1, 0, 0, true, QW)) | "Aux_qW0" →
O (Aux_top (1, 0, 0, false, QW))
    | "Aux_t_qW+" → O (Aux_top (1, 0, 1, true, QW)) | "Aux_qW+" →
O (Aux_top (1, 0, 1, false, QW))
    | "Aux_t_qW-" → O (Aux_top (1, 0, -1, true, QW)) | "Aux_qW-" →
O (Aux_top (1, 0, -1, false, QW))
    | "Aux_t_dL0" → O (Aux_top (0, 0, 0, true, DL)) | "Aux_dL0" →
O (Aux_top (0, 0, 0, false, DL))
    | "Aux_t_dL+" → O (Aux_top (0, 0, 1, true, DL)) | "Aux_dL+" →
O (Aux_top (0, 0, 1, false, DL))
    | "Aux_t_dL-" → O (Aux_top (0, 0, -1, true, DL)) | "Aux_dL-" →
O (Aux_top (0, 0, -1, false, DL))
    | "Aux_t_dR0" → O (Aux_top (0, 0, 0, true, DR)) | "Aux_dR0" →
O (Aux_top (0, 0, 0, false, DR))
    | "Aux_t_dR+" → O (Aux_top (0, 0, 1, true, DR)) | "Aux_dR+" →
O (Aux_top (0, 0, 1, false, DR))
    | "Aux_t_dR-" → O (Aux_top (0, 0, -1, true, DR)) | "Aux_dR-" →
O (Aux_top (0, 0, -1, false, DR))
    | _ → invalid_arg "Modellib_BSM.SSC.flavor_of_string"

let flavor_to_string = function
| M f →
  begin match f with
  | L 1 → "e-" | L (-1) → "e+"
  | L 2 → "mu-" | L (-2) → "mu+"
  | L 3 → "tau-" | L (-3) → "tau+"
  | L _ → invalid_arg
    "Modellib_BSM.SSC.flavor_to_string:␣invalid␣lepton"
  | N 1 → "nue" | N (-1) → "nuebar"
  | N 2 → "numu" | N (-2) → "numubar"
  | N 3 → "nutau" | N (-3) → "nutaubar"
  | N _ → invalid_arg
    "Modellib_BSM.SSC.flavor_to_string:␣invalid␣neutrino"
  | U 1 → "u" | U (-1) → "ubar"
  | U 2 → "c" | U (-2) → "cbar"
  | U 3 → "t" | U (-3) → "tbar"
  | U _ → invalid_arg
    "Modellib_BSM.SSC.flavor_to_string:␣invalid␣up␣type␣quark"
  | D 1 → "d" | D (-1) → "dbar"
  | D 2 → "s" | D (-2) → "sbar"
  | D 3 → "b" | D (-3) → "bbar"
  | D _ → invalid_arg
    "Modellib_BSM.SSC.flavor_to_string:␣invalid␣down␣type␣quark"
  end
end

```

```

| G f →
  begin match f with
  | Gl → "gl"
  | Ga → "A" | Z → "Z"
  | Wp → "W+" | Wm → "W-"
  end
| O f →
  begin match f with
  | Phip → "phi+" | Phim → "phi-" | Phi0 → "phi0"
  | H → "H" | Rsigma → "Rsigma"
  | Rphin → "Rphin" | Rhip → "Rphi+" | Rphim → "Rphi-"
  | Rhipp → "Rphi++" | Rphimm → "Rphi--"
  | Rf → "Rf"
  | Rtn → "Rtn" | Rtp → "Rt+" | Rtm → "Rt-"
  | Rtp → "Rt++" | Rtm → "Rt--"
  | Aux_top (_, _, ch, n, v) → "Aux_" ^ (if n then "t_" else "") ^ (
    begin match v with
    | TTGG → "ttGG" | TBWA → "tbWA" | TBWZ →
      "tbWZ"
    | TTWW → "ttWW" | BBWW → "bbWW"
    | QGUG → "qGuG" | QBUB → "qBuB"
    | QW → "qW" | DL → "dL" | DR → "dR"
    end ) ^ ( if ch > 0 then "+" else if ch < 0 then "-" else "0" )
  end
end

let flavor_to_TeX = function
| M f →
  begin match f with
  | L 1 → "e~-" | L (-1) → "e~+"
  | L 2 → "\\mu~-" | L (-2) → "\\mu~+"
  | L 3 → "\\tau~-" | L (-3) → "\\tau~+"
  | L _ → invalid_arg
    "Modellib_BSM.SSC.flavor_to_TeX: invalid lepton"
  | N 1 → "\\nu_e" | N (-1) → "\\bar{\\nu}_e"
  | N 2 → "\\nu_\\mu" | N (-2) → "\\bar{\\nu}_\\mu"
  | N 3 → "\\nu_\\tau" | N (-3) → "\\bar{\\nu}_\\tau"
  | N _ → invalid_arg
    "Modellib_BSM.SSC.flavor_to_TeX: invalid neutrino"
  | U 1 → "u" | U (-1) → "\\bar{u}"
  | U 2 → "c" | U (-2) → "\\bar{c}"
  | U 3 → "t" | U (-3) → "\\bar{t}"
  | U _ → invalid_arg
    "Modellib_BSM.SSC.flavor_to_TeX: invalid up type quark"
  | D 1 → "d" | D (-1) → "\\bar{d}"
  | D 2 → "s" | D (-2) → "\\bar{s}"
  | D 3 → "b" | D (-3) → "\\bar{b}"
  | D _ → invalid_arg
    "Modellib_BSM.SSC.flavor_to_TeX: invalid down type quark"
  end
| G f →

```

```

begin match f with
| Gl → "g"
| Ga → "\\gamma" | Z → "Z"
| Wp → "W^+" | Wm → "W^-"
end
| Of →
begin match f with
| Phip → "\\phi^+" | Phim → "\\phi^-" | Phi0 →
"\\phi^0"
| H → "H" | Rsigma → "\\sigma"
| Rhip → "\\phi^+" | Rphim → "\\phi^-" | Rphin →
"\\phi^0"
| Rhipp → "\\phi^{++}" | Rphimm → "\\phi^{--}"
| Rf → "f"
| Rtp → "t^+" | Rtm → "t^-" | Rtn → "t^0"
| Rtp → "t^{++}" | Rtm → "t^{--}"
| Aux_top(−, −, ch, n, v) → "\\textnormal{Aux}_" ^ (if n then "t_" else "") ^ (
begin match v with
| TTGG → "ttGG" | TBWA → "tbWA" | TBWZ →
"tbWZ"
| TTWW → "ttWW" | BBWW → "bbWW"
| QGUG → "qGuG" | QBUB → "qBuB"
| QW → "qW" | DL → "dL" | DR → "dR"
end) ^ (if ch > 0 then "^+" else if ch < 0 then "^-" else "^0") ^ "}"
end
end

let flavor_symbol = function
| Mf →
begin match f with
| Ln when n > 0 → "l" ^ string_of_int n
| Ln → "l" ^ string_of_int (abs n) ^ "b"
| Nn when n > 0 → "n" ^ string_of_int n
| Nn → "n" ^ string_of_int (abs n) ^ "b"
| Un when n > 0 → "u" ^ string_of_int n
| Un → "u" ^ string_of_int (abs n) ^ "b"
| Dn when n > 0 → "d" ^ string_of_int n
| Dn → "d" ^ string_of_int (abs n) ^ "b"
end
| Gf →
begin match f with
| Gl → "gl"
| Ga → "a" | Z → "z"
| Wp → "wp" | Wm → "wm"
end
| Of →
begin match f with
| Phip → "pp" | Phim → "pm" | Phi0 → "p0"
| H → "h" | Rsigma → "rsi"
| Rhip → "rpp" | Rphim → "rpm" | Rphin → "rpn"
| Rhipp → "rppp" | Rphimm → "rpm"

```

```

|  $Rf \rightarrow "rf"$ 
|  $Rtp \rightarrow "rtp" \mid Rtm \rightarrow "rtm" \mid Rtn \rightarrow "rtn"$ 
|  $Rtpp \rightarrow "rtpp" \mid Rtm m \rightarrow "rtmm"$ 
|  $Aux\_top(-, -, ch, n, v) \rightarrow "aux\_ " \wedge (\text{if } n \text{ then } "t\_ " \text{ else } "") \wedge ($ 
  begin match  $v$  with
    |  $TTGG \rightarrow "ttgg" \mid TBWA \rightarrow "tbwa" \mid TBWZ \rightarrow$ 
"tbwz"
    |  $TTWW \rightarrow "ttww" \mid BBWW \rightarrow "bbww"$ 
    |  $QGUG \rightarrow "qgug" \mid QBUB \rightarrow "qbub"$ 
    |  $QW \rightarrow "qw" \mid DL \rightarrow "dl" \mid DR \rightarrow "dr"$ 
  end)  $\wedge " " \wedge (\text{if } ch > 0 \text{ then } "p" \text{ else if } ch < 0 \text{ then } "m" \text{ else } "0")$ 
end

```

Introducing new Resonances from 45, there are no PDG values

```

let  $pdg = \text{function}$ 
|  $M f \rightarrow$ 
  begin match  $f$  with
    |  $L n \text{ when } n > 0 \rightarrow 9 + 2 \times n$ 
    |  $L n \rightarrow -9 + 2 \times n$ 
    |  $N n \text{ when } n > 0 \rightarrow 10 + 2 \times n$ 
    |  $N n \rightarrow -10 + 2 \times n$ 
    |  $U n \text{ when } n > 0 \rightarrow 2 \times n$ 
    |  $U n \rightarrow 2 \times n$ 
    |  $D n \text{ when } n > 0 \rightarrow -1 + 2 \times n$ 
    |  $D n \rightarrow 1 + 2 \times n$ 
  end
|  $G f \rightarrow$ 
  begin match  $f$  with
    |  $Gl \rightarrow 21$ 
    |  $Ga \rightarrow 22 \mid Z \rightarrow 23$ 
    |  $Wp \rightarrow 24 \mid Wm \rightarrow (-24)$ 
  end
|  $O f \rightarrow$ 
  begin match  $f$  with
    |  $Phip \mid Phim \rightarrow 27 \mid Phi0 \rightarrow 26$ 
    |  $H \rightarrow 25 \mid Rsigma \rightarrow 45$ 
    |  $Rphin \rightarrow 46 \mid Rphip \mid Rphim \rightarrow 47$ 
    |  $Rhipp \mid Rphimm \rightarrow 48$ 
    |  $Rf \rightarrow 52$ 
    |  $Rtn \rightarrow 53 \mid Rtp \mid Rtm \rightarrow 54$ 
    |  $Rtpp \mid Rtm m \rightarrow 55$ 
    |  $Aux\_top(-, -, -, -, -) \rightarrow 81$ 
  end
end

let  $mass\_symbol f =$ 
  "mass("  $\wedge string\_of\_int(abs(pdg f)) \wedge " )"$ 

let  $width\_symbol f =$ 
  "width("  $\wedge string\_of\_int(abs(pdg f)) \wedge " )"$ 

let  $constant\_symbol = \text{function}$ 
|  $Unit \rightarrow "unit" \mid Half \rightarrow "half" \mid Pi \rightarrow "PI"$ 

```

```

| Alpha_QED → "alpha" | E → "e" | G_weak → "g" | Vev →
"vev"
| I_G_weak → "ig"
| Sin2thw → "sin2thw" | Sinthw → "sinthw" | Costhw →
"costhw"
| Q_lepton → "qlep" | Q_up → "qup" | Q_down → "qdown"
| G_NC_lepton → "gnclep" | G_NC_neutrino → "gncneu"
| G_NC_up → "gncup" | G_NC_down → "gncdown"
| G_TVA_ttA → "gtva_tta" | G_TVA_bbA → "gtva_bba"
| G_VLR_ttZ → "gvlr_ttz" | G_TVA_ttZ → "gtva_ttz" |
G_TVA_bbZ → "gtva_bbz"
| G_VLR_btW → "gvlr_btw" | G_VLR_tbW → "gvlr_tbw"
| G_TLR_btW → "gtlr_btw" | G_TRL_tbW → "gtrl_tbw"
| G_TLR_btWA → "gtlr_btwa" | G_TRL_tbWA → "gtrl_tbwa"
| G_TLR_btWZ → "gtlr_btwz" | G_TRL_tbWZ → "gtrl_tbwz"
| G_TVA_ttWW → "gtva_ttw" | G_TVA_bbWW → "gtva_bbww"
| G_TVA_ttG → "gtva_ttg" | G_TVA_ttGG → "gtva_ttg"
| G_SP_ttH → "gsp_tth"
| G_VLR_qGuG → "gvlr_qgug"
| G_VLR_qBuB → "gvlr_qbub"
| G_VLR_qBuB_u → "gvlr_qbub_u" | G_VLR_qBuB_d → "gvlr_qbub_d"
| G_VLR_qBuB_e → "gvlr_qbub_e" | G_VL_qBuB_n → "gv_lqbub_n"
| G_VL_qW → "gv_lqw"
| G_VL_qW_u → "gv_lqw_u" | G_VL_qW_d → "gv_lqw_d"
| G_SL_DtR → "gsl_dttr" | G_SR_DtR → "gsr_dttr" |
G_SL_DtL → "gsl_dttl"
| G_SLR_DbR → "gslr_dbtr" | G_SL_DbL → "gsl_dbtl"
| G_CC → "gcc"
| G_CCQ (n1,n2) → "gccq" ^ string_of_int n1 ^ string_of_int n2
| I_Q_W → "iqw" | I_G_ZWW → "igzww"
| G_WWWW → "gw4" | G_ZZWW → "gzzww"
| G_AZWW → "gazww" | G_AAWW → "gaaww"
| I_G1_AWW → "ig1a" | I_G1_ZWW → "ig1z"
| I_G1_plus_kappa_plus_G4_AWW → "ig1pkpg4a"
| I_G1_plus_kappa_plus_G4_ZWW → "ig1pkpg4z"
| I_G1_plus_kappa_minus_G4_AWW → "ig1pkmg4a"
| I_G1_plus_kappa_minus_G4_ZWW → "ig1pkmg4z"
| I_G1_minus_kappa_plus_G4_AWW → "ig1mkpg4a"
| I_G1_minus_kappa_plus_G4_ZWW → "ig1mkpg4z"
| I_G1_minus_kappa_minus_G4_AWW → "ig1mkmg4a"
| I_G1_minus_kappa_minus_G4_ZWW → "ig1mkmg4z"
| I_lambda_AWW → "ila"
| I_lambda_ZWW → "ilz"
| G5_AWW → "rg5a"
| G5_ZWW → "rg5z"
| I_kappa5_AWW → "ik5a"
| I_kappa5_ZWW → "ik5z"
| I_lambda5_AWW → "il5a" | I_lambda5_ZWW → "il5z"
| Alpha_WWWW0 → "alww0" | Alpha_WWWW2 → "alww2"
| Alpha_ZZWW0 → "alzw0" | Alpha_ZZWW1 → "alzw1"

```

```

| Alpha_ZZZZ → "alzz"
| D_Alpha_ZZWW0_S → "dalzz0-s(gkm,mkm,"
| D_Alpha_ZZWW0_T → "dalzz0-t(gkm,mkm,"
| D_Alpha_ZZWW1_S → "dalzz1-s(gkm,mkm,"
| D_Alpha_ZZWW1_T → "dalzz1-t(gkm,mkm,"
| D_Alpha_ZZWW1_U → "dalzz1-u(gkm,mkm,"
| D_Alpha_WWWW0_S → "dalww0-s(gkm,mkm,"
| D_Alpha_WWWW0_T → "dalww0-t(gkm,mkm,"
| D_Alpha_WWWW0_U → "dalww0-u(gkm,mkm,"
| D_Alpha_WWWW2_S → "dalww2-s(gkm,mkm,"
| D_Alpha_WWWW2_T → "dalww2-t(gkm,mkm,"
| D_Alpha_ZZZZ_S → "dalz4-s(gkm,mkm,"
| D_Alpha_ZZZZ_T → "dalz4-t(gkm,mkm,"
| G_HWW → "ghww" | G_HZZ → "ghzz"
| G_HHWW → "ghhww" | G_HHZZ → "ghhzz"
| G_SWW → "gsww" | G_SZZ → "gszz"
| G_SWW_T → "gswwt" | G_SZZ_T → "gszzt"
| G_PNWW → "gpnww" | G_PNZZ → "gpnzz"
| G_PWZ → "gpwz" | G_PWW → "gpww"
| G_FWW → "gfw" | G_FZZ → "gfzz"
| G_FWW_T → "gfwwt" | G_FZZ_T → "gfzzt"
| G_TNWW → "gtnew" | G_TNZZ → "gtnew"
| G_TWZ → "gtwz" | G_TWW → "gtww"
| G_SWW → "gssww" | G_SSZZ → "gsszz"
| G_Htt → "ghtt" | G_Hbb → "ghbb"
| G_Htautau → "ghtautau" | G_Hcc → "ghcc" | G_Hmm →
"ghmm"
| G_HGaZ → "ghgaz" | G_HGaGa → "ghgaga" | G_Hgg →
"ghgg"
| G_HGaGa_anom → "ghgaga-ac" | G_HGaZ_anom → "ghgaz-ac"
| G_HZZ_anom → "ghzz-ac" | G_HWW_anom → "ghww-ac"
| G_HGaZ_u → "ghgaz-u" | G_HZZ_u → "ghzz-u"
| G_HWW_u → "ghww-u"
| G_H3 → "gh3" | G_H4 → "gh4"
| Gs → "gs" | I_Gs → "igs" | G2 → "gs**2"
| Mass f → "mass" ^ flavor_symbol f
| Width f → "width" ^ flavor_symbol f
| K_Matrix_Coeff i → "kc" ^ string_of_int i
| K_Matrix_Pole i → "kp" ^ string_of_int i
end

```

## 13.7 Interface of *Modellib\_MSSM*

### 13.7.1 More Hardcoded Models

```

module type MSSM_flags =
sig
  val include_goldstone : bool
  val include_four : bool

```

```

    val ckm_present : bool
    val gravitino : bool
    val higgs_triangle : bool
  end

module MSSM_no_goldstone : MSSM_flags
module MSSM_goldstone : MSSM_flags
module MSSM_no_4 : MSSM_flags
module MSSM_no_4_ckm : MSSM_flags
module MSSM_Grav : MSSM_flags
module MSSM_Hgg : MSSM_flags
module MSSM : functor (F : MSSM_flags) → Model.T with module Ch = Charges.QQ

```

### 13.8 Implementation of *Modellib\_MSSM*

*Id* : *modellib\_MSSM.ml*49262013 – 12 – 0412 : 35 : 06Zjr\_reuter

```

let rcs_file = RCS.parse "Modellib_MSSM" ["MSSM"]
{ RCS.revision = "$Revision: 4926$";
  RCS.date = "$Date: 2013-12-04 13:35:06 +0100 (Wed, 04 Dec 2013)$";
  RCS.author = "$Author: jr_reuter$";
  RCS.source
    = "$URL: svn+ssh://jr_reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/s"

```

#### 13.8.1 Minimal Supersymmetric Standard Model

```

module type MSSM_flags =
sig
  val include_goldstone : bool
  val include_four : bool
  val ckm_present : bool
  val gravitino : bool
  val higgs_triangle : bool
end

module MSSM_no_goldstone : MSSM_flags =
struct
  let include_goldstone = false
  let include_four = true
  let ckm_present = false
  let gravitino = false
  let higgs_triangle = false
end

module MSSM_goldstone : MSSM_flags =
struct
  let include_goldstone = true
  let include_four = true
  let ckm_present = false
  let gravitino = false

```

```

    let higgs_triangle = false
  end

module MSSM_no_4 : MSSM_flags =
  struct
    let include_goldstone = false
    let include_four = false
    let ckm_present = false
    let gravitino = false
    let higgs_triangle = false
  end

module MSSM_no_4_ckm : MSSM_flags =
  struct
    let include_goldstone = false
    let include_four = false
    let ckm_present = true
    let gravitino = false
    let higgs_triangle = false
  end

module MSSM_Grav : MSSM_flags =
  struct
    let include_goldstone = false
    let include_four = false
    let ckm_present = false
    let gravitino = true
    let higgs_triangle = false
  end

module MSSM_Hgg : MSSM_flags =
  struct
    let include_goldstone = false
    let include_four = false
    let ckm_present = false
    let gravitino = false
    let higgs_triangle = true
  end

module MSSM (Flags : MSSM_flags) =
  struct
    let rCS = RCS.rename rcs_file "Modellib_MSSM.MSSM"
      [ "MSSM" ]

    open Coupling

    let default_width = ref Timelike
    let use_fudged_width = ref false

    let options = Options.create
      [ "constant_width", Arg.Unit (fun () → default_width := Constant),
        "use_constant_width_(also_in_t-channel)";
        "fudged_width", Arg.Set use_fudged_width,
        "use_fudge_factor_for_charge_particle_width";

```



```

    "custom_width", Arg.String (fun f → default_width := Custom f),
    "use_custom_width";
    "cancel_widths", Arg.Unit (fun () → default_width := Vanishing),
    "use_vanishing_width"]

type gen =
  | G of int | GG of gen × gen

let rec string_of_gen = function
  | G n when n > 0 → string_of_int n
  | G n → string_of_int (abs n) ^ "c"
  | GG (g1, g2) → string_of_gen g1 ^ "-" ^ string_of_gen g2

```

With this we distinguish the flavour.

```

type sff =
  | SL | SN | SU | SD

let string_of_sff = function
  | SL → "s1" | SN → "sn" | SU → "su" | SD → "sd"

```

With this we distinguish the mass eigenstates. At the moment we have to cheat a little bit for the sneutrinos. Because we are dealing with massless neutrinos there is only one sort of sneutrino.

```

type sfm =
  | M1 | M2

let string_of_sfm = function
  | M1 → "1" | M2 → "2"

```

We also introduce special types for the charginos and neutralinos.

```

type char =
  | C1 | C2 | C1c | C2c

type neu =
  | N1 | N2 | N3 | N4

let int_of_char = function
  | C1 → 1 | C2 → 2 | C1c → -1 | C2c → -2

let string_of_char = function
  | C1 → "1" | C2 → "2" | C1c → "-1" | C2c → "-2"

let conj_char = function
  | C1 → C1c | C2 → C2c | C1c → C1 | C2c → C2

let string_of_neu = function
  | N1 → "1" | N2 → "2" | N3 → "3" | N4 → "4"

```

Also we need types to distinguish the Higgs bosons. We follow the conventions of Kuroda, which means

$$H_1 = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_1 + H^0 \cos \alpha - h^0 \sin \alpha + iA^0 \sin \beta - i\phi^0 \cos \beta) \\ H^- \sin \beta - \phi^- \cos \beta \end{pmatrix}, \quad (13.77)$$

$$H_2 = \left( \frac{1}{\sqrt{2}} (v_2 + H^0 \sin \alpha + h^0 \cos \alpha + iA^0 \cos \beta + i\phi^0 \sin \beta) \right) \quad (13.78)$$

This is a different sign convention compared to, e.g., Weinberg's volume iii. We will refer to it as *GS+*.

```

type higgs =
  | H1 (* the light scalar Higgs *)
  | H2 (* the heavy scalar Higgs *)
  | H3 (* the pseudoscalar Higgs *)
  | H4 (* the charged Higgs *)
  | H5 (* the neutral Goldstone boson *)
  | H6 (* the charged Goldstone boson *)
  | DH of higgs × higgs

let rec string_of_higgs = function
  | H1 → "h1" | H2 → "h2" | H3 → "h3" | H4 → "h4"
  | H5 → "p1" | H6 → "p2"
  | DH (h1, h2) → string_of_higgs h1 ^ string_of_higgs h2

type flavor =
  | L of int | N of int
  | U of int | D of int
  | Sup of sfm × int | Sdown of sfm × int
  | Ga | Wp | Wm | Z | Gl
  | Slepton of sfm × int | Sneutrino of int
  | Neutralino of neu | Chargino of char
  | Gluino | Grino
  | Phip | Phim | Phi0 | H_Heavy | H_Light | Hp | Hm | A

type gauge = unit

let gauge_symbol () =
  failwith "Modellib_MSSM.MSSM.gauge_symbol: internal error"

At this point we will forget graviton and -tino.

let lep_family g = [ L g; N g; Slepton (M1, g);
                    Slepton (M2, g); Sneutrino g ]

let family g =
  [ L g; N g; Slepton (M1, g); Slepton (M2, g); Sneutrino g;
    U g; D g; Sup (M1, g); Sup (M2, g); Sdown (M1, g);
    Sdown (M2, g) ]

let external_flavors'' =
  [ "1st_Generation", ThoList.flatmap family [1; -1];
    "2nd_Generation", ThoList.flatmap family [2; -2];
    "3rd_Generation", ThoList.flatmap family [3; -3];
    "Gauge_Bosons", [Ga; Z; Wp; Wm; Gl];
    "Charginos", [Chargino C1; Chargino C2; Chargino C1c; Chargino C2c];
    "Neutralinos", [Neutralino N1; Neutralino N2; Neutralino N3;
                    Neutralino N4];
    "Higgs_Bosons", [H_Heavy; H_Light; Hp; Hm; A];
    "Gluinos", [Gluino] ]

```

```

let external_flavors' =
  if Flags.gravitino then external_flavors'' @ ["Gravitino", [Grino]]
  else
    external_flavors''
let external_flavors () =
  if Flags.include_goldstone then external_flavors' @ ["Goldstone_Bosons",
    [Phip; Phim; Phi0]]
  else
    external_flavors'
let flavors () = ThoList.flatmap snd (external_flavors ())
let spinor n =
  if n ≥ 0 then
    Spinor
  else if
    n ≤ 0 then
    ConjSpinor
  else
    invalid_arg "Modellib_MSSM.MSSM.spinor:_internal_error"
let lorentz = function
  | L g → spinor g | N g → spinor g
  | U g → spinor g | D g → spinor g
  | Chargino c → spinor (int_of_char c)
  | Ga → Vector
  | Gl → Vector
  | Wp | Wm | Z → Massive_Vector
  | H_Heavy | H_Light | Hp | Hm | A → Scalar
  | Phip | Phim | Phi0 → Scalar
  | Sup _ | Sdown _ | Slepton _ | Sneutrino _ → Scalar
  | Neutralino _ → Majorana
  | Gluino → Majorana
  | Grino → Vectorspinor
let color = function
  | U g → Color.SUN (if g > 0 then 3 else -3)
  | Sup (m, g) → Color.SUN (if g > 0 then 3 else -3)
  | D g → Color.SUN (if g > 0 then 3 else -3)
  | Sdown (m, g) → Color.SUN (if g > 0 then 3 else -3)
  | Gl | Gluino → Color.AdjSUN 3
  | _ → Color.Singlet
let prop_spinor n =
  if n ≥ 0 then
    Prop_Spinor
  else if
    n ≤ 0 then
    Prop_ConjSpinor
  else
    invalid_arg "Modellib_MSSM.MSSM.prop_spinor:_internal_error"
let propagator = function

```

```

| L g → prop-spinor g | N g → prop-spinor g
| U g → prop-spinor g | D g → prop-spinor g
| Chargino c → prop-spinor (int_of_char c)
| Ga | Gl → Prop-Feynman
| Wp | Wm | Z → Prop-Unitarity
| H-Heavy | H-Light | Hp | Hm | A → Prop-Scalar
| Phip | Phim | Phi0 → if Flags.include_goldstone then Prop-Scalar
                        else Only-Insertion
| Slepton _ | Sneutrino _ | Sup _ | Sdown _ → Prop-Scalar
| Gluino → Prop-Majorana | Neutralino _ → Prop-Majorana
| Grino → Only-Insertion

```

Note, that we define the gravitino only as an insertion since when using propagators we are effectively going to a higher order in the gravitational coupling. This would enforce us to also include higher-dimensional vertices with two gravitinos for a consistent power counting in  $1/M_{\text{Planck}}$ .

Optionally, ask for the fudge factor treatment for the widths of charged particles. Currently, this only applies to  $W^\pm$  and top.

```

let width f =
  if !use_fudged_width then
    match f with
    | Wp | Wm | U 3 | U (-3) → Fudged
    | _ → !default_width
  else
    !default_width

```

For the Goldstone bosons we adopt the conventions of the Kuroda paper.

$$H_1 \equiv \begin{pmatrix} (v_1 + H^0 \cos \alpha - h^0 \sin \alpha + iA^0 \sin \beta - i \cos \beta \phi^0) / \sqrt{2} \\ H^- \sin \beta - \phi^- \cos \beta \end{pmatrix} \quad (13.79a)$$

$$H_2 \equiv \begin{pmatrix} H^+ \cos \beta + \phi^+ \sin \beta \\ (v_2 + H^0 \sin \alpha + h^0 \cos \alpha + iA^0 \cos \beta + i\phi^0 \sin \beta) / \sqrt{2} \end{pmatrix} \quad (13.79b)$$

```

let goldstone = function
| Wp → Some (Phip, Coupling.Const 1)
| Wm → Some (Phim, Coupling.Const 1)
| Z → Some (Phi0, Coupling.Const 1)
| _ → None

```

```

let conjugate = function
| L g → L (-g) | N g → N (-g)
| U g → U (-g) | D g → D (-g)
| Sup (m, g) → Sup (m, -g)
| Sdown (m, g) → Sdown (m, -g)
| Slepton (m, g) → Slepton (m, -g)
| Sneutrino g → Sneutrino (-g)
| Gl → Gl (* — Gl0 -i Gl0 *)
| Ga → Ga | Z → Z | Wp → Wm | Wm → Wp
| H-Heavy → H-Heavy | H-Light → H-Light | A → A

```

```

| Hp → Hm | Hm → Hp
| Phip → Phim | Phim → Phip | Phi0 → Phi0
| Gluino → Gluino
| Grino → Grino
| Neutralino n → Neutralino n | Chargino c → Chargino (conj_char c)

let fermion = function
| L g → if g > 0 then 1 else -1
| N g → if g > 0 then 1 else -1
| U g → if g > 0 then 1 else -1
| D g → if g > 0 then 1 else -1
| Gl | Ga | Z | Wp | Wm → 0 (* — Gl0 -i 0 *)
| H_Heavy | H_Light | Hp | Hm | A → 0
| Phip | Phim | Phi0 → 0
| Neutralino _ → 2
| Chargino c → if (int_of_char c) > 0 then 1 else -1
| Sup _ → 0 | Sdown _ → 0
| Slepton _ → 0 | Sneutrino _ → 0
| Gluino | Grino → 2

```

Because the O'Cam1 compiler only allows 248 constructors we must divide the constants into subgroups of constants, e.g. for the Higgs couplings. In the MSSM there are a lot of angles among the parameters, the Weinberg-angle, the angle describing the Higgs vacuum structure, the mixing angle of the real parts of the Higgs dubletts, the mixing angles of the sfermions. Therefore we are going to define the trigonometric functions of those angles not as constants but as functors of the angles. Sums and differences of angles are only used as arguments for the  $\alpha$  and  $\beta$  angles, so it makes no sense to define special functions for differences and sums of angles.

```

type angle =
| Thw | Al | Be | Th_SF of sff × int | Delta | CKM_12 |
CKM_13 | CKM_23

let string_of_angle = function
| Thw → "thw" | Al → "al" | Be → "be" | Delta → "d"
| CKM_12 → "ckm12" | CKM_13 → "ckm13" | CKM_23 →
"ckm23"
| Th_SF (f, g) → "th" ^ string_of_sff f ^ string_of_int g

```

We introduce a Boolean type *vc* as a pseudonym for Vertex Conjugator to distinguish between vertices containing complex mixing matrices like the CKM-matrix or the sfermion or neutralino/chargino-mixing matrices, which have to become complex conjugated. The true-option stands for the conjugated vertex, the false-option for the unconjugated vertex.

```

type vc = bool

type constant =
| Unit | Pi | Alpha_QED | Sin2thw
| Sin of angle | Cos of angle | E | G | Vev | Tanb | Tana
| Cos2be | Cos2al | Sin2be | Sin2al | Sin4al | Sin4be | Cos4be
| Cosapb | Cosamb | Sinapb | Sinamb | Cos2am2b | Sin2am2b
| Eidelta

```

```

| Mu | AU of int | AD of int | AL of int
| V_CKM of int×int | M_SF of sff × int×sfm × sfm
| M_V of char×char (* left chargino mixing matrix *)
| M_U of char×char (* right chargino mixing matrix *)
| M_N of neu × neu (* neutralino mixing matrix *)
| V_0 of neu × neu | A_0 of neu × neu | V_P of char×char |
A_P of char×char
| L_CN of char×neu | R_CN of char×neu | L_NC of neu × char |
R_NC of neu × char
| S_NNH1 of neu × neu | P_NNH1 of neu × neu
| S_NNH2 of neu × neu | P_NNH2 of neu × neu
| S_NNA of neu × neu | P_NNA of neu × neu
| S_NNG of neu × neu | P_NNG of neu × neu
| L_CNG of char×neu | R_CNG of char×neu
| L_NCH of neu × char | R_NCH of neu × char
| Q_lepton | Q_up | Q_down | Q_charg
| G_Z | G_CC | G_CCQ of vc × int×int
| G_NC_neutrino | G_NC_lepton | G_NC_up | G_NC_down
| I_Q_W | I_G_ZWW | G_WWWW | G_ZZWW | G_PZWW |
G_PPWW
| G_strong | G_SS | I_G_S | G_S_Sqrt
| G_s
| M of flavor | W of flavor
| G_NZN of neu × neu | G_CZC of char×char
| G_YUK of int×int
| G_YUK_1 of int×int | G_YUK_2 of int×int | G_YUK_3 of int×int
| G_YUK_4 of int×int | G_NHC of neu×char | G_CHN of char×neu
| G_YUK_C of vc × int×char×sff × sfm
| G_YUK_Q of vc × int×int×char×sff × sfm
| G_YUK_N of vc × int×neu × sff × sfm
| G_YUK_G of vc × int×sff × sfm
| G_NGC of neu × char | G_CGN of char×neu
| SUM_1
| G_NWC of neu × char | G_CWN of char×neu
| G_CH1C of char×char | G_CH2C of char×char | G_CAC of char×char
| G_CGC of char×char
| G_SWS of vc × int×int×sfm × sfm
| G_SLSNW of vc × int×sfm
| G_ZSF of sff × int×sfm × sfm
| G_CICIH1 of neu×neu | G_CICIH2 of neu×neu | G_CICIA of neu×
neu
| G_CICIG of neu × neu
| G_GH of int | G_GHGo of int
| G_GLGLH | G_GLGLHH | G_GLGLA | G_PPH | G_PPHH |
G_PPA
| G_WWSFSF of sff × int×sfm × sfm
| G_WPSLSN of vc × int×sfm
| G_H3 of int | G_H4 of int
| G_HGo3 of int | G_HGo4 of int | G_GG4 of int
| G_H1SFSF of sff×int×sfm×sfm | G_H2SFSF of sff×int×sfm×sfm

```

---

```

|  $G\_ASF\!SF$  of  $sff \times int \times sfm \times sfm$ 
|  $G\_HSNSL$  of  $vc \times int \times sfm$ 
|  $G\_GoS\!F\!SF$  of  $sff \times int \times sfm \times sfm$ 
|  $G\_GoSNSL$  of  $vc \times int \times sfm$ 
|  $G\_HSUSD$  of  $vc \times sfm \times sfm \times int \times int$  |  $G\_GSUSD$  of  $vc \times sfm \times$ 
 $sfm \times int \times int$ 
|  $G\_WPSUSD$  of  $vc \times sfm \times sfm \times int \times int$ 
|  $G\_WZSUSD$  of  $vc \times sfm \times sfm \times int \times int$ 
|  $G\_WZSLN$  of  $vc \times int \times sfm$  |  $G\_G\!l\!G\!l\!S\!Q\!S\!Q$ 
|  $G\_PPS\!F\!SF$  of  $sff$ 
|  $G\_ZZS\!F\!SF$  of  $sff \times int \times sfm \times sfm$  |  $G\_ZPS\!F\!SF$  of  $sff \times int \times sfm \times sfm$ 
|  $G\_G\!l\!ZS\!F\!SF$  of  $sff \times int \times sfm \times sfm$  |  $G\_G\!l\!PS\!Q\!S\!Q$ 
|  $G\_G\!l\!WSUSD$  of  $vc \times sfm \times sfm \times int \times int$ 
|  $G\_GH_4$  of  $int$  |  $G\_GHGo_4$  of  $int$ 
|  $G\_H1H2S\!F\!SF$  of  $sff \times sfm \times sfm \times int$ 
|  $G\_H1H1S\!F\!SF$  of  $sff \times sfm \times sfm \times int$ 
|  $G\_H2H2S\!F\!SF$  of  $sff \times sfm \times sfm \times int$ 
|  $G\_HHS\!F\!SF$  of  $sff \times sfm \times sfm \times int$ 
|  $G\_AAS\!F\!SF$  of  $sff \times sfm \times sfm \times int$ 
|  $G\_HH1SLN$  of  $vc \times sfm \times int$  |  $G\_HH2SLN$  of  $vc \times sfm \times int$ 
|  $G\_HASLN$  of  $vc \times sfm \times int$ 
|  $G\_HH1SUSD$  of  $vc \times sfm \times sfm \times int \times int$ 
|  $G\_HH2SUSD$  of  $vc \times sfm \times sfm \times int \times int$ 
|  $G\_HASUSD$  of  $vc \times sfm \times sfm \times int \times int$ 
|  $G\_AG0S\!F\!SF$  of  $sff \times sfm \times sfm \times int$ 
|  $G\_HGS\!F\!SF$  of  $sff \times sfm \times sfm \times int$ 
|  $G\_GGS\!F\!SF$  of  $sff \times sfm \times sfm \times int$ 
|  $G\_G0G0S\!F\!SF$  of  $sff \times sfm \times sfm \times int$ 
|  $G\_HGSNSL$  of  $vc \times sfm \times int$  |  $G\_H1GSNSL$  of  $vc \times sfm \times int$ 
|  $G\_H2GSNSL$  of  $vc \times sfm \times int$  |  $G\_AGNSL$  of  $vc \times sfm \times int$ 
|  $G\_GGSNSL$  of  $vc \times sfm \times int$ 
|  $G\_HGSUSD$  of  $vc \times sfm \times sfm \times int \times int$ 
|  $G\_H1GSUSD$  of  $vc \times sfm \times sfm \times int \times int$ 
|  $G\_H2GSUSD$  of  $vc \times sfm \times sfm \times int \times int$ 
|  $G\_AGSUSD$  of  $vc \times sfm \times sfm \times int \times int$ 
|  $G\_GGSUSD$  of  $vc \times sfm \times sfm \times int \times int$ 
|  $G\_SN_4$  of  $int \times int$ 
|  $G\_SN2SL2\_1$  of  $sfm \times sfm \times int \times int$  |  $G\_SN2SL2\_2$  of  $sfm \times sfm \times$ 
 $int \times int$ 
|  $G\_SF_4$  of  $sff \times sff \times sfm \times sfm \times sfm \times sfm \times int \times int$ 
|  $G\_SF_4\_3$  of  $sff \times sff \times sfm \times sfm \times sfm \times sfm \times int \times int \times int$ 
|  $G\_SF_4\_4$  of  $sff \times sff \times sfm \times sfm \times sfm \times sfm \times int \times int \times int \times int$ 
|  $G\_SL_4$  of  $sfm \times sfm \times sfm \times sfm \times int$ 
|  $G\_SL_4\_2$  of  $sfm \times sfm \times sfm \times sfm \times int \times int$ 
|  $G\_SN2SQ2$  of  $sff \times sfm \times sfm \times int \times int$ 
|  $G\_SL2SQ2$  of  $sff \times sfm \times sfm \times sfm \times sfm \times int \times int$ 
|  $G\_SUSDNSL$  of  $vc \times sfm \times sfm \times sfm \times int \times int \times int$ 
|  $G\_SU_4$  of  $sfm \times sfm \times sfm \times sfm \times int$ 
|  $G\_SU_4\_2$  of  $sfm \times sfm \times sfm \times sfm \times int \times int$ 
|  $G\_SD_4$  of  $sfm \times sfm \times sfm \times sfm \times int$ 

```

```

| G_SD4_2 of sfm × sfm × sfm × sfm × int × int
| G_SU2SD2 of sfm × sfm × sfm × sfm × int × int × int × int
| G_HSF31 of higgs × int × sfm × sfm × sff × sff
| G_HSF32 of higgs × int × int × sfm × sfm × sff × sff
| G_HSF41 of higgs × int × sfm × sfm × sff × sff
| G_HSF42 of higgs × int × int × sfm × sfm × sff × sff
| G_Grav | G_Gr_Ch of char | G_Gr_Z_Neu of neu
| G_Gr_A_Neu of neu | G_Gr4_Neu of neu
| G_Gr4_A_Ch of char | G_Gr4_Z_Ch of char
| G_Grav_N | G_Grav_U of int × sfm | G_Grav_D of int × sfm
| G_Grav_L of int × sfm | G_Grav_Uc of int × sfm | G_Grav_Dc of int × sfm
| G_Grav_Lc of int × sfm | G_GravGl
| G_Gr_H_Ch of char | G_Gr_H1_Neu of neu
| G_Gr_H2_Neu of neu | G_Gr_H3_Neu of neu
| G_Gr4A_Sl of int × sfm | G_Gr4A_Slc of int × sfm
| G_Gr4A_Su of int × sfm | G_Gr4A_Suc of int × sfm
| G_Gr4A_Sd of int × sfm | G_Gr4A_Sdc of int × sfm
| G_Gr4Z_Sn | G_Gr4Z_Snc
| G_Gr4Z_Sl of int × sfm | G_Gr4Z_Slc of int × sfm
| G_Gr4Z_Su of int × sfm | G_Gr4Z_Suc of int × sfm
| G_Gr4Z_Sd of int × sfm | G_Gr4Z_Sdc of int × sfm
| G_Gr4W_Sl of int × sfm | G_Gr4W_Slc of int × sfm
| G_Gr4W_Su of int × sfm | G_Gr4W_Suc of int × sfm
| G_Gr4W_Sd of int × sfm | G_Gr4W_Sdc of int × sfm
| G_Gr4W_Sn | G_Gr4W_Snc
| G_Gr4Gl_Su of int × sfm | G_Gr4Gl_Suc of int × sfm
| G_Gr4Gl_Sd of int × sfm | G_Gr4Gl_Sdc of int × sfm
| G_Gr4_Z_H1 of neu | G_Gr4_Z_H2 of neu | G_Gr4_Z_H3 of neu
| G_Gr4_W_H of neu | G_Gr4_W_Hc of neu | G_Gr4_H_A of char
| G_Gr4_H_Z of char

```

Two integer counters for the QCD and EW order of the couplings.

```

type orders = int × int
let orders = function
| _ → (0, 0)
let ferm_of_sff = function
| SL, g → (L g) | SN, g → (N g)
| SU, g → (U g) | SD, g → (D g)

```

$$\alpha_{\text{QED}} = \frac{1}{137.0359895} \quad (13.80a)$$

$$\sin^2 \theta_w = 0.23124 \quad (13.80b)$$

Here we must perhaps allow for complex input parameters. So split them into their modulus and their phase. At first, we leave them real; the generalization to complex parameters is obvious.

```

module Ch = Charges.QQ

```



```

let ( // ) = Algebra.Small_Rational.make

let generation' = function
| 1 → [ 1//1; 0//1; 0//1]
| 2 → [ 0//1; 1//1; 0//1]
| 3 → [ 0//1; 0//1; 1//1]
| -1 → [-1//1; 0//1; 0//1]
| -2 → [ 0//1; -1//1; 0//1]
| -3 → [ 0//1; 0//1; -1//1]
| n → invalid_arg ("MSSM.generation':␣" ^ string_of_int n)

let generation f =
  if Flags.ckm_present then
    []
  else
    match f with
    | L n | N n | U n | D n | Sup (_, n)
    | Sdown (_, n) | Slepton (_, n)
    | Sneutrino n → generation' n
    | _ → [0//1; 0//1; 0//1]

let charge = function
| L n → if n > 0 then -1//1 else 1//1
| Slepton (_, n) → if n > 0 then -1//1 else 1//1
| N n → 0//1
| Sneutrino n → 0//1
| U n → if n > 0 then 2//3 else -2//3
| Sup (_, n) → if n > 0 then 2//3 else -2//3
| D n → if n > 0 then -1//3 else 1//3
| Sdown (_, n) → if n > 0 then -1//3 else 1//3
| Gl | Ga | Z | Neutralino _ | Gluino → 0//1
| Wp → 1//1
| Wm → -1//1
| H_Heavy | H_Light | Phi0 → 0//1
| Hp | Phip → 1//1
| Hm | Phim → -1//1
| Chargino (C1 | C2) → 1//1
| Chargino (C1c | C2c) → -1//1
| _ → 0//1

let lepton = function
| L n | N n → if n > 0 then 1//1 else -1//1
| Slepton (_, n)
| Sneutrino n → if n > 0 then 1//1 else -1//1
| _ → 0//1

let baryon = function
| U n | D n → if n > 0 then 1//1 else -1//1
| Sup (_, n) | Sdown (_, n) → if n > 0 then 1//1 else -1//1
| _ → 0//1

let charges f =
  [ charge f; lepton f; baryon f ] @ generation f

```

```

let parameters () =
  { input = [];
    derived = [];
    derived_arrays = [] }

module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)

```

For the couplings there are generally two possibilities concerning the sign of the covariant derivative.

$$\text{CD}^\pm = \partial_\mu \pm ig T^a A_\mu^a \quad (13.81)$$

The particle data group defines the signs consistently to be positive. Since the convention for that signs also influence the phase definitions of the gaugino/higgsino fields via the off-diagonal entries in their mass matrices it would be the best to adopt that convention.

\*\* REVISED: Compatible with CD+. \*\*

```

let electromagnetic_currents_3 g =
  [((U (-g), Ga, U g), FBF (1, Psibar, V, Psi), Q_up);
   ((D (-g), Ga, D g), FBF (1, Psibar, V, Psi), Q_down);
   ((L (-g), Ga, L g), FBF (1, Psibar, V, Psi), Q_lepton)]

```

\*\* REVISED: Compatible with CD+. \*\*

```

let electromagnetic_sfermion_currents g m =
  [((Ga, Slepton (m, -g), Slepton (m, g)), Vector_Scalar_Scalar 1, Q_lepton);
   ((Ga, Sup (m, -g), Sup (m, g)), Vector_Scalar_Scalar 1, Q_up);
   ((Ga, Sdown (m, -g), Sdown (m, g)), Vector_Scalar_Scalar 1, Q_down)]

```

\*\* REVISED: Compatible with CD+. \*\*

```

let electromagnetic_currents_2 c =
  let cc = conj_char c in
  [((Chargino cc, Ga, Chargino c), FBF (1, Psibar, V, Psi), Q_charg)]

```

\*\* REVISED: Compatible with CD+. \*\*

```

let neutral_currents g =
  [((L (-g), Z, L g), FBF (1, Psibar, VA, Psi), G_NC_lepton);
   ((N (-g), Z, N g), FBF (1, Psibar, VA, Psi), G_NC_neutrino);
   ((U (-g), Z, U g), FBF (1, Psibar, VA, Psi), G_NC_up);
   ((D (-g), Z, D g), FBF (1, Psibar, VA, Psi), G_NC_down)]

```

$$\mathcal{L}_{\text{CC}} = \mp \frac{g}{2\sqrt{2}} \sum_i \bar{\psi}_i \gamma^\mu (1 - \gamma_5) (T^+ W_\mu^+ + T^- W_\mu^-) \psi_i, \quad (13.82)$$

where the sign corresponds to  $\text{CD}_\pm$ , respectively.

\*\* REVISED: Compatible with CD+. \*\*

Remark: The definition with the other sign compared to the SM files comes from the fact that  $g_{cc} = 1/(2\sqrt{2})$  is used overwhelmingly often in the SUSY

Feynman rules, so that JR decided to use a different definition for  $g_{cc}$  in SM and MSSM.

```
let charged_currents g =
  [ ((L (-g), Wm, N g), FBF ((-1), Psibar, VL, Psi), G_CC);
    ((N (-g), Wp, L g), FBF ((-1), Psibar, VL, Psi), G_CC) ]
```

The quark with the inverted generation (the antiparticle) is the outgoing one, the other the incoming. The vertex attached to the outgoing up-quark contains the CKM matrix element *not* complex conjugated, while the vertex with the outgoing down-quark has the conjugated CKM matrix element.

\*\* REVISED: Compatible with CD+. \*\*

```
let charged_quark_currents g h =
  [ ((D (-g), Wm, U h), FBF ((-1), Psibar, VL, Psi), G_CCQ (true,g,h));
    ((U (-g), Wp, D h), FBF ((-1), Psibar, VL, Psi), G_CCQ (false,h,g))] 
```

\*\* REVISED: Compatible with CD+. \*\*

```
let charged_chargino_currents n c =
  let cc = conj_char c in
  [ ((Chargino cc, Wp, Neutralino n),
      FBF (1, Psibar, VLR, Chi), G_CWN (c,n));
    ((Neutralino n, Wm, Chargino c),
      FBF (1, Chibar, VLR, Psi), G_NWC (n,c)) ]
```

\*\* REVISED: Compatible with CD+. \*\*

```
let charged_slepton_currents g m =
  [ ((Wm, Slepton (m, -g), Sneutrino g), Vector_Scalar_Scalar (-1), G_SLSNW
      (true,g,m));
    ((Wp, Slepton (m, g), Sneutrino (-g)), Vector_Scalar_Scalar 1, G_SLSNW
      (false,g,m)) ]
```

\*\* REVISED: Compatible with CD+. \*\*

```
let charged_squark_currents' g h m1 m2 =
  [ ((Wm, Sup (m1, g), Sdown (m2, -h)), Vector_Scalar_Scalar (-1), G_SWS
      (true,g,h,m1,m2));
    ((Wp, Sup (m1, -g), Sdown (m2, h)), Vector_Scalar_Scalar 1, G_SWS
      (false,g,h,m1,m2)) ]
let charged_squark_currents g h = List.flatten (Product.list2
  (charged_squark_currents' g h) [M1; M2] [M1; M2])
```

\*\* REVISED: Compatible with CD+. \*\*

```
let neutral_sfermion_currents' g m1 m2 =
  [ ((Z, Slepton (m1, -g), Slepton (m2, g)), Vector_Scalar_Scalar (-1), G_ZSF
      (SL, g, m1, m2));
    ((Z, Sup (m1, -g), Sup (m2, g)), Vector_Scalar_Scalar (-1), G_ZSF
      (SU, g, m1, m2));
    ((Z, Sdown (m1, -g), Sdown (m2, g)), Vector_Scalar_Scalar (-1), G_ZSF
      (SD, g, m1, m2)) ]
let neutral_sfermion_currents g =
  List.flatten (Product.list2 (neutral_sfermion_currents'
    g) [M1; M2] [M1; M2]) @
```

```
[ ((Z, Sneutrino (-g), Sneutrino g), Vector_Scalar_Scalar (-1), G_ZSF
(SN, g, M1, M1)) ]
```

The reality of the coupling of the Z-boson to two identical neutralinos makes the vector part of the coupling vanish. So we distinguish them not by the name but by the structure of the couplings.

\*\* REVISED: Compatible with CD+. \*\*

```
let neutral_Z_1 (n, m) =
  [ ((Neutralino n, Z, Neutralino m), FBF (1, Chibar, VA, Chi),
    (G_NZN (n, m))) ]
(***) REVISED: Compatible with CD+. (***)
let neutral_Z_2 n =
  [ ((Neutralino n, Z, Neutralino n), FBF (1, Chibar, Coupling.A, Chi),
    (G_NZN (n, n)) )]
```

\*\* REVISED: Compatible with CD+. \*\*

```
let charged_Z c1 c2 =
  let cc1 = conj_char c1 in
  ((Chargino cc1, Z, Chargino c2), FBF ((-1), Psibar, VA, Psi),
    G_CZC (c1, c2))
```

\*\* REVISED: Compatible with CD+. \*\*

```
let yukawa_v =
  [ ((Gluino, Gl, Gluino), FBF (1, Chibar, V, Chi), Gs) ]
```

\*\* REVISED: Independent of the sign of CD. \*\*

```
let yukawa_higgs g =
  [ ((N (-g), Hp, L g), FBF (1, Psibar, Coupling.SR, Psi), G_YUK (6, g));
    ((L (-g), Hm, N g), FBF (1, Psibar, Coupling.SL, Psi), G_YUK (6, g));
    ((L (-g), H_Heavy, L g), FBF (1, Psibar, S, Psi), G_YUK (7, g));
    ((L (-g), H_Light, L g), FBF (1, Psibar, S, Psi), G_YUK (8, g));
    ((L (-g), A, L g), FBF (1, Psibar, P, Psi), G_YUK (9, g));
    ((U (-g), H_Heavy, U g), FBF (1, Psibar, S, Psi), G_YUK (10, g));
    ((U (-g), H_Light, U g), FBF (1, Psibar, S, Psi), G_YUK (11, g));
    ((U (-g), A, U g), FBF (1, Psibar, P, Psi), G_YUK (12, g));
    ((D (-g), H_Heavy, D g), FBF (1, Psibar, S, Psi), G_YUK (13, g));
    ((D (-g), H_Light, D g), FBF (1, Psibar, S, Psi), G_YUK (14, g));
    ((D (-g), A, D g), FBF (1, Psibar, P, Psi), G_YUK (15, g)) ]
```

\*\* REVISED: Compatible with CD+ and GS+. \*\*

```
let yukawa_goldstone g =
  [ ((N (-g), Phip, L g), FBF (1, Psibar, Coupling.SR, Psi), G_YUK (19, g));
    ((L (-g), Phim, N g), FBF (1, Psibar, Coupling.SL, Psi), G_YUK (19, g));
    ((L (-g), Phi0, L g), FBF (1, Psibar, P, Psi), G_YUK (16, g));
    ((U (-g), Phi0, U g), FBF (1, Psibar, P, Psi), G_YUK (17, g));
    ((D (-g), Phi0, D g), FBF (1, Psibar, P, Psi), G_YUK (18, g)) ]
```

\*\* REVISED: Independent of the sign of CD. \*\*

```
let yukawa_higgs_quark (g, h) =
  [ ((U (-g), Hp, D h), FBF (1, Psibar, SLR, Psi), G_YUK_1 (g, h));
```

$((D(-h), Hm, U g), FBF(1, Psibar, SLR, Psi), G\_YUK\_2(g, h))]$

\*\* REVISED: Compatible with CD+ and GS+. \*\*

```
let yukawa_goldstone_quark g h =
  [ ((U(-g), Phip, D h), FBF(1, Psibar, SLR, Psi), G_YUK_3(g, h));
    ((D(-h), Phim, U g), FBF(1, Psibar, SLR, Psi), G_YUK_4(g, h)) ]
```

\*\* REVISED: Compatible with CD+.

```
let yukawa_higgs_2' (c1, c2) =
  let cc1 = conj_char c1 in
  [ ((Chargino cc1, H_Heavy, Chargino c2), FBF(1, Psibar, SLR, Psi),
      G_CH2C(c1, c2));
    ((Chargino cc1, H_Light, Chargino c2), FBF(1, Psibar, SLR, Psi),
      G_CH1C(c1, c2));
    ((Chargino cc1, A, Chargino c2), FBF(1, Psibar, SLR, Psi),
      G_CAC(c1, c2)) ]
let yukawa_higgs_2'' c =
  let cc = conj_char c in
  [ ((Chargino cc, H_Heavy, Chargino c), FBF(1, Psibar, S, Psi),
      G_CH2C(c, c));
    ((Chargino cc, H_Light, Chargino c), FBF(1, Psibar, S, Psi),
      G_CH1C(c, c));
    ((Chargino cc, A, Chargino c), FBF(1, Psibar, P, Psi),
      G_CAC(c, c)) ]
let yukawa_higgs_2 =
  ThoList.flatmap yukawa_higgs_2' [(C1, C2); (C2, C1)] @
  ThoList.flatmap yukawa_higgs_2'' [C1; C2]
```

\*\* REVISED: Compatible with CD+ and GS+. \*\*

```
let yukawa_goldstone_2' (c1, c2) =
  let cc1 = conj_char c1 in
  [ ((Chargino cc1, Phi0, Chargino c2), FBF(1, Psibar, SLR, Psi),
      G_CGC(c1, c2)) ]
let yukawa_goldstone_2'' c =
  let cc = conj_char c in
  [ ((Chargino cc, Phi0, Chargino c), FBF(1, Psibar, P, Psi),
      G_CGC(c, c)) ]
let yukawa_goldstone_2 =
  ThoList.flatmap yukawa_goldstone_2' [(C1, C2); (C2, C1)] @
  ThoList.flatmap yukawa_goldstone_2'' [C1; C2]
```

\*\* REVISED: Compatible with CD+. \*\*

```
let higgs_charg_neutr n c =
  let cc = conj_char c in
  [ ((Neutralino n, Hm, Chargino c), FBF(-1, Chibar, SLR, Psi),
      G_NHC(n, c));
    ((Chargino cc, Hp, Neutralino n), FBF(-1, Psibar, SLR, Chi),
      G_CHN(c, n)) ]
```

\*\* REVISED: Compatible with CD+ and GS+. \*\*

```

let goldstone_charg_neutr n c =
  let cc = conj_char c in
  [ ((Neutralino n, Phim, Chargino c), FBF (1, Chibar, SLR, Psi),
      G_NGC (n, c));
    ((Chargino cc, Phip, Neutralino n), FBF (1, Psibar, SLR, Chi),
      G_CGN (c, n)) ]

** REVISED: Compatible with CD+. **

let higgs_neutr' (n, m) =
  [ ((Neutralino n, H_Heavy, Neutralino m), FBF (1, Chibar, SP, Chi),
      G_CICIH2 (n, m));
    ((Neutralino n, H_Light, Neutralino m), FBF (1, Chibar, SP, Chi),
      G_CICIH1 (n, m));
    ((Neutralino n, A, Neutralino m), FBF (1, Chibar, SP, Chi),
      G_CICIA (n, m)) ]

let higgs_neutr'' n =
  [ ((Neutralino n, H_Heavy, Neutralino n), FBF (1, Chibar, S, Chi),
      G_CICIH2 (n, n));
    ((Neutralino n, H_Light, Neutralino n), FBF (1, Chibar, S, Chi),
      G_CICIH1 (n, n));
    ((Neutralino n, A, Neutralino n), FBF (1, Chibar, P, Chi),
      G_CICIA (n, n)) ]

let higgs_neutr =
  ThoList.flatmap higgs_neutr' [(N1, N2); (N1, N3); (N1, N4);
                                (N2, N3); (N2, N4); (N3, N4)] @
  ThoList.flatmap higgs_neutr'' [N1; N2; N3; N4]

** REVISED: Compatible with CD+ and GS+. **

let goldstone_neutr' (n, m) =
  [ ((Neutralino n, Phi0, Neutralino m), FBF (1, Chibar, SP, Chi),
      G_CICIG (n, m)) ]

let goldstone_neutr'' n =
  [ ((Neutralino n, Phi0, Neutralino n), FBF (1, Chibar, P, Chi),
      G_CICIG (n, n)) ]

let goldstone_neutr =
  ThoList.flatmap goldstone_neutr' [(N1, N2); (N1, N3); (N1, N4);
                                    (N2, N3); (N2, N4); (N3, N4)] @
  ThoList.flatmap goldstone_neutr'' [N1; N2; N3; N4]

** REVISED: Compatible with CD+. **

let yukawa_n_1 n g =
  [ ((Neutralino n, Slepton (M1, -g), L g), FBF (1, Chibar, Coupling.SL,
      Psi), G_YUK_N (true, g, n, SL, M1));
    ((Neutralino n, Slepton (M2, -g), L g), FBF (1, Chibar, SR, Psi),
      G_YUK_N (true, g, n, SL, M2));
    ((L (-g), Slepton (M1, g), Neutralino n), FBF (1, Psibar, SR, Chi),
      G_YUK_N (false, g, n, SL, M1));
    ((L (-g), Slepton (M2, g), Neutralino n), FBF (1, Psibar, Coupling.SL,
      Chi), G_YUK_N (false, g, n, SL, M2));
    ((Neutralino n, Sup (M1, -g), U g), FBF (1, Chibar, Coupling.SL,

```

```

    Psi), G_YUK_N (true,g,n,SU,M1));
    ((Neutralino n, Sup (M2,-g), U g), FBF (1, Chibar, SR, Psi),
     G_YUK_N (true,g,n,SU,M2));
    ((U (-g), Sup (M1,g), Neutralino n), FBF (1, Psibar, SR, Chi),
     G_YUK_N (false,g,n,SU,M1));
    ((U (-g), Sup (M2,g), Neutralino n), FBF (1, Psibar, Coupling.SL,
     Chi), G_YUK_N (false,g,n,SU,M2));
    ((Neutralino n, Sdown (M1,-g), D g), FBF (1, Chibar, Coupling.SL,
     Psi), G_YUK_N (true,g,n,SD,M1));
    ((Neutralino n, Sdown (M2,-g), D g), FBF (1, Chibar, SR, Psi),
     G_YUK_N (true,g,n,SD,M2));
    ((D (-g), Sdown (M1,g), Neutralino n), FBF (1, Psibar, SR, Chi),
     G_YUK_N (false,g,n,SD,M1));
    ((D (-g), Sdown (M2,g), Neutralino n), FBF (1, Psibar, Coupling.SL,
     Chi), G_YUK_N (false,g,n,SD,M2)) ]
let yukawa_n_2 n m =
  [ ((Neutralino n, Slepton (m,-3), L 3), FBF (1, Chibar, SLR, Psi),
    G_YUK_N (true,3,n,SL,m));
    ((L (-3), Slepton (m,3), Neutralino n), FBF (1, Psibar, SLR, Chi),
    G_YUK_N (false,3,n,SL,m));
    ((Neutralino n, Sup (m,-3), U 3), FBF (1, Chibar, SLR, Psi),
    G_YUK_N (true,3,n,SU,m));
    ((U (-3), Sup (m,3), Neutralino n), FBF (1, Psibar, SLR, Chi),
    G_YUK_N (false,3,n,SU,m));
    ((Neutralino n, Sdown (m,-3), D 3), FBF (1, Chibar, SLR, Psi),
    G_YUK_N (true,3,n,SD,m));
    ((D (-3), Sdown (m,3), Neutralino n), FBF (1, Psibar, SLR, Chi),
    G_YUK_N (false,3,n,SD,m)) ]
let yukawa_n_3 n g =
  [ ((Neutralino n, Sneutrino (-g), N g), FBF (1, Chibar, Coupling.SL,
    Psi), G_YUK_N (true,g,n,SN,M1));
    ((N (-g), Sneutrino g, Neutralino n), FBF (1, Psibar, SR, Chi),
    G_YUK_N (false,g,n,SN,M1)) ]
let yukawa_n_4 g =
  [ ((U (-g), Sup (M1,g), Gluino), FBF ((-1), Psibar, SR, Chi), G_S_Sqrt);
    ((D (-g), Sdown (M1,g), Gluino), FBF ((-1), Psibar, SR, Chi), G_S_Sqrt);
    ((Gluino, Sup (M1,-g), U g), FBF ((-1), Chibar, Coupling.SL, Psi), G_S_Sqrt);
    ((Gluino, Sdown (M1,-g), D g), FBF ((-1), Chibar, Coupling.SL, Psi), G_S_Sqrt);
    ((U (-g), Sup (M2,g), Gluino), FBF (1, Psibar, Coupling.SL, Chi), G_S_Sqrt);
    ((D (-g), Sdown (M2,g), Gluino), FBF (1, Psibar, Coupling.SL, Chi), G_S_Sqrt);
    ((Gluino, Sup (M2,-g), U g), FBF (1, Chibar, SR, Psi), G_S_Sqrt);
    ((Gluino, Sdown (M2,-g), D g), FBF (1, Chibar, SR, Psi), G_S_Sqrt)]
let yukawa_n_5 m =
  [ ((U (-3), Sup (m,3), Gluino), FBF (1, Psibar, SLR, Chi),
    G_YUK_G (false,3,SU,m));
    ((D (-3), Sdown (m,3), Gluino), FBF (1, Psibar, SLR, Chi),
    G_YUK_G (false,3,SD,m));
    ((Gluino, Sup (m,-3), U 3), FBF (1, Chibar, SLR, Psi),
    G_YUK_G (true,3,SU,m));
    ((Gluino, Sdown (m,-3), D 3), FBF (1, Chibar, SLR, Psi),

```

```

      G_YUK_G (true,3,SD,m))]]
let yukawa_n =
  List.flatten (Product.list2 yukawa_n_1 [N1; N2; N3; N4] [1;2]) @
  List.flatten (Product.list2 yukawa_n_2 [N1; N2; N3; N4] [M1; M2]) @
  List.flatten (Product.list2 yukawa_n_3 [N1; N2; N3; N4] [1;2;3]) @
  ThoList.flatmap yukawa_n_4 [1;2] @
  ThoList.flatmap yukawa_n_5 [M1; M2]
** REVISED: Compatible with CD+. **

let yukawa_c_1 c g =
  let cc = conj_char c in
  [ ((L (-g), Sneutrino g, Chargino cc), BBB (1, Psibar, Coupling.SR,
    Psibar), G_YUK_C (true,g,c,SN,M1));
    ((Chargino c, Sneutrino (-g), L g), PBP (1, Psi, Coupling.SL, Psi),
    G_YUK_C (false,g,c,SN,M1)) ]
let yukawa_c_2 c =
  let cc = conj_char c in
  [ ((L (-3), Sneutrino 3, Chargino cc), BBB (1, Psibar, SLR,
    Psibar), G_YUK_C (true,3,c,SN,M1));
    ((Chargino c, Sneutrino (-3), L 3), PBP (1, Psi, SLR, Psi),
    G_YUK_C (false,3,c,SN,M1)) ]
let yukawa_c_3 c m g =
  let cc = conj_char c in
  [ ((N (-g), Slepton (m,g), Chargino c), FBF (1, Psibar, Coupling.SR,
    Psi), G_YUK_C (true,g,c,SL,m));
    ((Chargino cc, Slepton (m,-g), N g), FBF (1, Psibar, Coupling.SL,
    Psi), G_YUK_C (false,g,c,SL,m)) ]
let yukawa_c c =
  ThoList.flatmap (yukawa_c_1 c) [1;2] @
  yukawa_c_2 c @
  List.flatten (Product.list2 (yukawa_c_3 c) [M1] [1;2]) @
  List.flatten (Product.list2 (yukawa_c_3 c) [M1;M2] [3])
** REVISED: Compatible with CD+. **

let yukawa_cq' c (g,h) m =
  let cc = conj_char c in
  [ ((Chargino c, Sup (m,-g), D h), PBP (1, Psi, SLR, Psi),
    G_YUK_Q (false,g,h,c,SU,m));
    ((D (-h), Sup (m,g), Chargino cc), BBB (1, Psibar, SLR, Psibar),
    G_YUK_Q (true,g,h,c,SU,m));
    ((Chargino cc, Sdown (m,-h), U g), FBF (1, Psibar, SLR, Psi),
    G_YUK_Q (true,g,h,c,SD,m));
    ((U (-g), Sdown (m,h), Chargino c), FBF (1, Psibar, SLR, Psi),
    G_YUK_Q (false,g,h,c,SD,m)) ]
let yukawa_cq'' c (g,h) =
  let cc = conj_char c in
  [ ((Chargino c, Sup (M1,-g), D h), PBP (1, Psi, Coupling.SL, Psi),
    G_YUK_Q (false,g,h,c,SU,M1));
    ((D (-h), Sup (M1,g), Chargino cc),
    BBB (1, Psibar, Coupling.SR, Psibar), G_YUK_Q (true,g,h,c,SU,M1));

```



```

      ((Chargino cc, Sdown (M1, -h), U g),
       FBF (1, Psibar, Coupling.SL, Psi), G_YUK_Q (true, g, h, c, SD, M1));
      ((U (-g), Sdown (M1, h), Chargino c),
       FBF (1, Psibar, Coupling.SR, Psi), G_YUK_Q (false, g, h, c, SD, M1)) ]
let yukawa_cq c =
  if Flags.ckm-present then
    List.flatten (Product.list2 (yukawa_cq' c) [(1, 3); (2, 3); (3, 3);
                                                (3, 2); (3, 1)] [M1; M2]) @
    ThoList.flatmap (yukawa_cq'' c) [(1, 1); (1, 2); (2, 1); (2, 2)]
  else
    ThoList.flatmap (yukawa_cq' c (3, 3)) [M1; M2] @
    ThoList.flatmap (yukawa_cq'' c) [(1, 1); (2, 2)]

** REVISED: Compatible with CD+. Remark: Singlet and octet gluon ex-
change. The coupling is divided by sqrt(2) to account for the correct normal-
ization of the Lie algebra generators. **

let col_currents g =
  [ ((D (-g), Gl, D g), FBF ((-1), Psibar, V, Psi), Gs);
    ((U (-g), Gl, U g), FBF ((-1), Psibar, V, Psi), Gs)]

** REVISED: Compatible with CD+. Remark: Singlet and octet gluon ex-
change. The coupling is divided by sqrt(2) to account for the correct normal-
ization of the Lie algebra generators. **

let col_sfermion_currents g m =
  [ ((Gl, Sup (m, -g), Sup (m, g)), Vector_Scalar_Scalar (-1), Gs);
    ((Gl, Sdown (m, -g), Sdown (m, g)), Vector_Scalar_Scalar (-1), Gs)]

The gravitino coupling is generically 1/(4MPl.)
** Triple vertices containing graivitinos. **

let triple_gravitino' g =
  [ ((Grino, Sneutrino (-g), N g), GBG (1, Gravbar, Coupling.SL, Psi), G_Grav_N);
    ((N (-g), Sneutrino g, Grino), GBG (1, Psibar, Coupling.SL, Grav), G_Grav_N)]

let triple_gravitino'' g m =
  [ ((Grino, Slepton (m, -g), L g), GBG (1, Gravbar, SLR, Psi), G_Grav_L (g, m));
    ((L (-g), Slepton (m, g), Grino), GBG (1, Psibar, SLR, Grav), G_Grav_Lc (g, m));
    ((Grino, Sup (m, -g), U g), GBG (1, Gravbar, SLR, Psi), G_Grav_U (g, m));
    ((U (-g), Sup (m, g), Grino), GBG (1, Psibar, SLR, Grav), G_Grav_Uc (g, m));
    ((Grino, Sdown (m, -g), D g), GBG (1, Gravbar, SLR, Psi), G_Grav_D (g, m));
    ((D (-g), Sdown (m, g), Grino), GBG (1, Psibar, SLR, Grav), G_Grav_Dc (g, m))]

let higgs_ch_gravitino c =
  let cc = conj_char c in
  [ ((Grino, Hm, Chargino c), GBG (1, Gravbar, SLR, Psi), G_Gr_H_Ch c);
    ((Chargino cc, Hp, Grino), GBG (1, Psibar, SLR, Grav), G_Gr_H_Ch cc)]

let higgs_neu_gravitino n =
  [ ((Grino, H_Light, Neutralino n), GBG (1, Gravbar, SLR, Chi), G_Gr_H1_Neu n);
    ((Grino, H_Heavy, Neutralino n), GBG (1, Gravbar, SLR, Chi), G_Gr_H2_Neu n);
    ((Grino, A, Neutralino n), GBG (1, Gravbar, SLR, Chi), G_Gr_H3_Neu n)]

let gravitino_gaugino_3 =

```

```
[ ((Grino, Gl, Gluino), GBG (1, Gravbar, V, Chi), G_Grav);
  ((Gluino, Gl, Grino), GBG (1, Chibar, V, Grav), G_Grav);
  ((Chargino C1c, Wp, Grino), GBG (1, Psibar, VLR, Grav), G_Gr_Ch C1);
  ((Chargino C2c, Wp, Grino), GBG (1, Psibar, VLR, Grav), G_Gr_Ch C2);
  ((Grino, Wm, Chargino C1), GBG (1, Gravbar, VLR, Psi), G_Gr_Ch C1c);
  ((Grino, Wm, Chargino C2), GBG (1, Gravbar, VLR, Psi), G_Gr_Ch C2c);
  ((Grino, Z, Neutralino N1), GBG (1, Gravbar, VLR, Chi), G_Gr_Z_Neu N1);
  ((Grino, Z, Neutralino N2), GBG (1, Gravbar, VLR, Chi), G_Gr_Z_Neu N2);
  ((Grino, Z, Neutralino N3), GBG (1, Gravbar, VLR, Chi), G_Gr_Z_Neu N3);
  ((Grino, Z, Neutralino N4), GBG (1, Gravbar, VLR, Chi), G_Gr_Z_Neu N4);
  ((Grino, Ga, Neutralino N1), GBG (1, Gravbar, VLR, Chi), G_Gr_A_Neu N1);
  ((Grino, Ga, Neutralino N2), GBG (1, Gravbar, VLR, Chi), G_Gr_A_Neu N2);
  ((Grino, Ga, Neutralino N3), GBG (1, Gravbar, VLR, Chi), G_Gr_A_Neu N3);
  ((Grino, Ga, Neutralino N4), GBG (1, Gravbar, VLR, Chi), G_Gr_A_Neu N4)]
```

```
let triple_gravitino =
  ThoList.flatmap triple_gravitino' [1; 2; 3] @
  List.flatten (Product.list2 triple_gravitino'' [1; 2; 3] [M1; M2]) @
  ThoList.flatmap higgs_ch_gravitino [C1; C2] @
  ThoList.flatmap higgs_neu_gravitino [N1; N2; N3; N4] @
  gravitino_gaugino_3
```

\*\* REVISED: Compatible with CD+. \*\*

```
let triple_gauge =
  [ ((Ga, Wm, Wp), Gauge_Gauge_Gauge 1, I-Q-W);
    ((Z, Wm, Wp), Gauge_Gauge_Gauge 1, I-G-ZWW);
    ((Gl, Gl, Gl), Gauge_Gauge_Gauge 1, I-G-S)]
```

\*\* REVISED: Independent of the sign of CD. \*\*

```
let gauge4 = Vector4 [(2, C_13_42); (-1, C_12_34); (-1, C_14_23)]
let gluon4 = Vector4 [(-1, C_13_42); (-1, C_12_34); (-1, C_14_23)]
let minus_gauge4 = Vector4 [(-2, C_13_42); (1, C_12_34); (1, C_14_23)]
let quartic_gauge =
  [ (Wm, Wp, Wm, Wp), gauge4, G_WWWW;
    (Wm, Z, Wp, Z), minus_gauge4, G_ZZWW;
    (Wm, Z, Wp, Ga), minus_gauge4, G_PZWW;
    (Wm, Ga, Wp, Ga), minus_gauge4, G_PPWW;
    (Gl, Gl, Gl, Gl), gauge4, G_SS]
```

The *Scalar\_Vector\_Vector* couplings do not depend on the choice of the sign of the covariant derivative since they are quadratic in the gauge couplings.

\*\* REVISED: Compatible with CD+. \*\*

\*\* Revision: 2005-03-10: first two vertices corrected. \*\*

```
let gauge_higgs =
  [ ((Wm, Hp, A), Vector_Scalar_Scalar 1, G_GH 1);
    ((Wp, Hm, A), Vector_Scalar_Scalar 1, G_GH 1);
    ((Z, H_Heavy, A), Vector_Scalar_Scalar 1, G_GH 3);
    ((Z, H_Light, A), Vector_Scalar_Scalar 1, G_GH 2);
    ((H_Heavy, Wp, Wm), Scalar_Vector_Vector 1, G_GH 5);
    ((H_Light, Wp, Wm), Scalar_Vector_Vector 1, G_GH 4);
    ((Wm, Hp, H_Heavy), Vector_Scalar_Scalar 1, G_GH 7);
```

```

((Wp, Hm, H_Heavy), Vector_Scalar_Scalar (-1), G_GH 7);
((Wm, Hp, H_Light), Vector_Scalar_Scalar 1, G_GH 6);
((Wp, Hm, H_Light), Vector_Scalar_Scalar (-1), G_GH 6);
((H_Heavy, Z, Z), Scalar_Vector_Vector 1, G_GH 9);
((H_Light, Z, Z), Scalar_Vector_Vector 1, G_GH 8);
((Z, Hp, Hm), Vector_Scalar_Scalar 1, G_GH 10);
((Ga, Hp, Hm), Vector_Scalar_Scalar 1, G_GH 11) ] @
(if Flags.higgs_triangle then
  [((H_Light, Gl, Gl), Dim5_Scalar_Gauge2 1, G_GLGLH);
   ((H_Heavy, Gl, Gl), Dim5_Scalar_Gauge2 1, G_GLGLHH);
   ((A, Gl, Gl), Dim5_Scalar_Gauge2_Skew 1, G_GLGLA);
   ((H_Light, Ga, Ga), Dim5_Scalar_Gauge2 1, G_PPH);
   ((H_Heavy, Ga, Ga), Dim5_Scalar_Gauge2 1, G_PPHH);
   ((A, Ga, Ga), Dim5_Scalar_Gauge2 1, G_PPA)]
else
  [])
** REVISED: Compatible with CD+ and GS+. **

let gauge_higgs_gold =
[ ((Wp, Phi0, Phim), Vector_Scalar_Scalar 1, G_GH 1);
  ((Wm, Phi0, Phip), Vector_Scalar_Scalar 1, G_GH 1);
  ((Z, H_Heavy, Phi0), Vector_Scalar_Scalar 1, G_GH 2);
  ((Z, H_Light, Phi0), Vector_Scalar_Scalar (-1), G_GH 3);
  ((Wp, H_Heavy, Phim), Vector_Scalar_Scalar 1, G_GH 6);
  ((Wm, H_Heavy, Phip), Vector_Scalar_Scalar (-1), G_GH 6);
  ((Wp, H_Light, Phim), Vector_Scalar_Scalar (-1), G_GH 7);
  ((Wm, H_Light, Phip), Vector_Scalar_Scalar 1, G_GH 7);
  ((Phim, Wp, Ga), Scalar_Vector_Vector 1, G_GHGo 1);
  ((Phip, Wm, Ga), Scalar_Vector_Vector 1, G_GHGo 1);
  ((Phim, Wp, Z), Scalar_Vector_Vector 1, G_GHGo 2);
  ((Phip, Wm, Z), Scalar_Vector_Vector 1, G_GHGo 2);
  ((Z, Phip, Phim), Vector_Scalar_Scalar 1, G_GH 10);
  ((Ga, Phip, Phim), Vector_Scalar_Scalar 1, G_GH 11) ]

let gauge_higgs4 =
[ ((A, A, Z, Z), Scalar2_Vector2 1, G_GH4 1);
  ((H_Heavy, H_Heavy, Z, Z), Scalar2_Vector2 1, G_GH4 3);
  ((H_Light, H_Light, Z, Z), Scalar2_Vector2 1, G_GH4 2);
  ((Hp, Hm, Z, Z), Scalar2_Vector2 1, G_GH4 4);
  ((Hp, Hm, Ga, Ga), Scalar2_Vector2 1, G_GH4 5);
  ((Hp, Hm, Ga, Z), Scalar2_Vector2 1, G_GH4 6);
  ((Hp, H_Heavy, Wm, Z), Scalar2_Vector2 1, G_GH4 8);
  ((Hm, H_Heavy, Wp, Z), Scalar2_Vector2 1, G_GH4 8);
  ((Hp, H_Light, Wm, Z), Scalar2_Vector2 1, G_GH4 7);
  ((Hm, H_Light, Wp, Z), Scalar2_Vector2 1, G_GH4 7);
  ((Hp, H_Heavy, Wm, Ga), Scalar2_Vector2 1, G_GH4 10);
  ((Hm, H_Heavy, Wp, Ga), Scalar2_Vector2 1, G_GH4 10);
  ((Hp, H_Light, Wm, Ga), Scalar2_Vector2 1, G_GH4 9);
  ((Hm, H_Light, Wp, Ga), Scalar2_Vector2 1, G_GH4 9);
  ((A, A, Wp, Wm), Scalar2_Vector2 1, G_GH4 11);
  ((H_Heavy, H_Heavy, Wp, Wm), Scalar2_Vector2 1, G_GH4 13);

```

```

((H_Light, H_Light, Wp, Wm), Scalar2_Vector2 1, G_GH4 12);
((Hp, Hm, Wp, Wm), Scalar2_Vector2 1, G_GH4 14);
((Hp, A, Wm, Z), Scalar2_Vector2 1, G_GH4 15);
((Hm, A, Wp, Z), Scalar2_Vector2 (-1), G_GH4 15);
((Hp, A, Wm, Ga), Scalar2_Vector2 1, G_GH4 16);
((Hm, A, Wp, Ga), Scalar2_Vector2 (-1), G_GH4 16) ]

let gauge_higgs_gold4 =
[ ((Z, Z, Phi0, Phi0), Scalar2_Vector2 1, G_GHGo4 1);
  ((Z, Z, Phip, Phim), Scalar2_Vector2 1, G_GHGo4 2);
  ((Ga, Ga, Phip, Phim), Scalar2_Vector2 1, G_GHGo4 3);
  ((Z, Ga, Phip, Phim), Scalar2_Vector2 1, G_GHGo4 4);
  ((Wp, Wm, Phip, Phim), Scalar2_Vector2 1, G_GHGo4 5);
  ((Wp, Wm, Phi0, Phi0), Scalar2_Vector2 1, G_GHGo4 5);
  ((Wp, Z, Phim, Phi0), Scalar2_Vector2 1, G_GHGo4 6);
  ((Wm, Z, Phip, Phi0), Scalar2_Vector2 (-1), G_GHGo4 6);
  ((Wp, Ga, Phim, Phi0), Scalar2_Vector2 1, G_GHGo4 7);
  ((Wm, Ga, Phip, Phi0), Scalar2_Vector2 (-1), G_GHGo4 7);
  ((Wp, Z, Phim, H_Heavy), Scalar2_Vector2 1, G_GHGo4 9);
  ((Wm, Z, Phip, H_Heavy), Scalar2_Vector2 1, G_GHGo4 9);
  ((Wp, Ga, Phim, H_Heavy), Scalar2_Vector2 1, G_GHGo4 11);
  ((Wm, Ga, Phip, H_Heavy), Scalar2_Vector2 1, G_GHGo4 11);
  ((Wp, Z, Phim, H_Light), Scalar2_Vector2 1, G_GHGo4 8);
  ((Wm, Z, Phip, H_Light), Scalar2_Vector2 1, G_GHGo4 8);
  ((Wp, Ga, Phim, H_Light), Scalar2_Vector2 1, G_GHGo4 10);
  ((Wm, Ga, Phip, H_Light), Scalar2_Vector2 1, G_GHGo4 10) ]

let gauge_sfermion4' g m1 m2 =
[ ((Wp, Wm, Slepton (m1, g), Slepton (m2, -g)), Scalar2_Vector2 1,
   G_WWSFSF (SL, g, m1, m2));
  ((Z, Ga, Slepton (m1, g), Slepton (m2, -g)), Scalar2_Vector2 1,
   G_ZPSFSF (SL, g, m1, m2));
  ((Z, Z, Slepton (m1, g), Slepton (m2, -g)), Scalar2_Vector2 1, G_ZZSFSF
   (SL, g, m1, m2));
  ((Wp, Wm, Sup (m1, g), Sup (m2, -g)), Scalar2_Vector2 1, G_WWSFSF
   (SU, g, m1, m2));
  ((Wp, Wm, Sdown (m1, g), Sdown (m2, -g)), Scalar2_Vector2 1, G_WWSFSF
   (SD, g, m1, m2));
  ((Z, Z, Sup (m1, g), Sup (m2, -g)), Scalar2_Vector2 1, G_ZZSFSF
   (SU, g, m1, m2));
  ((Z, Z, Sdown (m1, g), Sdown (m2, -g)), Scalar2_Vector2 1, G_ZZSFSF
   (SD, g, m1, m2));
  ((Z, Ga, Sup (m1, g), Sup (m2, -g)), Scalar2_Vector2 1, G_ZPSFSF
   (SU, g, m1, m2));
  ((Z, Ga, Sdown (m1, g), Sdown (m2, -g)), Scalar2_Vector2 1, G_ZPSFSF
   (SD, g, m1, m2)) ]

let gauge_sfermion4'' g m =
[ ((Wp, Ga, Slepton (m, g), Sneutrino (-g)), Scalar2_Vector2 1, G_WPSLSN
   (false, g, m));
  ((Wm, Ga, Slepton (m, -g), Sneutrino g), Scalar2_Vector2 1,
   G_WPSLSN (true, g, m));

```

```

((Wp, Z, Slepton (m, g), Sneutrino (-g)), Scalar2_Vector2 1, G_WZSLSN
  (false, g, m));
((Wm, Z, Slepton (m, -g), Sneutrino g), Scalar2_Vector2 1,
  G_WZSLSN (true, g, m));
((Ga, Ga, Slepton (m, g), Slepton (m, -g)), Scalar2_Vector2 1, G_PPSFSF SL);
((Ga, Ga, Sup (m, g), Sup (m, -g)), Scalar2_Vector2 1, G_PPSFSF SU);
((Ga, Ga, Sdown (m, g), Sdown (m, -g)), Scalar2_Vector2 1, G_PPSFSF SD)]
let gauge_sfermion4 g =
  List.flatten (Product.list2 (gauge_sfermion4' g) [M1; M2] [M1; M2]) @
  ThoList.flatmap (gauge_sfermion4'' g) [M1; M2] @
  [ ((Wp, Wm, Sneutrino g, Sneutrino (-g)), Scalar2_Vector2 1, G_WWSFSF
    (SN, g, M1, M1));
    ((Z, Z, Sneutrino g, Sneutrino (-g)), Scalar2_Vector2 1, G_ZZSFSF
    (SN, g, M1, M1)) ]
let gauge_squark4'' g h m1 m2 =
  [ ((Wp, Ga, Sup (m1, -g), Sdown (m2, h)), Scalar2_Vector2 1, G_WPSUSD
    (false, m1, m2, g, h));
    ((Wm, Ga, Sup (m1, g), Sdown (m2, -h)), Scalar2_Vector2 1, G_WPSUSD
    (true, m1, m2, g, h));
    ((Wp, Z, Sup (m1, -g), Sdown (m2, h)), Scalar2_Vector2 1, G_WZSUSD
    (false, m1, m2, g, h));
    ((Wm, Z, Sup (m1, g), Sdown (m2, -h)), Scalar2_Vector2 1, G_WZSUSD
    (true, m1, m2, g, h)) ]
let gauge_squark4' g h = List.flatten (Product.list2 (gauge_squark4'' g h)
  [M1; M2] [M1; M2])
let gauge_squark4 =
  if Flags.ckm_present then
    List.flatten (Product.list2 gauge_squark4' [1; 2; 3] [1; 2; 3])
  else
    ThoList.flatmap (fun g → gauge_squark4' g g) [1; 2; 3]
let gluon_w_squark'' g h m1 m2 =
  [ ((Gl, Wp, Sup (m1, -g), Sdown (m2, h)),
    Scalar2_Vector2 1, G_GLWSUSD (false, m1, m2, g, h));
    ((Gl, Wm, Sup (m1, g), Sdown (m2, -h)),
    Scalar2_Vector2 1, G_GLWSUSD (true, m1, m2, g, h)) ]
let gluon_w_squark' g h =
  List.flatten (Product.list2 (gluon_w_squark'' g h) [M1; M2] [M1; M2])
let gluon_w_squark =
  if Flags.ckm_present then
    List.flatten (Product.list2 gluon_w_squark' [1; 2; 3] [1; 2; 3])
  else
    ThoList.flatmap (fun g → gluon_w_squark' g g) [1; 2; 3]
let gluon_gauge_squark' g m1 m2 =
  [ ((Gl, Z, Sup (m1, g), Sup (m2, -g)), Scalar2_Vector2 2, G_GLZSFSF (SU, g, m1, m2));
    ((Gl, Z, Sdown (m1, g), Sdown (m2, -g)), Scalar2_Vector2 2, G_GLZSFSF (SD, g, m1, m2)) ]
let gluon_gauge_squark'' g m =
  [ ((Gl, Ga, Sup (m, g), Sup (m, -g)), Scalar2_Vector2 2, G_GLPSQSQ);
    ((Gl, Ga, Sdown (m, g), Sdown (m, -g)), Scalar2_Vector2 (-1), G_GLPSQSQ) ]
let gluon_gauge_squark g =

```

```

List.flatten (Product.list2 (gluon_gauge_squark' g) [M1; M2] [M1; M2]) @
ThoList.flatmap (gluon_gauge_squark'' g) [M1; M2]

let gluon2_squark2 g m =
  [ ((Gl, Gl, Sup (m, g), Sup (m, -g)), Scalar2_Vector2 1, G_GlGlSQSQ);
    ((Gl, Gl, Sdown (m, g), Sdown (m, -g)), Scalar2_Vector2 1, G_GlGlSQSQ)]

** REVISED: Independent of the sign of CD. **

let higgs =
  [ ((Hp, Hm, H_Heavy), Scalar_Scalar_Scalar 1, G_H3 1);
    ((Hp, Hm, H_Light), Scalar_Scalar_Scalar 1, G_H3 2);
    ((H_Heavy, H_Heavy, H_Light), Scalar_Scalar_Scalar 1, G_H3 3);
    ((H_Heavy, H_Heavy, H_Heavy), Scalar_Scalar_Scalar 1, G_H3 4);
    ((H_Light, H_Light, H_Light), Scalar_Scalar_Scalar 1, G_H3 5);
    ((H_Heavy, H_Light, H_Light), Scalar_Scalar_Scalar 1, G_H3 6);
    ((H_Heavy, A, A), Scalar_Scalar_Scalar 1, G_H3 7);
    ((H_Light, A, A), Scalar_Scalar_Scalar 1, G_H3 8) ]

** REVISED: Compatible with GS+, independent of the sign of CD. **

let higgs_gold =
  [ ((H_Heavy, A, Phi0), Scalar_Scalar_Scalar 1, G_HGo3 1);
    ((H_Light, A, Phi0), Scalar_Scalar_Scalar 1, G_HGo3 2);
    ((H_Heavy, Hp, Phim), Scalar_Scalar_Scalar 1, G_HGo3 3);
    ((H_Heavy, Hm, Phip), Scalar_Scalar_Scalar 1, G_HGo3 3);
    ((H_Light, Hp, Phim), Scalar_Scalar_Scalar 1, G_HGo3 4);
    ((H_Light, Hm, Phip), Scalar_Scalar_Scalar 1, G_HGo3 4);
    ((A, Hp, Phim), Scalar_Scalar_Scalar (-1), G_HGo3 5);
    ((A, Hm, Phip), Scalar_Scalar_Scalar 1, G_HGo3 5);
    ((H_Heavy, Phi0, Phi0), Scalar_Scalar_Scalar (-1), G_H3 7);
    ((H_Heavy, Phip, Phim), Scalar_Scalar_Scalar (-1), G_H3 7);
    ((H_Light, Phi0, Phi0), Scalar_Scalar_Scalar (-1), G_H3 8);
    ((H_Light, Phip, Phim), Scalar_Scalar_Scalar (-1), G_H3 8) ]

Here follow purely scalar quartic vertices which are only available for the no-
Whizard colored version.

** REVISED: Independent of the sign of CD. **

let higgs4 =
  [ ((Hp, Hm, Hp, Hm), Scalar4 1, G_H4 1);
    ((Hp, Hm, H_Heavy, H_Heavy), Scalar4 1, G_H4 2);
    ((Hp, Hm, H_Light, H_Light), Scalar4 1, G_H4 3);
    ((Hp, Hm, H_Heavy, H_Light), Scalar4 1, G_H4 4);
    ((Hp, Hm, A, A), Scalar4 1, G_H4 5);
    ((H_Heavy, H_Heavy, H_Heavy, H_Heavy), Scalar4 1, G_H4 6);
    ((H_Light, H_Light, H_Light, H_Light), Scalar4 1, G_H4 6);
    ((H_Heavy, H_Heavy, H_Light, H_Light), Scalar4 1, G_H4 7);
    ((H_Heavy, H_Light, H_Light, H_Light), Scalar4 1, G_H4 8);
    ((H_Heavy, H_Heavy, H_Heavy, H_Light), Scalar4 (-1), G_H4 8);
    ((H_Heavy, H_Heavy, A, A), Scalar4 1, G_H4 9);
    ((H_Light, H_Light, A, A), Scalar4 (-1), G_H4 9);
    ((H_Heavy, H_Light, A, A), Scalar4 1, G_H4 10);
    ((A, A, A, A), Scalar4 1, G_H4 11) ]

```

\*\* REVISED: Compatible with GS+, independent of the sign of CD. \*\*

```

let higgs_gold4 =
[ ((H_Heavy, H_Heavy, A, Phi0), Scalar4 1, G_HGo4 1);
  ((H_Heavy, H_Light, A, Phi0), Scalar4 1, G_HGo4 2);
  ((H_Light, H_Light, A, Phi0), Scalar4 (-1), G_HGo4 1);
  ((A, A, A, Phi0), Scalar4 3, G_HGo4 3);
  ((Hp, Hm, A, Phi0), Scalar4 1, G_HGo4 3);
  ((H_Heavy, H_Heavy, Hp, Phim), Scalar4 1, G_HGo4 4);
  ((H_Heavy, H_Heavy, Hm, Phip), Scalar4 1, G_HGo4 4);
  ((H_Heavy, H_Light, Hp, Phim), Scalar4 1, G_HGo4 5);
  ((H_Heavy, H_Light, Hm, Phip), Scalar4 1, G_HGo4 5);
  ((H_Light, H_Light, Hp, Phim), Scalar4 (-1), G_HGo4 4);
  ((H_Light, H_Light, Hm, Phip), Scalar4 (-1), G_HGo4 4);
  ((A, A, Hp, Phim), Scalar4 1, G_HGo4 6);
  ((A, A, Hm, Phip), Scalar4 1, G_HGo4 6);
  ((H_Heavy, A, Hp, Phim), Scalar4 1, G_HGo4 7);
  ((H_Heavy, A, Hm, Phip), Scalar4 (-1), G_HGo4 7);
  ((H_Light, A, Hp, Phim), Scalar4 1, G_HGo4 8);
  ((H_Light, A, Hm, Phip), Scalar4 (-1), G_HGo4 8);
  ((Hp, Hm, Hp, Phim), Scalar4 2, G_HGo4 6);
  ((Hp, Hm, Hm, Phip), Scalar4 2, G_HGo4 6);
  ((H_Heavy, H_Heavy, Phi0, Phi0), Scalar4 (-1), G_H4 9);
  ((H_Heavy, H_Light, Phi0, Phi0), Scalar4 (-1), G_H4 10);
  ((H_Light, H_Light, Phi0, Phi0), Scalar4 1, G_H4 9);
  ((A, A, Phi0, Phi0), Scalar4 1, G_HGo4 9);
  ((Hp, Hm, Phi0, Phi0), Scalar4 1, G_HGo4 10);
  ((H_Heavy, Hp, Phim, Phi0), Scalar4 1, G_HGo4 8);
  ((H_Heavy, Hm, Phip, Phi0), Scalar4 (-1), G_HGo4 8);
  ((H_Light, Hp, Phim, Phi0), Scalar4 (-1), G_HGo4 7);
  ((H_Light, Hm, Phip, Phi0), Scalar4 1, G_HGo4 7);
  ((A, Hp, Phim, Phi0), Scalar4 1, G_HGo4 11);
  ((A, Hm, Phip, Phi0), Scalar4 1, G_HGo4 11);
  ((H_Heavy, H_Heavy, Phip, Phim), Scalar4 1, G_HGo4 12);
  ((H_Heavy, H_Light, Phip, Phim), Scalar4 1, G_HGo4 13);
  ((H_Light, H_Light, Phip, Phim), Scalar4 1, G_HGo4 14);
  ((A, A, Phip, Phim), Scalar4 1, G_HGo4 15);
  ((Hp, Hm, Phip, Phim), Scalar4 1, G_HGo4 16);
  ((Hp, Hp, Phim, Phim), Scalar4 1, G_HGo4 17);
  ((Hm, Hm, Phip, Phip), Scalar4 1, G_HGo4 17);
  ((Hp, Phim, Phi0, Phi0), Scalar4 (-1), G_HGo4 6);
  ((Hm, Phip, Phi0, Phi0), Scalar4 (-1), G_HGo4 6);
  ((A, Phi0, Phi0, Phi0), Scalar4 (-3), G_HGo4 6);
  ((A, Phi0, Phip, Phim), Scalar4 (-1), G_HGo4 6);
  ((Hp, Phim, Phip, Phim), Scalar4 (-2), G_HGo4 6);
  ((Hm, Phip, Phip, Phim), Scalar4 (-2), G_HGo4 6) ]

```

\*\* REVISED: Independent of the sign of CD and GS. \*\*

```

let goldstone4 =
[ ((Phi0, Phi0, Phi0, Phi0), Scalar4 1, G_GG4 1);
  ((Phip, Phim, Phi0, Phi0), Scalar4 1, G_GG4 2);

```

```
((Phip, Phim, Phip, Phim), Scalar4 1, G_GG4 3) ]
```

The vertices of the type Higgs - Sfermion - Sfermion are independent of the choice of the CD sign since they are quadratic in the gauge coupling.

\*\* REVISED: Independent of the sign of CD. \*\*

```
let higgs_sneutrino' g =
  [ ((H_Heavy, Sneutrino g, Sneutrino (-g)), Scalar_Scalar_Scalar 1,
      G_H2SFSF (SN, g, M1, M1));
    ((H_Light, Sneutrino g, Sneutrino (-g)), Scalar_Scalar_Scalar 1,
      G_H1SFSF (SN, g, M1, M1));
    ((Hp, Sneutrino (-g), Slepton (M1, g)), Scalar_Scalar_Scalar 1,
      G_HSNSL (false, g, M1));
    ((Hm, Sneutrino g, Slepton (M1, -g)), Scalar_Scalar_Scalar 1,
      G_HSNSL (true, g, M1)) ]
let higgs_sneutrino'' =
  [ ((Hp, Sneutrino (-3), Slepton (M2, 3)), Scalar_Scalar_Scalar 1,
      G_HSNSL (false, 3, M2));
    ((Hm, Sneutrino 3, Slepton (M2, -3)), Scalar_Scalar_Scalar 1,
      G_HSNSL (false, 3, M2)) ]
let higgs_sneutrino =
  ThoList.flatmap higgs_sneutrino' [1; 2; 3] @ higgs_sneutrino''
```

Under the assumption that there is no mixing between the left- and right-handed sfermions for the first two generations there is only a coupling of the form Higgs - sfermion1 - sfermion2 for the third generation. All the others are suppressed by  $m_f/M_W$ .

\*\* REVISED: Independent of the sign of CD. \*\*

```
let higgs_sfermion' g m1 m2 =
  [ ((H_Heavy, Slepton (m1, g), Slepton (m2, -g)), Scalar_Scalar_Scalar 1,
      G_H2SFSF (SL, g, m1, m2));
    ((H_Light, Slepton (m1, g), Slepton (m2, -g)), Scalar_Scalar_Scalar 1,
      G_H1SFSF (SL, g, m1, m2));
    ((H_Heavy, Sup (m1, g), Sup (m2, -g)), Scalar_Scalar_Scalar 1,
      G_H2SFSF (SU, g, m1, m2));
    ((H_Heavy, Sdown (m1, g), Sdown (m2, -g)), Scalar_Scalar_Scalar 1,
      G_H2SFSF (SD, g, m1, m2));
    ((H_Light, Sup (m1, g), Sup (m2, -g)), Scalar_Scalar_Scalar 1,
      G_H1SFSF (SU, g, m1, m2));
    ((H_Light, Sdown (m1, g), Sdown (m2, -g)), Scalar_Scalar_Scalar 1,
      G_H1SFSF (SD, g, m1, m2)) ]
let higgs_sfermion'' m1 m2 =
  [ ((A, Slepton (m1, 3), Slepton (m2, -3)), Scalar_Scalar_Scalar 1,
      G_ASFSF (SL, 3, m1, m2));
    ((A, Sup (m1, 3), Sup (m2, -3)), Scalar_Scalar_Scalar 1,
      G_ASFSF (SU, 3, m1, m2));
    ((A, Sdown (m1, 3), Sdown (m2, -3)), Scalar_Scalar_Scalar 1,
      G_ASFSF (SD, 3, m1, m2)) ]
let higgs_sfermion = List.flatten (Product.list2 (higgs_sfermion' 3)
  [M1; M2] [M1; M2]) @
  (higgs_sfermion' 1 M1 M1) @ (higgs_sfermion' 1 M2 M2) @
```



```
(higgs_sfermion' 2 M1 M1) @ (higgs_sfermion' 2 M2 M2) @
List.flatten (Product.list2 higgs_sfermion'' [M1; M2] [M1; M2])
```

\*\* REVISED: Independent of the sign of CD, compatible with GS+. \*\*

```
let goldstone_sfermion' g m1 m2 =
  [ ((Phi0, Slepton (m1, g), Slepton (m2, -g)), Scalar_Scalar_Scalar 1,
      G_GoSFSF (SL, g, m1, m2));
    ((Phi0, Sup (m1, g), Sup (m2, -g)), Scalar_Scalar_Scalar 1,
      G_GoSFSF (SU, g, m1, m2));
    ((Phi0, Sdown (m1, g), Sdown (m2, -g)), Scalar_Scalar_Scalar 1,
      G_GoSFSF (SD, g, m1, m2))]
let goldstone_sfermion'' g =
  [ ((Phip, Sneutrino (-g), Slepton (M1, g)), Scalar_Scalar_Scalar 1,
      G_GoSNSL (false, g, M1));
    ((Phim, Sneutrino g, Slepton (M1, -g)), Scalar_Scalar_Scalar 1,
      G_GoSNSL (true, g, M1)) ]
let goldstone_sfermion''' g =
  [ ((Phip, Sneutrino (-g), Slepton (M2, g)), Scalar_Scalar_Scalar 1,
      G_GoSNSL (false, g, M2));
    ((Phim, Sneutrino g, Slepton (M2, -g)), Scalar_Scalar_Scalar 1,
      G_GoSNSL (true, g, M2))]
let goldstone_sfermion =
  List.flatten (Product.list2 (goldstone_sfermion' 3) [M1; M2] [M1; M2]) @
  ThoList.flatmap goldstone_sfermion'' [1; 2; 3] @
  goldstone_sfermion''' 3
```

\*\* REVISED: Independent of the sign of CD. \*\*

```
let higgs_squark' g h m1 m2 =
  [ ((Hp, Sup (m1, -g), Sdown (m2, h)), Scalar_Scalar_Scalar 1,
      G_HSUSD (false, m1, m2, g, h));
    ((Hm, Sup (m1, g), Sdown (m2, -h)), Scalar_Scalar_Scalar 1,
      G_HSUSD (true, m1, m2, g, h)) ]
let higgs_squark_a g h = higgs_squark' g h M1 M1
let higgs_squark_b (g, h) = List.flatten (Product.list2 (higgs_squark' g h)
  [M1; M2] [M1; M2])
let higgs_squark =
  if Flags.ckm_present then
    List.flatten (Product.list2 higgs_squark_a [1; 2] [1; 2]) @
    ThoList.flatmap higgs_squark_b [(1, 3); (2, 3); (3, 3); (3, 1); (3, 2)]
  else
    higgs_squark_a 1 1 @ higgs_squark_a 2 2 @ higgs_squark_b (3, 3)
```

\*\* REVISED: Independent of the sign of CD, compatible with GS+. \*\*

```
let goldstone_squark' g h m1 m2 =
  [ ((Phip, Sup (m1, -g), Sdown (m2, h)), Scalar_Scalar_Scalar 1,
      G_GSUSD (false, m1, m2, g, h));
    ((Phim, Sup (m1, g), Sdown (m2, -h)), Scalar_Scalar_Scalar 1,
      G_GSUSD (true, m1, m2, g, h)) ]
let goldstone_squark_a g h = goldstone_squark' g h M1 M1
let goldstone_squark_b (g, h) = List.flatten (Product.list2
```



```

      G_H1H2SFSF (SD, m1, m2, g));
    ((Hp, Hm, Sup (m1, g), Sup (m2, -g)), Scalar4 1, G_HHSFSF (SU, m1, m2, g));
    ((Hp, Hm, Sdown (m1, g), Sdown (m2, -g)), Scalar4 1, G_HHSFSF (SD, m1, m2, g));
    ((A, A, Sup (m1, g), Sup (m2, -g)), Scalar4 1, G_AASFSF (SU, m1, m2, g));
    ((A, A, Sdown (m1, g), Sdown (m2, -g)), Scalar4 1, G_AASFSF (SD, m1, m2, g)) ]
let higgs_sfermion4 g = List.flatten (Product.list2 (higgs_sfermion4' g)
                                                    [M1; M2] [M1; M2])

let higgs_squark4' g h m1 m2 =
  [ ((Hp, H_Light, Sup (m1, -g), Sdown (m2, h)), Scalar4 1,
      G_HH1SUSD (false, m1, m2, g, h));
    ((Hm, H_Light, Sup (m1, g), Sdown (m2, -h)), Scalar4 1,
      G_HH1SUSD (true, m1, m2, g, h));
    ((Hp, H_Heavy, Sup (m1, -g), Sdown (m2, h)), Scalar4 1,
      G_HH2SUSD (false, m1, m2, g, h));
    ((Hm, H_Heavy, Sup (m1, g), Sdown (m2, -h)), Scalar4 1,
      G_HH2SUSD (true, m1, m2, g, h));
    ((Hp, A, Sup (m1, -g), Sdown (m2, h)), Scalar4 1,
      G_HASUSD (false, m1, m2, g, h));
    ((Hm, A, Sup (m1, g), Sdown (m2, -h)), Scalar4 1,
      G_HASUSD (true, m1, m2, g, h)) ]
let higgs_squark4 g h = List.flatten (Product.list2 (higgs_squark4' g h)
                                                    [M1; M2] [M1; M2])

let higgs_gold_sneutrino' g m =
  [ ((Hp, Phi0, Sneutrino (-g), Slepton (m, g)), Scalar4 1, G_HGSNSL (false, m, g));
    ((Hm, Phi0, Sneutrino g, Slepton (m, -g)), Scalar4 1, G_HGSNSL (true, m, g));
    ((H_Heavy, Phip, Sneutrino (-g), Slepton (m, g)), Scalar4 1,
      G_H2GSNSL (false, m, g));
    ((H_Heavy, Phim, Sneutrino g, Slepton (m, -g)), Scalar4 1,
      G_H2GSNSL (true, m, g));
    ((H_Light, Phip, Sneutrino (-g), Slepton (m, g)), Scalar4 1,
      G_H1GSNSL (false, m, g));
    ((H_Light, Phim, Sneutrino g, Slepton (m, -g)), Scalar4 1,
      G_H1GSNSL (true, m, g));
    ((A, Phip, Sneutrino (-g), Slepton (m, g)), Scalar4 1, G_AGSNSL (false, m, g));
    ((A, Phim, Sneutrino g, Slepton (m, -g)), Scalar4 1, G_AGSNSL (true, m, g));
    ((Phi0, Phip, Sneutrino (-g), Slepton (m, g)), Scalar4 1, G_GGSNSL (false, m, g));
    ((Phi0, Phim, Sneutrino g, Slepton (m, -g)), Scalar4 1, G_GGSNSL (true, m, g)) ]
let higgs_gold_sneutrino g =
  ThoList.flatmap (higgs_gold_sneutrino' g) [M1; M2] @
  [ ((A, Phi0, Sneutrino g, Sneutrino (-g)), Scalar4 1,
      G_AG0SFSF (SN, M1, M1, g));
    ((Hp, Phim, Sneutrino g, Sneutrino (-g)), Scalar4 1,
      G_HGSFSF (SN, M1, M1, g));
    ((Hm, Phip, Sneutrino g, Sneutrino (-g)), Scalar4 1,
      G_HGSFSF (SN, M1, M1, g));
    ((Phip, Phim, Sneutrino g, Sneutrino (-g)), Scalar4 1,
      G_GGSFSF (SN, M1, M1, g));
    ((Phi0, Phi0, Sneutrino g, Sneutrino (-g)), Scalar4 1,
      G_G0G0SFSF (SN, M1, M1, g)) ]

```

```

let higgs_gold_sfermion' g m1 m2 =
  [ ((A, Phi0, Slepton (m1, g), Slepton (m2, -g)), Scalar4 1,
      G_AG0SFSF (SL, m1, m2, g));
    ((Hp, Phim, Slepton (m1, g), Slepton (m2, -g)), Scalar4 1,
      G_HGSFSF (SL, m1, m2, g));
    ((Hm, Phip, Slepton (m1, g), Slepton (m2, -g)), Scalar4 1,
      G_HGSFSF (SL, m1, m2, g));
    ((Phip, Phim, Slepton (m1, g), Slepton (m2, -g)), Scalar4 1,
      G_GGSFSF (SL, m1, m2, g));
    ((Phi0, Phi0, Slepton (m1, g), Slepton (m2, -g)), Scalar4 1,
      G_G0G0SFSF (SL, m1, m2, g));
    ((A, Phi0, Sup (m1, g), Sup (m2, -g)), Scalar4 1, G_AG0SFSF (SU, m1, m2, g));
    ((A, Phi0, Sdown (m1, g), Sdown (m2, -g)), Scalar4 1,
      G_AG0SFSF (SD, m1, m2, g));
    ((Hp, Phim, Sup (m1, g), Sup (m2, -g)), Scalar4 1, G_HGSFSF (SU, m1, m2, g));
    ((Hm, Phip, Sup (m1, g), Sup (m2, -g)), Scalar4 1, G_HGSFSF (SU, m1, m2, g));
    ((Hp, Phim, Sdown (m1, g), Sdown (m2, -g)), Scalar4 1,
      G_HGSFSF (SD, m1, m2, g));
    ((Hm, Phip, Sdown (m1, g), Sdown (m2, -g)), Scalar4 1,
      G_HGSFSF (SD, m1, m2, g));
    ((Phip, Phim, Sup (m1, g), Sup (m2, -g)), Scalar4 1,
      G_GGSFSF (SU, m1, m2, g));
    ((Phip, Phim, Sdown (m1, g), Sdown (m2, -g)), Scalar4 1,
      G_GGSFSF (SD, m1, m2, g));
    ((Phi0, Phi0, Sup (m1, g), Sup (m2, -g)), Scalar4 1,
      G_G0G0SFSF (SU, m1, m2, g));
    ((Phi0, Phi0, Sdown (m1, g), Sdown (m2, -g)), Scalar4 1,
      G_G0G0SFSF (SD, m1, m2, g)) ]
let higgs_gold_sfermion g = List.flatten (Product.list2
  (higgs_gold_sfermion' g) [M1; M2] [M1; M2])

let higgs_gold_squark' g h m1 m2 =
  [ ((Hp, Phi0, Sup (m1, -g), Sdown (m2, h)), Scalar4 1,
      G_HGSUSD (false, m1, m2, g, h));
    ((Hm, Phi0, Sup (m1, g), Sdown (m2, -h)), Scalar4 1,
      G_HGSUSD (true, m1, m2, g, h));
    ((H_Heavy, Phip, Sup (m1, -g), Sdown (m2, h)), Scalar4 1,
      G_H2GSUSD (false, m1, m2, g, h));
    ((H_Heavy, Phim, Sup (m1, g), Sdown (m2, -h)), Scalar4 1,
      G_H2GSUSD (true, m1, m2, g, h));
    ((H_Light, Phip, Sup (m1, -g), Sdown (m2, h)), Scalar4 1,
      G_H1GSUSD (false, m1, m2, g, h));
    ((H_Light, Phim, Sup (m1, g), Sdown (m2, -h)), Scalar4 1,
      G_H1GSUSD (true, m1, m2, g, h));
    ((A, Phip, Sup (m1, -g), Sdown (m2, h)), Scalar4 1,
      G_AGSUSD (false, m1, m2, g, h));
    ((A, Phim, Sup (m1, g), Sdown (m2, -h)), Scalar4 1,
      G_AGSUSD (true, m1, m2, g, h));
    ((Phi0, Phip, Sup (m1, -g), Sdown (m2, h)), Scalar4 1,
      G_GGSUSD (false, m1, m2, g, h));

```

```

      ((Phi0, Phim, Sup (m1, g), Sdown (m2, -h)), Scalar4 1,
       G_GGSUSD (true, m1, m2, g, h)) ]
let higgs_gold_squark g h = List.flatten (Product.list2 (higgs_gold_squark'
  g h) [M1; M2] [M1; M2])

let sneutrino4' (g, h) =
  [ ((Sneutrino g, Sneutrino h, Sneutrino (-g), Sneutrino (-h)), Scalar4 1,
    G_SN4 (g, h))]
let sneutrino4 = ThoList.flatmap sneutrino4'
  [(1, 1); (1, 2); (1, 3); (2, 2); (2, 3); (3, 3)]

let sneu2_slep2_1' g h m1 m2 =
  ((Sneutrino (-g), Sneutrino g, Slepton (m1, -h), Slepton (m2, h)), Scalar4 1,
   G_SN2SL2_1 (m1, m2, g, h))
let sneu2_slep2_2' (g, h) m1 m2 =
  ((Sneutrino g, Sneutrino (-h), Slepton (m1, -g), Slepton (m2, h)), Scalar4 1,
   G_SN2SL2_2 (m1, m2, g, h))
let sneu2_slep2_1 g h = Product.list2 (sneu2_slep2_1' g h) [M1; M2] [M1; M2]
let sneu2_slep2_2 (g, h) = Product.list2 (sneu2_slep2_2' (g, h)) [M1; M2] [M1; M2]

```

The 4-slepton-vertices have the following structure: The sleptons come up in pairs of a positive and a negative slepton of the same generation; there is no vertex with e.g. two negative selectrons and two positive smuons, that of course would be a contradiction to the conservation of the separate slepton numbers of each generation which is not implemented in the MSSM. Because there is no CKM-mixing for the sleptons (in case of massless neutrinos) we maximally have two different generations of sleptons in a 4-slepton-vertex.

```

let slepton4_1gen' g (m1, m2, m3, m4) =
  [ ((Slepton (m1, -g), Slepton (m2, g), Slepton (m3, -g), Slepton (m4, g)),
    Scalar4 1, G_SL4 (m1, m2, m3, m4, g)) ]
let slepton4_1gen g = ThoList.flatmap (slepton4_1gen' g) [(M1, M1, M1, M1);
  (M1, M1, M1, M2); (M1, M1, M2, M1); (M1, M1, M2, M2); (M1, M2, M1, M2); (M1, M2, M2, M1);
  (M1, M2, M2, M2); (M2, M1, M2, M2); (M2, M2, M2, M2) ]
let slepton4_2gen' (g, h) (m1, m2) (m3, m4) =
  ((Slepton (m1, -g), Slepton (m2, g), Slepton (m3, -h), Slepton (m4, h)),
   Scalar4 1, G_SL4_2 (m1, m2, m3, m4, g, h))
let slepton4_2gen (g, h) =
  Product.list2 (slepton4_2gen' (g, h)) [(M1, M1); (M1, M2); (M2, M1); (M2, M2)]
  [(M1, M1); (M1, M2); (M2, M1); (M2, M2)]

let sneu2_squark2' g h m1 m2 =
  [ ((Sneutrino (-g), Sneutrino g, Sup (m1, -h), Sup (m2, h)), Scalar4 1,
    G_SN2SQ2 (SU, m1, m2, g, h));
    ((Sneutrino (-g), Sneutrino g, Sdown (m1, -h), Sdown (m2, h)), Scalar4 1,
    G_SN2SQ2 (SD, m1, m2, g, h)) ]
let sneu2_squark2 g h = List.flatten (Product.list2 (sneu2_squark2' g h)
  [M1; M2] [M1; M2])

let slepton2_squark2'' g h m1 m2 m3 m4 =
  [ ((Slepton (m1, -g), Slepton (m2, g), Sup (m3, -h), Sup (m4, h)), Scalar4 1,
    G_SL2SQ2 (SU, m1, m2, m3, m4, g, h));
    ((Slepton (m1, -g), Slepton (m2, g), Sdown (m3, -h), Sdown (m4, h)),
    Scalar4 1, G_SL2SQ2 (SD, m1, m2, m3, m4, g, h)) ]

```

```

      Scalar4 1, G_SL2SQ2 (SD, m1, m2, m3, m4, g, h)) ]
let slepton2_squark2' g h m1 m2 =
  List.flatten (Product.list2 (slepton2_squark2'' g h m1 m2) [M1; M2] [M1; M2])
let slepton2_squark2 g h =
  List.flatten (Product.list2 (slepton2_squark2' g h) [M1; M2] [M1; M2])
let slep_sneu_squark2'' g1 g2 g3 m1 m2 m3 =
  [ ((Sup (m1, -g1), Sdown (m2, g2), Slepton (m3, -g3), Sneutrino g3),
      Scalar4 1, G_SUSDSNSL (false, m1, m2, m3, g1, g2, g3));
    ((Sup (m1, g1), Sdown (m2, -g2), Slepton (m3, g3), Sneutrino (-g3)),
      Scalar4 1, G_SUSDSNSL (true, m1, m2, m3, g1, g2, g3)) ]
let slep_sneu_squark2' g1 g2 g3 m1 =
  List.flatten (Product.list2 (slep_sneu_squark2'' g1 g2 g3 m1)
    [M1; M2] [M1; M2])
let slep_sneu_squark2 g1 g2 =
  List.flatten (Product.list2 (slep_sneu_squark2' g1 g2) [1; 2; 3] [M1; M2])

```

There are three kinds of 4-squark-vertices: Four up-Squarks, four down-squarks or two up- and two down-squarks.

```

let sup4_1gen' g (m1, m2, m3, m4) =
  [ ((Sup (m1, -g), Sup (m2, g), Sup (m3, -g), Sup (m4, g)), Scalar4 1,
      G_SU4 (m1, m2, m3, m4, g)) ]
let sup4_1gen g = ThoList.flatmap (sup4_1gen' g) [(M1, M1, M1, M1);
  (M1, M1, M1, M2); (M1, M1, M2, M1); (M1, M1, M2, M2); (M1, M2, M1, M2); (M1, M2, M2, M1);
  (M1, M2, M2, M2); (M2, M1, M2, M2); (M2, M2, M2, M2) ]
let sup4_2gen' (g, h) (m1, m2) (m3, m4) =
  ((Sup (m1, -g), Sup (m2, g), Sup (m3, -h), Sup (m4, h)), Scalar4 1,
    G_SU4_2 (m1, m2, m3, m4, g, h))
let sup4_2gen (g, h) =
  Product.list2 (sup4_2gen' (g, h)) [(M1, M1); (M1, M2); (M2, M1); (M2, M2)]
  [(M1, M1); (M1, M2); (M2, M1); (M2, M2)]
let sdown4_1gen' g (m1, m2, m3, m4) =
  [ ((Sdown (m1, -g), Sdown (m2, g), Sdown (m3, -g), Sdown (m4, g)), Scalar4 1,
      G_SD4 (m1, m2, m3, m4, g)) ]
let sdown4_1gen g = ThoList.flatmap (sdown4_1gen' g) [(M1, M1, M1, M1);
  (M1, M1, M1, M2); (M1, M1, M2, M1); (M1, M1, M2, M2); (M1, M2, M1, M2); (M1, M2, M2, M1);
  (M1, M2, M2, M2); (M2, M1, M2, M2); (M2, M2, M2, M2) ]
let sdown4_2gen' (g, h) (m1, m2) (m3, m4) =
  ((Sdown (m1, -g), Sdown (m2, g), Sdown (m3, -h), Sdown (m4, h)), Scalar4 1,
    G_SD4_2 (m1, m2, m3, m4, g, h))
let sdown4_2gen (g, h) =
  Product.list2 (sdown4_2gen' (g, h)) [(M1, M1); (M1, M2); (M2, M1); (M2, M2)]
  [(M1, M1); (M1, M2); (M2, M1); (M2, M2)]
let sup2_sdown2_3 g1 g2 g3 g4 m1 m2 m3 m4 =
  ((Sup (m1, -g1), Sup (m2, g2), Sdown (m3, -g3), Sdown
    (m4, g4)), Scalar4 1, G_SU2SD2 (m1, m2, m3, m4, g1, g2, g3, g4))
let sup2_sdown2_2 g1 g2 g3 g4 m1 m2 =
  Product.list2 (sup2_sdown2_3 g1 g2 g3 g4 m1 m2) [M1; M2] [M1; M2]
let sup2_sdown2_1 g1 g2 g3 g4 =
  List.flatten (Product.list2 (sup2_sdown2_2 g1 g2 g3 g4) [M1; M2] [M1; M2])

```

```

let sup2_sdown2 g1 g2 =
  List.flatten (Product.list2 (sup2_sdown2_1 g1 g2) [1; 2; 3] [1; 2; 3])

let quartic_grav_gauge g m =
  [ ((Grino, Slepton (m, -g), Ga, L g), GBBG (1, Gravbar, SLRV, Psi), G-Gr4A-Sl (g, m));
    ((L (-g), Slepton (m, g), Ga, Grino), GBBG (1, Psibar, SLRV, Grav), G-Gr4A-Slc (g, m));
    ((Grino, Sup (m, -g), Ga, U g), GBBG (1, Gravbar, SLRV, Psi), G-Gr4A-Su (g, m));
    ((U (-g), Sup (m, g), Ga, Grino), GBBG (1, Psibar, SLRV, Grav), G-Gr4A-Suc (g, m));
    ((Grino, Sdown (m, -g), Ga, D g), GBBG (1, Gravbar, SLRV, Psi), G-Gr4A-Sd (g, m));
    ((D (-g), Sdown (m, g), Ga, Grino), GBBG (1, Psibar, SLRV, Grav), G-Gr4A-Sdc (g, m));
    ((Grino, Slepton (m, -g), Z, L g), GBBG (1, Gravbar, SLRV, Psi), G-Gr4Z-Sl (g, m));
    ((L (-g), Slepton (m, g), Z, Grino), GBBG (1, Psibar, SLRV, Grav), G-Gr4Z-Slc (g, m));
    ((Grino, Sup (m, -g), Z, U g), GBBG (1, Gravbar, SLRV, Psi), G-Gr4Z-Su (g, m));
    ((U (-g), Sup (m, g), Z, Grino), GBBG (1, Psibar, SLRV, Grav), G-Gr4Z-Suc (g, m));
    ((Grino, Sdown (m, -g), Z, D g), GBBG (1, Gravbar, SLRV, Psi), G-Gr4Z-Sd (g, m));
    ((D (-g), Sdown (m, g), Z, Grino), GBBG (1, Psibar, SLRV, Grav), G-Gr4Z-Sdc (g, m));
    ((Grino, Sup (m, -g), Gl, U g), GBBG (1, Gravbar, SLRV, Psi), G-Gr4Gl-Su (g, m));
    ((U (-g), Sup (m, g), Gl, Grino), GBBG (1, Psibar, SLRV, Grav), G-Gr4Gl-Suc (g, m));
    ((Grino, Sdown (m, -g), Gl, D g), GBBG (1, Gravbar, SLRV, Psi), G-Gr4Gl-Sd (g, m));
    ((D (-g), Sdown (m, g), Gl, Grino), GBBG (1, Psibar, SLRV, Grav), G-Gr4Gl-Sdc (g, m));
    ((Grino, Slepton (m, -g), Wm, N g), GBBG (1, Gravbar, SLV, Psi), G-Gr4W-Sl (g, m));
    ((N (-g), Slepton (m, g), Wp, Grino), GBBG (1, Psibar, SLV, Grav), G-Gr4Z-Slc (g, m));
    ((Grino, Sup (m, -g), Wp, D g), GBBG (1, Gravbar, SLV, Psi), G-Gr4W-Su (g, m));
    ((D (-g), Sup (m, g), Wm, Grino), GBBG (1, Psibar, SLV, Grav), G-Gr4W-Suc (g, m));
    ((Grino, Sdown (m, -g), Wm, U g), GBBG (1, Gravbar, SLV, Psi), G-Gr4W-Sd (g, m));
    ((U (-g), Sdown (m, g), Wp, Grino), GBBG (1, Psibar, SLV, Grav), G-Gr4W-Sdc (g, m)) ]

let quartic_grav_sneutrino g =
  [ ((Grino, Sneutrino (-g), Z, N g), GBBG (1, Gravbar, SLV, Psi), G-Gr4Z-Sn);
    ((N (-g), Sneutrino g, Z, Grino), GBBG (1, Psibar, SLV, Grav), G-Gr4Z-Snc);
    ((Grino, Sneutrino (-g), Wp, L g), GBBG (1, Gravbar, SLV, Psi), G-Gr4W-Sn);
    ((L (-g), Sneutrino g, Wm, Grino), GBBG (1, Psibar, SLV, Grav), G-Gr4W-Snc) ]

let quartic_grav_neu n =
  [ ((Grino, Wp, Wm, Neutralino n), GBBG (1, Gravbar, V2LR, Chi), G-Gr4-Neu n);
    ((Grino, H-Light, Z, Neutralino n), GBBG (1, Gravbar, SLRV, Chi), G-Gr4-Z-H1 n);
    ((Grino, H-Heavy, Z, Neutralino n), GBBG (1, Gravbar, SLRV, Chi), G-Gr4-Z-H2 n);
    ((Grino, A, Z, Neutralino n), GBBG (1, Gravbar, SLRV, Chi), G-Gr4-Z-H3 n);
    ((Grino, Hm, Wp, Neutralino n), GBBG (1, Gravbar, SLRV, Chi), G-Gr4-W-H n);
    ((Grino, Hp, Wm, Neutralino n), GBBG (1, Gravbar, SLRV, Chi), G-Gr4-W-Hc n) ]

let quartic_grav_char c =
  let cc = conj_char c in
  [ ((Grino, Wm, Ga, Chargino c), GBBG (1, Gravbar, V2LR, Psi), G-Gr4-A-Ch c);
    ((Grino, Wm, Z, Chargino c), GBBG (1, Gravbar, V2LR, Psi), G-Gr4-Z-Ch c);
    ((Chargino cc, Wp, Ga, Grino), GBBG ((-1), Psibar, V2LR, Grav), G-Gr4-A-Ch cc);
    ((Chargino cc, Wp, Z, Grino), GBBG ((-1), Psibar, V2LR, Grav), G-Gr4-Z-Ch cc);
    ((Grino, Hm, Ga, Chargino c), GBBG (1, Gravbar, SLRV, Psi), G-Gr4-H-A c);
    ((Chargino cc, Hp, Ga, Grino), GBBG (1, Psibar, SLRV, Grav), G-Gr4-H-A cc);
    ((Grino, Hm, Z, Chargino c), GBBG (1, Gravbar, SLRV, Psi), G-Gr4-H-Z c);
    ((Chargino cc, Hp, Z, Grino), GBBG (1, Psibar, SLRV, Grav), G-Gr4-H-Z cc) ]

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```

let quartic_gravitino =
  [((Grino, Gl, Gl, Gluino), GBBG (1, Gravbar, V2, Chi), G_GravGl)] @
  ThoList.flatmap quartic_grav_neu [N1; N2; N3; N4] @
  ThoList.flatmap quartic_grav_char [C1; C2] @
  List.flatten (Product.list2 quartic_grav_gauge [1; 2; 3] [M1; M2]) @
  ThoList.flatmap quartic_grav_sneutrino [1; 2; 3]

let vertices3'' =
  if Flags.ckm_present then
    (ThoList.flatmap electromagnetic_currents_3 [1; 2; 3] @
      ThoList.flatmap electromagnetic_currents_2 [C1; C2] @
      List.flatten (Product.list2
        electromagnetic_sfermion_currents [1; 2; 3] [M1; M2]) @
      ThoList.flatmap neutral_currents [1; 2; 3] @
      ThoList.flatmap neutral_sfermion_currents [1; 2; 3] @
      ThoList.flatmap charged_currents [1; 2; 3] @
      List.flatten (Product.list2 charged_slepton_currents [1; 2; 3]
        [M1; M2]) @
      List.flatten (Product.list2 charged_quark_currents [1; 2; 3]
        [1; 2; 3]) @
      List.flatten (Product.list2 charged_squark_currents [1; 2; 3]
        [1; 2; 3]) @
      ThoList.flatmap yukawa_higgs_quark [(1, 3); (2, 3); (3, 3); (3, 1); (3, 2)] @
      yukawa_higgs 3 @ yukawa_n @
      ThoList.flatmap yukawa_c [C1; C2] @
      ThoList.flatmap yukawa_cq [C1; C2] @
      List.flatten (Product.list2 charged_chargino_currents [N1; N2; N3; N4]
        [C1; C2]) @ triple_gauge @
      ThoList.flatmap neutral_Z_1 [(N1, N2); (N1, N3); (N1, N4); (N2, N3); (N2, N4);
        (N3, N4)] @
      ThoList.flatmap neutral_Z_2 [N1; N2; N3; N4] @
      Product.list2 charged_Z [C1; C2] [C1; C2] @
      gauge_higgs @ higgs @ yukawa_higgs_2 @
      List.flatten (Product.list2 higgs_charg_neutr [N1; N2; N3; N4] [C1; C2]) @
      higgs_neutr @ higgs_sneutrino @ higgs_sfermion @
      higgs_squark @ yukawa_v @
      ThoList.flatmap col_currents [1; 2; 3] @
      List.flatten (Product.list2 col_sfermion_currents [1; 2; 3] [M1; M2]))
  else
    (ThoList.flatmap electromagnetic_currents_3 [1; 2; 3] @
      ThoList.flatmap electromagnetic_currents_2 [C1; C2] @
      List.flatten (Product.list2
        electromagnetic_sfermion_currents [1; 2; 3] [M1; M2]) @
      ThoList.flatmap neutral_currents [1; 2; 3] @
      ThoList.flatmap neutral_sfermion_currents [1; 2; 3] @
      ThoList.flatmap charged_currents [1; 2; 3] @
      List.flatten (Product.list2 charged_slepton_currents [1; 2; 3]
        [M1; M2]) @
      charged_quark_currents 1 1 @
      charged_quark_currents 2 2 @

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```

charged_quark_currents 3 3 @
charged_squark_currents 1 1 @
charged_squark_currents 2 2 @
charged_squark_currents 3 3 @
ThoList.flatmap yukawa_higgs_quark [(3, 3)] @
yukawa_higgs 3 @ yukawa_n @
ThoList.flatmap yukawa_c [C1; C2] @
ThoList.flatmap yukawa_cq [C1; C2] @
List.flatten (Product.list2 charged_chargino_currents [N1; N2; N3; N4]
              [C1; C2]) @ triple_gauge @
ThoList.flatmap neutral_Z_1 [(N1, N2); (N1, N3); (N1, N4); (N2, N3); (N2, N4);
                             (N3, N4)] @
ThoList.flatmap neutral_Z_2 [N1; N2; N3; N4] @
Product.list2 charged_Z [C1; C2] [C1; C2] @
gauge_higgs @ higgs @ yukawa_higgs_2 @
List.flatten (Product.list2 higgs_charg_neutr [N1; N2; N3; N4] [C1; C2]) @
higgs_neutr @ higgs_sneutrino @ higgs_sfermion @
higgs_squark @ yukawa_v @
ThoList.flatmap col_currents [1; 2; 3] @
List.flatten (Product.list2 col_sfermion_currents [1; 2; 3] [M1; M2]))

let vertices3' =
  if Flags.gravitino then (vertices3'' @ triple_gravitino)
  else vertices3''
let vertices3 =
  if Flags.include_goldstone then
    (vertices3' @ yukawa_goldstone 3 @
     gauge_higgs_gold @ higgs_gold @ yukawa_goldstone_2 @
     (if Flags.ckm_present then
        List.flatten (Product.list2 yukawa_goldstone_quark [1; 2; 3]
                                   [1; 2; 3]) @
        List.flatten (Product.list2 goldstone_charg_neutr [N1; N2; N3; N4]
                                   [C1; C2])
      )
    )
  else
    yukawa_goldstone_quark 1 1 @
    yukawa_goldstone_quark 2 2 @
    yukawa_goldstone_quark 3 3) @
    goldstone_neutr @ goldstone_sfermion @ goldstone_squark)
  else vertices3'

let vertices4''' =
  (quartic_gauge @ higgs4 @ gauge_higgs4 @
   ThoList.flatmap gauge_sfermion4 [1; 2; 3] @
   gauge_squark4 @ gluon_w_squark @
   List.flatten (Product.list2 gluon2_squark2 [1; 2; 3] [M1; M2]) @
   ThoList.flatmap gluon_gauge_squark [1; 2; 3])
let vertices4'' =
  if Flags.gravitino then (vertices4''' @ quartic_gravitino)
  else vertices4'''
let vertices4' =
  if Flags.include_four then

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(vertices4'' @
  ThoList.flatmap higgs_sfermion4 [1; 2; 3] @
  ThoList.flatmap higgs_sneutrino4 [1; 2; 3] @
  List.flatten (Product.list2 higgs_squark4 [1; 2; 3] [1; 2; 3]) @
  sneutrino4 @
  List.flatten (Product.list2 sneu2_slep2_1 [1; 2; 3] [1; 2; 3]) @
  ThoList.flatmap sneu2_slep2_2 [(1, 2); (1, 3); (2, 3); (2, 1); (3, 1); (3, 2)] @
  ThoList.flatmap slepton4_1gen [1; 2; 3] @
  ThoList.flatmap slepton4_2gen [(1, 2); (1, 3); (2, 3)] @
  List.flatten (Product.list2 sneu2_squark2 [1; 2; 3] [1; 2; 3]) @
  List.flatten (Product.list2 slepton2_squark2 [1; 2; 3] [1; 2; 3]) @
  List.flatten (Product.list2 slep_sneu_squark2 [1; 2; 3] [1; 2; 3]) @
  ThoList.flatmap sup4_1gen [1; 2; 3] @
  ThoList.flatmap sup4_2gen [(1, 2); (1, 3); (2, 3)] @
  ThoList.flatmap sdown4_1gen [1; 2; 3] @
  ThoList.flatmap sdown4_2gen [(1, 2); (1, 3); (2, 3)] @
  List.flatten (Product.list2 sup2_sdown2 [1; 2; 3] [1; 2; 3]))
else
  vertices4''
let vertices4' =
  if Flags.include_goldstone then
    (vertices4' @ higgs_gold4 @ gauge_higgs_gold4 @ goldstone4 @
      ThoList.flatmap higgs_gold_sneutrino [1; 2; 3] @
      ThoList.flatmap higgs_gold_sfermion [1; 2; 3] @
      List.flatten (Product.list2 higgs_gold_squark [1; 2; 3] [1; 2; 3]))
  else
    vertices4'
let vertices () = (vertices3, vertices4, [])
let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 4
let flavor_of_string s =
  match s with
  | "e-" → L 1 | "e+" → L (-1)
  | "mu-" → L 2 | "mu+" → L (-2)
  | "tau-" → L 3 | "tau+" → L (-3)
  | "nue" → N 1 | "nuebar" → N (-1)
  | "numu" → N 2 | "numubar" → N (-2)
  | "nutau" → N 3 | "nutaubar" → N (-3)
  | "se1-" → Slepton (M1, 1) | "se1+" → Slepton (M1, -1)
  | "smu1-" → Slepton (M1, 2) | "smu1+" → Slepton (M1, -2)
  | "stau1-" → Slepton (M1, 3) | "stau1+" → Slepton (M1, -3)
  | "se2-" → Slepton (M2, 1) | "se2+" → Slepton (M2, -1)
  | "smu2-" → Slepton (M2, 2) | "smu2+" → Slepton (M2, -2)
  | "stau2-" → Slepton (M2, 3) | "stau2+" → Slepton (M2, -3)
  | "snue" → Sneutrino 1 | "snue*" → Sneutrino (-1)
  | "snumu" → Sneutrino 2 | "snumu*" → Sneutrino (-2)

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| "sntau" → Sneutrino 3 | "sntau*" → Sneutrino (-3)
| "u" → U 1 | "ubar" → U (-1)
| "c" → U 2 | "cbar" → U (-2)
| "t" → U 3 | "tbar" → U (-3)
| "d" → D 1 | "dbar" → D (-1)
| "s" → D 2 | "sbar" → D (-2)
| "b" → D 3 | "bbar" → D (-3)
| "A" → Ga | "Z" | "ZO" → Z
| "W+" → Wp | "W-" → Wm
| "gl" | "g" → Gl
| "H" → H_Heavy | "h" → H_Light | "A0" → A
| "H+" → Hp | "H-" → Hm
| "phi0" → Phi0 | "phi+" → Phip | "phim" → Phim
| "su1" → Sup (M1,1) | "su1c" → Sup (M1,-1)
| "sc1" → Sup (M1,2) | "sc1c" → Sup (M1,-2)
| "st1" → Sup (M1,3) | "st1c" → Sup (M1,-3)
| "su2" → Sup (M2,1) | "su2c" → Sup (M2,-1)
| "sc2" → Sup (M2,2) | "sc2c" → Sup (M2,-2)
| "st2" → Sup (M2,3) | "st2c" → Sup (M2,-3)
| "sgl" | "sg" → Gluino
| "sd1" → Sdown (M1,1) | "sd1c" → Sdown (M1,-1)
| "ss1" → Sdown (M1,2) | "ss1c" → Sdown (M1,-2)
| "sb1" → Sdown (M1,3) | "sb1c" → Sdown (M1,-3)
| "sd2" → Sdown (M2,1) | "sd2c" → Sdown (M2,-1)
| "ss2" → Sdown (M2,2) | "ss2c" → Sdown (M2,-2)
| "sb2" → Sdown (M2,3) | "sb2c" → Sdown (M2,-3)
| "neu1" → Neutralino N1 | "neu2" → Neutralino N2
| "neu3" → Neutralino N3 | "neu4" → Neutralino N4
| "ch1+" → Chargino C1 | "ch2+" → Chargino C2
| "ch1-" → Chargino C1c | "ch2-" → Chargino C2c
| "GR" → Grino
| _ → invalid_arg "Modellib_MSSM.MSSM.flavor_of_string"

let flavor_to_string = function
| L 1 → "e-" | L (-1) → "e+"
| L 2 → "mu-" | L (-2) → "mu+"
| L 3 → "tau-" | L (-3) → "tau+"
| N 1 → "nue" | N (-1) → "nuebar"
| N 2 → "numu" | N (-2) → "numubar"
| N 3 → "nutau" | N (-3) → "nutaubar"
| U 1 → "u" | U (-1) → "ubar"
| U 2 → "c" | U (-2) → "cbar"
| U 3 → "t" | U (-3) → "tbar"
| D 1 → "d" | D (-1) → "dbar"
| D 2 → "s" | D (-2) → "sbar"
| D 3 → "b" | D (-3) → "bbar"
| L _ → invalid_arg
      "Modellib_MSSM.MSSM.flavor_to_string:␣invalid␣lepton"
| N _ → invalid_arg
      "Modellib_MSSM.MSSM.flavor_to_string:␣invalid␣neutrino"

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| U _ → invalid_arg
|   "Modellib_MSSM.MSSM.flavor_to_string:␣invalid␣up␣type␣quark"
| D _ → invalid_arg
|   "Modellib_MSSM.MSSM.flavor_to_string:␣invalid␣down␣type␣quark"
| Gl → "g1" | Gluino → "sg1"
| Ga → "A" | Z → "Z" | Wp → "W+" | Wm → "W-"
| Phip → "phi+" | Phim → "phi-" | Phi0 → "phi0"
| H_Heavy → "H" | H_Light → "h" | A → "A0"
| Hp → "H+" | Hm → "H-"
| Slepton (M1,1) → "se1-" | Slepton (M1,-1) → "se1+"
| Slepton (M1,2) → "smu1-" | Slepton (M1,-2) → "smu1+"
| Slepton (M1,3) → "stau1-" | Slepton (M1,-3) → "stau1+"
| Slepton (M2,1) → "se2-" | Slepton (M2,-1) → "se2+"
| Slepton (M2,2) → "smu2-" | Slepton (M2,-2) → "smu2+"
| Slepton (M2,3) → "stau2-" | Slepton (M2,-3) → "stau2+"
| Sneutrino 1 → "snue" | Sneutrino (-1) → "snue*"
| Sneutrino 2 → "snumu" | Sneutrino (-2) → "snumu*"
| Sneutrino 3 → "snutau" | Sneutrino (-3) → "snutau*"
| Sup (M1,1) → "su1" | Sup (M1,-1) → "su1c"
| Sup (M1,2) → "sc1" | Sup (M1,-2) → "sc1c"
| Sup (M1,3) → "st1" | Sup (M1,-3) → "st1c"
| Sup (M2,1) → "su2" | Sup (M2,-1) → "su2c"
| Sup (M2,2) → "sc2" | Sup (M2,-2) → "sc2c"
| Sup (M2,3) → "st2" | Sup (M2,-3) → "st2c"
| Sdown (M1,1) → "sd1" | Sdown (M1,-1) → "sd1c"
| Sdown (M1,2) → "ss1" | Sdown (M1,-2) → "ss1c"
| Sdown (M1,3) → "sb1" | Sdown (M1,-3) → "sb1c"
| Sdown (M2,1) → "sd2" | Sdown (M2,-1) → "sd2c"
| Sdown (M2,2) → "ss2" | Sdown (M2,-2) → "ss2c"
| Sdown (M2,3) → "sb2" | Sdown (M2,-3) → "sb2c"
| Neutralino N1 → "neu1"
| Neutralino N2 → "neu2"
| Neutralino N3 → "neu3"
| Neutralino N4 → "neu4"
| Slepton _ → invalid_arg
|   "Modellib_MSSM.MSSM.flavor_to_string:␣invalid␣slepton"
| Sneutrino _ → invalid_arg
|   "Modellib_MSSM.MSSM.flavor_to_string:␣invalid␣sneutrino"
| Sup _ → invalid_arg
|   "Modellib_MSSM.MSSM.flavor_to_string:␣invalid␣up␣type␣squark"
| Sdown _ → invalid_arg
|   "Modellib_MSSM.MSSM.flavor_to_string:␣invalid␣down␣type␣squark"
| Chargino C1 → "ch1+" | Chargino C1c → "ch1-"
| Chargino C2 → "ch2+" | Chargino C2c → "ch2-"
| Grino → "GR"

let flavor_symbol = function
| L g when g > 0 → "l" ^ string_of_int g
| L g → "l" ^ string_of_int (abs g) ^ "b"
| N g when g > 0 → "n" ^ string_of_int g

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|  $N\ g \rightarrow "n" \wedge \text{string\_of\_int}\ (abs\ g) \wedge "b"$ 
|  $U\ g\ \text{when}\ g > 0 \rightarrow "u" \wedge \text{string\_of\_int}\ g$ 
|  $U\ g \rightarrow "u" \wedge \text{string\_of\_int}\ (abs\ g) \wedge "b"$ 
|  $D\ g\ \text{when}\ g > 0 \rightarrow "d" \wedge \text{string\_of\_int}\ g$ 
|  $D\ g \rightarrow "d" \wedge \text{string\_of\_int}\ (abs\ g) \wedge "b"$ 
|  $Gl \rightarrow "gl" \mid Ga \rightarrow "a" \mid Z \rightarrow "z"$ 
|  $Wp \rightarrow "wp" \mid Wm \rightarrow "wm"$ 
|  $Slepton\ (M1, g)\ \text{when}\ g > 0 \rightarrow "sl1" \wedge \text{string\_of\_int}\ g$ 
|  $Slepton\ (M1, g) \rightarrow "sl1c" \wedge \text{string\_of\_int}\ (abs\ g)$ 
|  $Slepton\ (M2, g)\ \text{when}\ g > 0 \rightarrow "sl2" \wedge \text{string\_of\_int}\ g$ 
|  $Slepton\ (M2, g) \rightarrow "sl2c" \wedge \text{string\_of\_int}\ (abs\ g)$ 
|  $Sneutrino\ g\ \text{when}\ g > 0 \rightarrow "sn" \wedge \text{string\_of\_int}\ g$ 
|  $Sneutrino\ g \rightarrow "snc" \wedge \text{string\_of\_int}\ (abs\ g)$ 
|  $Sup\ (M1, g)\ \text{when}\ g > 0 \rightarrow "su1" \wedge \text{string\_of\_int}\ g$ 
|  $Sup\ (M1, g) \rightarrow "su1c" \wedge \text{string\_of\_int}\ (abs\ g)$ 
|  $Sup\ (M2, g)\ \text{when}\ g > 0 \rightarrow "su2" \wedge \text{string\_of\_int}\ g$ 
|  $Sup\ (M2, g) \rightarrow "su2c" \wedge \text{string\_of\_int}\ (abs\ g)$ 
|  $Sdown\ (M1, g)\ \text{when}\ g > 0 \rightarrow "sd1" \wedge \text{string\_of\_int}\ g$ 
|  $Sdown\ (M1, g) \rightarrow "sd1c" \wedge \text{string\_of\_int}\ (abs\ g)$ 
|  $Sdown\ (M2, g)\ \text{when}\ g > 0 \rightarrow "sd2" \wedge \text{string\_of\_int}\ g$ 
|  $Sdown\ (M2, g) \rightarrow "sd2c" \wedge \text{string\_of\_int}\ (abs\ g)$ 
|  $Neutralino\ n \rightarrow "neu" \wedge (\text{string\_of\_neu}\ n)$ 
|  $Chargino\ c\ \text{when}\ (\text{int\_of\_char}\ c) > 0 \rightarrow "cp" \wedge \text{string\_of\_char}\ c$ 
|  $Chargino\ c \rightarrow "cm" \wedge \text{string\_of\_int}\ (abs\ (\text{int\_of\_char}\ c))$ 
|  $Gluino \rightarrow "sgl" \mid Phip \rightarrow "pp" \mid Phim \rightarrow "pm" \mid Phi0 \rightarrow "p0"$ 
|  $H\_Heavy \rightarrow "h0h" \mid H\_Light \rightarrow "h0l" \mid A \rightarrow "a0"$ 
|  $Hp \rightarrow "hp" \mid Hm \rightarrow "hm" \mid Grino \rightarrow "gv"$ 

let flavor_to_TeX = function
|  $L\ 1 \rightarrow "e^-" \mid L\ (-1) \rightarrow "e^+"$ 
|  $L\ 2 \rightarrow "\\mu^-" \mid L\ (-2) \rightarrow "\\mu^+"$ 
|  $L\ 3 \rightarrow "\\tau^-" \mid L\ (-3) \rightarrow "\\tau^+"$ 
|  $N\ 1 \rightarrow "\\nu_e" \mid N\ (-1) \rightarrow "\\bar{\nu}_e"$ 
|  $N\ 2 \rightarrow "\\nu_\mu" \mid N\ (-2) \rightarrow "\\bar{\nu}_\mu"$ 
|  $N\ 3 \rightarrow "\\nu_\tau" \mid N\ (-3) \rightarrow "\\bar{\nu}_\tau"$ 
|  $U\ 1 \rightarrow "u" \mid U\ (-1) \rightarrow "\\bar{u}"$ 
|  $U\ 2 \rightarrow "c" \mid U\ (-2) \rightarrow "\\bar{c}"$ 
|  $U\ 3 \rightarrow "t" \mid U\ (-3) \rightarrow "\\bar{t}"$ 
|  $D\ 1 \rightarrow "d" \mid D\ (-1) \rightarrow "\\bar{d}"$ 
|  $D\ 2 \rightarrow "s" \mid D\ (-2) \rightarrow "\\bar{s}"$ 
|  $D\ 3 \rightarrow "b" \mid D\ (-3) \rightarrow "\\bar{b}"$ 
|  $L\ _ \rightarrow \text{invalid\_arg}$ 
|  $N\ _ \rightarrow \text{invalid\_arg}$ 
|  $U\ _ \rightarrow \text{invalid\_arg}$ 
|  $D\ _ \rightarrow \text{invalid\_arg}$ 
|  $Gl \rightarrow "g" \mid Gluino \rightarrow "\\widetilde{g}"$ 

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|  $G_a \rightarrow "\backslash\backslash\gamma"$  |  $Z \rightarrow "Z"$  |  $W_p \rightarrow "W^+"$  |  $W_m \rightarrow "W^-"$ 
|  $Phip \rightarrow "\backslash\backslash\phi^+"$  |  $Phim \rightarrow "\backslash\backslash\phi^-"$  |  $Phi0 \rightarrow "\backslash\backslash\phi^0"$ 
|  $H\_Heavy \rightarrow "H^0"$  |  $H\_Light \rightarrow "h^0"$  |  $A \rightarrow "A^0"$ 
|  $Hp \rightarrow "H^+"$  |  $Hm \rightarrow "H^-"$ 
|  $Slepton (M1,1) \rightarrow "\backslash\backslash\widetilde{e}_{-1}^-"$ 
|  $Slepton (M1,-1) \rightarrow "\backslash\backslash\widetilde{e}_{-1}^+"$ 
|  $Slepton (M1,2) \rightarrow "\backslash\backslash\widetilde{\mu}_{-1}^-"$ 
|  $Slepton (M1,-2) \rightarrow "\backslash\backslash\widetilde{\mu}_{-1}^+"$ 
|  $Slepton (M1,3) \rightarrow "\backslash\backslash\widetilde{\tau}_{-1}^-"$ 
|  $Slepton (M1,-3) \rightarrow "\backslash\backslash\widetilde{\tau}_{-1}^+"$ 
|  $Slepton (M2,1) \rightarrow "\backslash\backslash\widetilde{e}_{-2}^-"$ 
|  $Slepton (M2,-1) \rightarrow "\backslash\backslash\widetilde{e}_{-2}^+"$ 
|  $Slepton (M2,2) \rightarrow "\backslash\backslash\widetilde{\mu}_{-2}^-"$ 
|  $Slepton (M2,-2) \rightarrow "\backslash\backslash\widetilde{\mu}_{-2}^+"$ 
|  $Slepton (M2,3) \rightarrow "\backslash\backslash\widetilde{\tau}_{-2}^-"$ 
|  $Slepton (M2,-3) \rightarrow "\backslash\backslash\widetilde{\tau}_{-2}^+"$ 
|  $Sneutrino 1 \rightarrow "\backslash\backslash\widetilde{\nu}_e"$ 
|  $Sneutrino (-1) \rightarrow "\backslash\backslash\widetilde{\nu}_e^*"$ 
|  $Sneutrino 2 \rightarrow "\backslash\backslash\widetilde{\nu}_\mu"$ 
|  $Sneutrino (-2) \rightarrow "\backslash\backslash\widetilde{\nu}_\mu^*"$ 
|  $Sneutrino 3 \rightarrow "\backslash\backslash\widetilde{\nu}_\tau"$ 
|  $Sneutrino (-3) \rightarrow "\backslash\backslash\widetilde{\nu}_\tau^*"$ 
|  $Sup (M1,1) \rightarrow "\backslash\backslash\widetilde{u}_{-1}"$ 
|  $Sup (M1,-1) \rightarrow "\backslash\backslash\widetilde{u}_{-1}^*"$ 
|  $Sup (M1,2) \rightarrow "\backslash\backslash\widetilde{c}_{-1}"$ 
|  $Sup (M1,-2) \rightarrow "\backslash\backslash\widetilde{c}_{-1}^*"$ 
|  $Sup (M1,3) \rightarrow "\backslash\backslash\widetilde{t}_{-1}"$ 
|  $Sup (M1,-3) \rightarrow "\backslash\backslash\widetilde{t}_{-1}^*"$ 
|  $Sup (M2,1) \rightarrow "\backslash\backslash\widetilde{u}_{-2}"$ 
|  $Sup (M2,-1) \rightarrow "\backslash\backslash\widetilde{u}_{-2}^*"$ 
|  $Sup (M2,2) \rightarrow "\backslash\backslash\widetilde{c}_{-2}"$ 
|  $Sup (M2,-2) \rightarrow "\backslash\backslash\widetilde{c}_{-2}^*"$ 
|  $Sup (M2,3) \rightarrow "\backslash\backslash\widetilde{t}_{-2}"$ 
|  $Sup (M2,-3) \rightarrow "\backslash\backslash\widetilde{t}_{-2}^*"$ 
|  $Sdown (M1,1) \rightarrow "\backslash\backslash\widetilde{d}_{-1}"$ 
|  $Sdown (M1,-1) \rightarrow "\backslash\backslash\widetilde{d}_{-1}^*"$ 
|  $Sdown (M1,2) \rightarrow "\backslash\backslash\widetilde{s}_{-1}"$ 
|  $Sdown (M1,-2) \rightarrow "\backslash\backslash\widetilde{s}_{-1}^*"$ 
|  $Sdown (M1,3) \rightarrow "\backslash\backslash\widetilde{b}_{-1}"$ 
|  $Sdown (M1,-3) \rightarrow "\backslash\backslash\widetilde{b}_{-1}^*"$ 
|  $Sdown (M2,1) \rightarrow "\backslash\backslash\widetilde{d}_{-2}"$ 
|  $Sdown (M2,-1) \rightarrow "\backslash\backslash\widetilde{d}_{-2}^*"$ 
|  $Sdown (M2,2) \rightarrow "\backslash\backslash\widetilde{s}_{-2}"$ 
|  $Sdown (M2,-2) \rightarrow "\backslash\backslash\widetilde{s}_{-2}^*"$ 
|  $Sdown (M2,3) \rightarrow "\backslash\backslash\widetilde{b}_{-2}"$ 
|  $Sdown (M2,-3) \rightarrow "\backslash\backslash\widetilde{b}_{-2}^*"$ 
|  $Neutralino N1 \rightarrow "\backslash\backslash\widetilde{\chi}^0_{-1}"$ 
|  $Neutralino N2 \rightarrow "\backslash\backslash\widetilde{\chi}^0_{-2}"$ 
|  $Neutralino N3 \rightarrow "\backslash\backslash\widetilde{\chi}^0_{-3}"$ 
|  $Neutralino N4 \rightarrow "\backslash\backslash\widetilde{\chi}^0_{-4}"$ 

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| Slepton _ → invalid_arg
|   "Modellib_MSSM.MSSM.flavor_to_TeX:_invalid_slepton"
| Sneutrino _ → invalid_arg
|   "Modellib_MSSM.MSSM.flavor_to_TeX:_invalid_sneutrino"
| Sup _ → invalid_arg
|   "Modellib_MSSM.MSSM.flavor_to_TeX:_invalid_up_type_squark"
| Sdown _ → invalid_arg
|   "Modellib_MSSM.MSSM.flavor_to_TeX:_invalid_down_type_squark"
| Chargino C1 → "\\widetilde{\\chi}_1^+"
| Chargino C1c → "\\widetilde{\\chi}_1^-"
| Chargino C2 → "\\widetilde{\\chi}_2^+"
| Chargino C2c → "\\widetilde{\\chi}_2^-"
| Grino → "\\widetilde{G}"

let pdg = function
| L g when g > 0 → 9 + 2 × g
| L g → - 9 + 2 × g
| N g when g > 0 → 10 + 2 × g
| N g → - 10 + 2 × g
| U g when g > 0 → 2 × g
| U g → 2 × g
| D g when g > 0 → - 1 + 2 × g
| D g → 1 + 2 × g
| Gl → 21 | Ga → 22 | Z → 23
| Wp → 24 | Wm → (-24)
| H_Light → 25 | H_Heavy → 35 | A → 36
| Hp → 37 | Hm → (-37)
| Phip | Phim → 27 | Phi0 → 26
| Slepton (M1, g) when g > 0 → 1000009 + 2 × g
| Slepton (M1, g) → - 1000009 + 2 × g
| Slepton (M2, g) when g > 0 → 2000009 + 2 × g
| Slepton (M2, g) → - 2000009 + 2 × g
| Sneutrino g when g > 0 → 1000010 + 2 × g
| Sneutrino g → - 1000010 + 2 × g
| Sup (M1, g) when g > 0 → 1000000 + 2 × g
| Sup (M1, g) → - 1000000 + 2 × g
| Sup (M2, g) when g > 0 → 2000000 + 2 × g
| Sup (M2, g) → - 2000000 + 2 × g
| Sdown (M1, g) when g > 0 → 999999 + 2 × g
| Sdown (M1, g) → - 999999 + 2 × g
| Sdown (M2, g) when g > 0 → 1999999 + 2 × g
| Sdown (M2, g) → - 1999999 + 2 × g
| Gluino → 1000021
| Grino → 1000039
| Chargino C1 → 1000024 | Chargino C1c → (-1000024)
| Chargino C2 → 1000037 | Chargino C2c → (-1000037)
| Neutralino N1 → 1000022 | Neutralino N2 → 1000023
| Neutralino N3 → 1000025 | Neutralino N4 → 1000035

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We must take care of the *pdg* numbers for the two different kinds of sfermions in the MSSM. The particle data group in its Monte Carlo particle numbering

scheme takes only into account mixtures of the third generation squarks and the stau. For the other sfermions we will use the number of the lefthanded field for the lighter mixed state and the one for the righthanded for the heavier. Below are the official pdg numbers from the Particle Data Group. In order not to produce arrays with some million entries in the Fortran code for the masses and the widths we introduce our private pdg numbering scheme which only extends not too far beyond 42. Our private scheme then has the following pdf numbers (for the sparticles the subscripts  $L/R$  and  $1/2$  are taken synonymously):



$d$	down-quark	1
$u$	up-quark	2
$s$	strange-quark	3
$c$	charm-quark	4
$b$	bottom-quark	5
$t$	top-quark	6
$e^-$	electron	11
$\nu_e$	electron-neutrino	12
$\mu^-$	muon	13
$\nu_\mu$	muon-neutrino	14
$\tau^-$	tau	15
$\nu_\tau$	tau-neutrino	16
$g$	gluon	(9) 21
$\gamma$	photon	22
$Z^0$	Z-boson	23
$W^+$	W-boson	24
$h^0$	light Higgs boson	25
$H^0$	heavy Higgs boson	35
$A^0$	pseudoscalar Higgs	36
$H^\pm$	charged Higgs	37
$\tilde{\psi}_\mu$	gravitino	39
$\tilde{d}_L$	down-squark 1	41
$\tilde{u}_L$	up-squark 1	42
$\tilde{s}_L$	strange-squark 1	43
$\tilde{c}_L$	charm-squark 1	44
$\tilde{b}_L$	bottom-squark 1	45
$\tilde{t}_L$	top-squark 1	46
$\tilde{d}_R$	down-squark 2	47
$\tilde{u}_R$	up-squark 2	48
$\tilde{s}_R$	strange-squark 2	49
$\tilde{c}_R$	charm-squark 2	50
$\tilde{b}_R$	bottom-squark 2	51
$\tilde{t}_R$	top-squark 2	52
$\tilde{e}_L$	selectron 1	53
$\tilde{\nu}_{e,L}$	electron-sneutrino	54
$\tilde{\mu}_L$	smuon 1	55
$\tilde{\nu}_{\mu,L}$	muon-sneutrino	56
$\tilde{\tau}_L$	stau 1	57
$\tilde{\nu}_{\tau,L}$	tau-sneutrino	58
$\tilde{e}_R$	selectron 2	59
$\tilde{\mu}_R$	smuon 2	61
$\tilde{\tau}_R$	stau 2	486 63
$\tilde{g}$	gluino	64
$\tilde{\chi}_1^0$	neutralino 1	65
$\tilde{\chi}_2^0$	neutralino 2	66
$\tilde{\chi}_3^0$	neutralino 3	67
$\tilde{\chi}_4^0$	neutralino 4	68
$\tilde{\chi}_1^\pm$	chargino 1	69

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let pdg_mw = function
| L g when g > 0 → 9 + 2 × g
| L g → - 9 + 2 × g
| N g when g > 0 → 10 + 2 × g
| N g → - 10 + 2 × g
| U g when g > 0 → 2 × g
| U g → 2 × g
| D g when g > 0 → - 1 + 2 × g
| D g → 1 + 2 × g
| Gl → 21 | Ga → 22 | Z → 23
| Wp → 24 | Wm → (-24)
| H_Light → 25 | H_Heavy → 35 | A → 36
| Hp → 37 | Hm → (-37)
| Phip | Phim → 27 | Phi0 → 26
| Sup (M1, g) when g > 0 → 40 + 2 × g
| Sup (M1, g) → - 40 + 2 × g
| Sup (M2, g) when g > 0 → 46 + 2 × g
| Sup (M2, g) → - 46 + 2 × g
| Sdown (M1, g) when g > 0 → 39 + 2 × g
| Sdown (M1, g) → - 39 + 2 × g
| Sdown (M2, g) when g > 0 → 45 + 2 × g
| Sdown (M2, g) → - 45 + 2 × g
| Slepton (M1, g) when g > 0 → 51 + 2 × g
| Slepton (M1, g) → - 51 + 2 × g
| Slepton (M2, g) when g > 0 → 57 + 2 × g
| Slepton (M2, g) → - 57 + 2 × g
| Sneutrino g when g > 0 → 52 + 2 × g
| Sneutrino g → - 52 + 2 × g
| Grino → 39
| Gluino → 64
| Chargino C1 → 69 | Chargino C1c → (-69)
| Chargino C2 → 70 | Chargino C2c → (-70)
| Neutralino N1 → 65 | Neutralino N2 → 66
| Neutralino N3 → 67 | Neutralino N4 → 68

let mass_symbol f =
"mass(" ^ string_of_int (abs (pdg_mw f)) ^ ")"

let width_symbol f =
"width(" ^ string_of_int (abs (pdg_mw f)) ^ ")"

let conj_symbol = function
| false, str → str
| true, str → str ^ "_c"

let constant_symbol = function
| Unit → "unit" | Pi → "PI"
| Alpha_QED → "alpha" | E → "e" | G → "g" | Vev → "vev"
| Sin2thw → "sin2thw" | Eidelta → "eidelta" | Mu → "mu" |
G_Z → "gz"
| Sin a → "sin" ^ string_of_angle a | Cos a → "cos" ^ string_of_angle a

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| Sin2am2b → "sin2am2b" | Cos2am2b → "cos2am2b" | Sinamb →
"sinamb"
| Sinapb → "sinapb" | Cosamb → "cosamb" | Cosapb → "cosapb"
| Cos4be → "cos4be" | Sin4be → "sin4be" | Sin4al → "sin4al"
| Sin2al → "sin2al" | Cos2al → "cos2al" | Sin2be → "sin2be"
| Cos2be → "cos2be" | Tana → "tana" | Tanb → "tanb"
| Q_lepton → "qlep" | Q_up → "qup" | Q_down → "qdown"
| Q_charg → "qchar"
| V_CKM (g1, g2) → "vckm-" ^ string_of_int g1 ^ string_of_int g2
| M_SF (f, g, m1, m2) → "mix-" ^ string_of_sff f ^ string_of_int g
^ string_of_sfm m1 ^ string_of_sfm m2
| AL g → "al-" ^ string_of_int g
| AD g → "ad-" ^ string_of_int g
| AU g → "au-" ^ string_of_int g
| A_0 (n1, n2) → "a0-" ^ string_of_neu n1 ^ string_of_neu n2
| A_P (c1, c2) → "ap-" ^ string_of_char c1 ^ string_of_char c2
| V_0 (n1, n2) → "v0-" ^ string_of_neu n1 ^ string_of_neu n2
| V_P (c1, c2) → "vp-" ^ string_of_char c1 ^ string_of_char c2
| M_N (n1, n2) → "mn-" ^ string_of_neu n1 ^ string_of_neu n2
| M_U (c1, c2) → "mu-" ^ string_of_char c1 ^ string_of_char c2
| M_V (c1, c2) → "mv-" ^ string_of_char c1 ^ string_of_char c2
| L_NC (n, c) → "lnc-" ^ string_of_neu n ^ string_of_char c
| R_NC (n, c) → "rnc-" ^ string_of_neu n ^ string_of_char c
| L_CN (c, n) → "lcn-" ^ string_of_char c ^ string_of_neu n
| R_CN (c, n) → "rcn-" ^ string_of_char c ^ string_of_neu n
| L_NCH (n, c) → "lnch-" ^ string_of_neu n ^ string_of_char c
| R_NCH (n, c) → "rnch-" ^ string_of_neu n ^ string_of_char c
| L_CNG (c, n) → "lcng-" ^ string_of_char c ^ string_of_neu n
| R_CNG (c, n) → "rcng-" ^ string_of_char c ^ string_of_neu n
| S_NNA (n1, n2) → "snna-" ^ string_of_neu n1 ^ string_of_neu n2
| P_NNA (n1, n2) → "pnna-" ^ string_of_neu n1 ^ string_of_neu n2
| S_NNG (n1, n2) → "snng-" ^ string_of_neu n1 ^ string_of_neu n2
| P_NNG (n1, n2) → "pnng-" ^ string_of_neu n1 ^ string_of_neu n2
| S_NNH1 (n1, n2) → "snnh1-" ^ string_of_neu n1 ^ string_of_neu n2
| P_NNH1 (n1, n2) → "pnnh1-" ^ string_of_neu n1 ^ string_of_neu n2
| S_NNH2 (n1, n2) → "snnh2-" ^ string_of_neu n1 ^ string_of_neu n2
| P_NNH2 (n1, n2) → "pnnh2-" ^ string_of_neu n1 ^ string_of_neu n2
| G_NC_lepton → "gnclep" | G_NC_neutrino → "gncneu"
| G_NC_up → "gncup" | G_NC_down → "gncdown"
| G_CC → "gcc"
| G_CCQ (vc, g1, g2) → conj_symbol (vc, "gccq-" ^ string_of_int g1 ^ "-"
^ string_of_int g2)
| I_Q_W → "iqw" | I_G_ZWW → "igzww"
| G_WWWW → "gw4" | G_ZZWW → "gzzww"
| G_PZWW → "gpzww" | G_PPWW → "gppww"
| G_GH 1 → "ghaw"
| G_GH 2 → "gh1az" | G_GH 3 → "gh2az"
| G_GH 4 → "gh1ww" | G_GH 5 → "gh2ww"
| G_GH 6 → "ghh1w" | G_GH 7 → "ghh2w"
| G_GH 8 → "gh1zz" | G_GH 9 → "gh2zz"

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| G_GH 10 → "ghhz" | G_GH 11 → "ghhp"
| G_GH _ → failwith "this_G_GH_coupling_is_not_available"
| G_GLGLH → "gglglh" | G_GLGLHH → "gglglhh"
| G_GLGLA → "gglgla" | G_PPH → "gpph"
| G_PPHH → "gpphh" | G_PPA → "gppa"
| G_GHGo n → "g_hgh(" ^ string_of_int n ^ ")"
| G_GH4 1 → "gaazz" | G_GH4 2 → "gh1h1zz" | G_GH4 3 →
"gh2h2zz"
| G_GH4 4 → "ghphmzz" | G_GH4 5 → "ghphmpp" | G_GH4 6 →
"ghphpz"
| G_GH4 7 → "ghh1wz" | G_GH4 8 → "ghh2wz"
| G_GH4 9 → "ghh1wp" | G_GH4 10 → "ghh2wp"
| G_GH4 11 → "gaaww" | G_GH4 12 → "gh1h1ww" | G_GH4 13 →
"gh2h2ww"
| G_GH4 14 → "ghhww" | G_GH4 15 → "ghawz" | G_GH4 16 →
"ghawp"
| G_GH4 _ → failwith "this_G_GH4_coupling_is_not_available"
| G_CICIH1 (n1,n2) → "gcicih1-" ^ string_of_neu n1 ^ "-"
^ string_of_neu n2
| G_CICIH2 (n1,n2) → "gcicih2-" ^ string_of_neu n1 ^ "-"
^ string_of_neu n2
| G_CICIA (n1,n2) → "gcicia-" ^ string_of_neu n1 ^ "-"
^ string_of_neu n2
| G_CICIG (n1,n2) → "gcicig-" ^ string_of_neu n1 ^ "-"
^ string_of_neu n2
| G_H3 n → "gh3-" ^ string_of_int n
| G_H4 n → "gh4-" ^ string_of_int n
| G_HGo3 n → "ghg3-" ^ string_of_int n
| G_HGo4 n → "ghg4-" ^ string_of_int n
| G_GG4 n → "ggg4-" ^ string_of_int n
| G_strong → "gs" | G_SS → "gs**2"
| Gs → "gs"
| I_G_S → "igs"
| G_S_Sqrt → "gssq"
| G_NWC (n,c) → "gnwc-" ^ string_of_neu n ^ "-" ^ string_of_char c
| G_CWN (c,n) → "gcwn-" ^ string_of_char c ^ "-" ^ string_of_neu n
| G_CH1C (c1,c2) → "gch1c-" ^ string_of_char c1 ^ "-" ^ string_of_char c2
| G_CH2C (c1,c2) → "gch2c-" ^ string_of_char c1 ^ "-" ^ string_of_char c2
| G_CAC (c1,c2) → "gcac-" ^ string_of_char c1 ^ "-" ^ string_of_char c2
| G_CGC (c1,c2) → "gcgc-" ^ string_of_char c1 ^ "-" ^ string_of_char c2
| G_YUK (i,g) → "g-yuk" ^ string_of_int i ^ "-" ^ string_of_int g
| G_NZN (n1,n2) → "gnzn-" ^ string_of_neu n1 ^ "-" ^ string_of_neu n2
| G_CZC (c1,c2) → "gczc-" ^ string_of_char c1 ^ "-" ^ string_of_char
c2
| G_YUK_1 (n,m) → "g-yuk1-" ^ string_of_int n ^ "-" ^ string_of_int m
| G_YUK_2 (n,m) → "g-yuk2-" ^ string_of_int n ^ "-" ^ string_of_int m
| G_YUK_3 (n,m) → "g-yuk3-" ^ string_of_int n ^ "-" ^ string_of_int m
| G_YUK_4 (n,m) → "g-yuk4-" ^ string_of_int n ^ "-" ^ string_of_int m
| G_YUK_C (vc,g,c,sf,m) → conj_symbol (vc, "g-yuk_ch" ^ string_of_char c
^ "-" ^ string_of_sff sf ^ string_of_sfm m ^ "-" ^ string_of_int g )

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| G_YUK_N (vc, g, n, sf, m) → conj_symbol (vc, "g-yuk-n" ^ string_of_neu n
    ^ "-" ^ string_of_sff sf ^ string_of_sfm m ^ "-" ^ string_of_int g)
| G_YUK_G (vc, g, sf, m) → conj_symbol (vc, "g-yuk-g" ^ string_of_sff sf
    ^ string_of_sfm m ^ "-" ^ string_of_int g)
| G_YUK_Q (vc, g1, g2, c, sf, m) → conj_symbol (vc, "g-yuk-ch" ^ string_of_char c
    ^ "-" ^ string_of_sff sf ^ string_of_sfm m ^ "-" ^ string_of_int g1
    ^ "-" ^ string_of_int g2)
| G_NHC (n, c) → "g-nhc-" ^ string_of_neu n ^ "-" ^ string_of_char c
| G_CHN (c, n) → "g-chn-" ^ string_of_neu n ^ "-" ^ string_of_char c
| G_NGC (n, c) → "g-ngc-" ^ string_of_neu n ^ string_of_char c
| G_CGN (c, n) → "g-cgn-" ^ string_of_char c ^ string_of_neu n
| SUM_1 → "sum1"
| G_SLSNW (vc, g, m) → conj_symbol (vc, "gs1" ^ string_of_sfm m ^ "-"
    ^ string_of_int g ^ "snw")
| G_ZSF (f, g, m1, m2) → "g" ^ string_of_sff f ^ string_of_sfm m1 ^ "z"
    ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int g
| G_WWSFSF (f, g, m1, m2) → "gww" ^ string_of_sff f ^ string_of_sfm m1
    ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int g
| G_WPSLSN (vc, g, m) → conj_symbol (vc, "gpws1" ^ string_of_sfm m
    ^ "sn-" ^ string_of_int g)
| G_WZSLSN (vc, g, m) → conj_symbol (vc, "gwzs1" ^ string_of_sfm m
    ^ "sn-" ^ string_of_int g)
| G_H1SFSF (f, g, m1, m2) → "gh1" ^ string_of_sff f ^ string_of_sfm m1
    ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int g
| G_H2SFSF (f, g, m1, m2) → "gh2" ^ string_of_sff f ^ string_of_sfm m1
    ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int g
| G_ASFSF (f, g, m1, m2) → "ga" ^ string_of_sff f ^ string_of_sfm m1
    ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int g
| G_HSNSL (vc, g, m) → conj_symbol (vc, "ghsns1" ^ string_of_sfm m ^ "-"
    ^ string_of_int g)
| G_GoSFSF (f, g, m1, m2) → "ggo" ^ string_of_sff f ^ string_of_sfm m1
    ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int g
| G_GoSNSL (vc, g, m) → conj_symbol (vc, "ggosns1" ^ string_of_sfm m ^ "-"
    ^ string_of_int g)
| G_HSUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "ghsu" ^ string_of_sfm m1
    ^ "sd" ^ string_of_sfm m2 ^ "-" ^ string_of_int g1 ^ "-"
    ^ string_of_int g2)
| G_GSUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "ggsu" ^ string_of_sfm m1
    ^ "sd" ^ string_of_sfm m2 ^ "-" ^ string_of_int g1 ^ "-"
    ^ string_of_int g2)
| G_WPSUSD (vc, m1, m2, n, m) → conj_symbol (vc, "gpwpsu" ^ string_of_sfm m1
    ^ "sd" ^ string_of_sfm m2 ^ "-" ^ string_of_int n ^ "-"
    ^ string_of_int m)
| G_WZSUSD (vc, m1, m2, n, m) → conj_symbol (vc, "gzwpsu" ^ string_of_sfm m1
    ^ "sd" ^ string_of_sfm m2 ^ "-" ^ string_of_int n ^ "-"
    ^ string_of_int m)
| G_SWS (vc, g1, g2, m1, m2) → conj_symbol (vc, "gs" ^ string_of_sfm m1 ^ "ws"
    ^ string_of_sfm m2 ^ "-" ^ string_of_int g1 ^ "-" ^ string_of_int g2)
| G_GlGlSqsQ → "gglglsqsq"
| G_PPSFSF f → "gpp" ^ string_of_sff f ^ string_of_sff f

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```

| G_ZZSF (f, g, m1, m2) → "gzz" ^ string_of_sff f ^ string_of_sfm m1
  ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int g
| G_ZPSF (f, g, m1, m2) → "gzp" ^ string_of_sff f ^ string_of_sfm m1
  ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int g
| G_GLPSQSQ → "gg1psqsq"
| G_GLZSF (f, g, m1, m2) → "gg1" ^ string_of_sff f ^ string_of_sfm m1
  ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int g
| G_GLWSUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "gg1wsu"
  ^ string_of_sfm m1 ^ "sd" ^ string_of_sfm m2 ^ "-" ^ string_of_int g1
  ^ "-" ^ string_of_int g2)
| G_GHGo4 1 → "gzzg0g0" | G_GHGo4 2 → "gzzgpgm"
| G_GHGo4 3 → "gppgpgm" | G_GHGo4 4 → "gzpgpgm"
| G_GHGo4 5 → "gwwgpgm" | G_GHGo4 6 → "gwwg0g0"
| G_GHGo4 7 → "gwzg0g" | G_GHGo4 8 → "gwzg0g"
| G_GHGo4 9 → "gwzh1g" | G_GHGo4 10 → "gwzh2g"
| G_GHGo4 11 → "gwph1g" | G_GHGo4 12 → "gwph2g"
| G_GHGo4 _ → failwith "Coupling_G_GHGo4_is_not_available"
| G_HSF31 (h, g, m1, m2, f1, f2) → "g-" ^ string_of_higgs h ^
  string_of_int g ^ string_of_sfm m1 ^ string_of_sfm m2 ^
  string_of_sff f1 ^ string_of_sff f2
| G_HSF32 (h, g1, g2, m1, m2, f1, f2) → "g-" ^ string_of_higgs h ^
  string_of_int g1 ^ "-" ^ string_of_int g2 ^ string_of_sfm m1 ^
  string_of_sfm m2 ^ string_of_sff f1 ^ string_of_sff f2
| G_HSF41 (h, g, m1, m2, f1, f2) → "g-" ^ string_of_higgs h ^
  string_of_int g ^ string_of_sfm m1 ^ string_of_sfm m2 ^
  string_of_sff f1 ^ string_of_sff f2
| G_HSF42 (h, g1, g2, m1, m2, f1, f2) → "g-" ^ string_of_higgs h ^
  string_of_int g1 ^ "-" ^ string_of_int g2 ^ string_of_sfm m1 ^
  string_of_sfm m2 ^ string_of_sff f1 ^ string_of_sff f2
| G_H1H1SFSF (f, m1, m2, n) → "gh1h1" ^ string_of_sff f ^ string_of_sfm
  m1 ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int n
| G_H1H2SFSF (f, m1, m2, n) → "gh1h2" ^ string_of_sff f ^ string_of_sfm
  m1 ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int n
| G_H2H2SFSF (f, m1, m2, n) → "gh2h2" ^ string_of_sff f ^ string_of_sfm
  m1 ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int n
| G_HHSFSF (f, m1, m2, n) → "ghh" ^ string_of_sff f ^ string_of_sfm m1
  ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int n
| G_AASF (f, m1, m2, n) → "gaa" ^ string_of_sff f ^ string_of_sfm m1
  ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int n
| G_HH1SUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "ghh1su"
  ^ string_of_sfm m1 ^ "sd" ^ string_of_sfm m2 ^ "-" ^ string_of_int g1
  ^ "-" ^ string_of_int g2)
| G_HH2SUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "ghh2su"
  ^ string_of_sfm m1 ^ "sd" ^ string_of_sfm m2 ^ "-" ^ string_of_int g1
  ^ "-" ^ string_of_int g2)
| G_HASUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "ghasu"
  ^ string_of_sfm m1 ^ "sd" ^ string_of_sfm m2 ^ "-"
  ^ string_of_int g1 ^ "-" ^ string_of_int g2 ^ "-c")
| G_HH1SLN (vc, m, g) → conj_symbol (vc, "ghh1sl" ^ string_of_sfm m
  ^ "sn-" ^ string_of_int g)

```

---

```

| G_HH2SLSN (vc, m, g) → conj_symbol (vc, "ghh2s1" ^ string_of_sfm m
                                         ^ "sn_" ^ string_of_int g)
| G_HASLSN (vc, m, g) → conj_symbol (vc, "ghas1" ^ string_of_sfm m
                                         ^ "sn_" ^ string_of_int g)
| G_AG0SFSF (f, m1, m2, n) → "gag0" ^ string_of_sff f ^ string_of_sfm m1
                               ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int n
| G_HGSFSF (f, m1, m2, n) → "ghg" ^ string_of_sff f ^ string_of_sfm m1
                              ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int n
| G_GGSFSF (f, m1, m2, n) → "ggg" ^ string_of_sff f ^ string_of_sfm m1
                              ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int n
| G_G0G0SFSF (f, m1, m2, n) → "gg0g0" ^ string_of_sff f ^ string_of_sfm m1
                                ^ string_of_sff f ^ string_of_sfm m2 ^ "-" ^ string_of_int n
| G_HGSNSL (vc, m, n) → conj_symbol (vc, "ghgsns1" ^ string_of_sfm m ^ "-"
                                         ^ string_of_int n)
| G_H1GSNSL (vc, m, n) → conj_symbol (vc, "gh1gsns1" ^ string_of_sfm m ^ "-"
                                         ^ string_of_int n)
| G_H2GSNSL (vc, m, n) → conj_symbol (vc, "gh2gsns1" ^ string_of_sfm m ^ "-"
                                         ^ string_of_int n)
| G_AGSNSL (vc, m, n) → conj_symbol (vc, "gagsns1" ^ string_of_sfm m ^ "-"
                                         ^ string_of_int n)
| G_GGSNSL (vc, m, n) → conj_symbol (vc, "gggsns1" ^ string_of_sfm m ^ "-"
                                         ^ string_of_int n)
| G_HGSUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "gghpsu" ^ string_of_sfm m1
                                                  ^ "sd" ^ string_of_sfm m2 ^ "-" ^ string_of_int g1 ^ "-"
                                                  ^ string_of_int g2)
| G_H1GSUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "gh1gpsu" ^ string_of_sfm m1
                                                  ^ "sd" ^ string_of_sfm m2 ^ "-" ^ string_of_int g1 ^ "-"
                                                  ^ string_of_int g2)
| G_H2GSUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "gh2gpsu" ^ string_of_sfm m1
                                                  ^ "sd" ^ string_of_sfm m2 ^ "-" ^ string_of_int g1 ^ "-"
                                                  ^ string_of_int g2)
| G_AGSUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "gagpsu" ^ string_of_sfm m1
                                                  ^ "sd" ^ string_of_sfm m2 ^ "-" ^ string_of_int g1 ^ "-"
                                                  ^ string_of_int g2)
| G_GGSUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "gggpsu" ^ string_of_sfm m1
                                                  ^ "sd" ^ string_of_sfm m2 ^ "-" ^ string_of_int g1 ^ "-"
                                                  ^ string_of_int g2)
| G_SN4 (g1, g2) → "gsn4_" ^ string_of_int g1 ^ "-" ^ string_of_int g2
| G_SN2SL2_1 (m1, m2, g1, g2) → "gs1_" ^ string_of_int g1 ^ "_s1_"
                                ^ string_of_int g1 ^ "_s1" ^ string_of_sfm m1 ^ "-" ^ string_of_int g2
                                ^ "_s1" ^ string_of_sfm m2 ^ "-" ^ string_of_int g2
| G_SN2SL2_2 (m1, m2, g1, g2) → "gs1_" ^ string_of_int g1 ^ "_s1_"
                                ^ string_of_int g2 ^ "_s1" ^ string_of_sfm m1 ^ "-" ^ string_of_int g1
                                ^ "_s1" ^ string_of_sfm m2 ^ "-" ^ string_of_int g2 ^ "_mix"
| G_SF4 (f1, f2, m1, m2, m3, m4, g1, g2) → "gsf" ^ string_of_sff f1 ^
                                             string_of_sff f2 ^ string_of_sfm m1 ^ string_of_sfm m2 ^
                                             string_of_sfm m3 ^ string_of_sfm m4 ^ string_of_int g1 ^
                                             string_of_int g2
| G_SF4_3 (f1, f2, m1, m2, m3, m4, g1, g2, g3) → "gsf" ^ string_of_sff f1 ^
                                                    string_of_sff f2 ^ string_of_sfm m1 ^ string_of_sfm m2 ^

```

```

        string_of_sfm m3 ^ string_of_sfm m4 ^ string_of_int g1 ^
        string_of_int g2 ^ "-" ^ string_of_int g3
    | G_SF4_4 (f1, f2, m1, m2, m3, m4, g1, g2, g3, g4) → "gsf" ^ string_of_sff f1 ^
        string_of_sff f2 ^ string_of_sfm m1 ^ string_of_sfm m2 ^
        string_of_sfm m3 ^ string_of_sfm m4 ^ string_of_int g1 ^ "-" ^
        string_of_int g2 ^ string_of_int g3 ^ "-" ^ string_of_int g4
    | G_SL4 (m1, m2, m3, m4, g) → "gsl" ^ string_of_sfm m1 ^ "-"
        ^ "s1" ^ string_of_sfm m2 ^ "-" ^ "s1" ^ string_of_sfm m3 ^ "-"
        ^ "s1" ^ string_of_sfm m4 ^ "-" ^ string_of_int g
    | G_SL4_2 (m1, m2, m3, m4, g1, g2) → "gsl" ^ string_of_sfm m1 ^ "-"
        ^ "s1" ^ string_of_sfm m2 ^ "-" ^ "s1" ^ string_of_sfm m3 ^ "-"
        ^ "s1" ^ string_of_sfm m4 ^ "-" ^ string_of_int g1 ^ "-" ^
        string_of_int g2
    | G_SN2SQ2 (f, m1, m2, g1, g2) → "gsn-" ^ string_of_int g1 ^ "-sn-"
        ^ string_of_int g1 ^ "-" ^ string_of_sff f ^ string_of_sfm m1 ^ "-"
        ^ string_of_int g2 ^ "-" ^ string_of_sff f ^ string_of_sfm m2 ^ "-"
        ^ string_of_int g2
    | G_SL2SQ2 (f, m1, m2, m3, m4, g1, g2) → "gsl" ^ string_of_sfm m1 ^ "-"
        ^ string_of_int g1 ^ "-s1" ^ string_of_sfm m2 ^ "-" ^ string_of_int g1
        ^ "-" ^ string_of_sff f ^ string_of_sfm m3 ^ "-" ^ string_of_int g2
        ^ "-" ^ string_of_sff f ^ string_of_sfm m4 ^ "-" ^ string_of_int g2
    | G_SUSDSNSL (vc, m1, m2, m3, g1, g2, g3) → conj_symbol (vc, "gsl"
        ^ string_of_sfm m3 ^ "-" ^ string_of_int g3 ^ "-sn-" ^ string_of_int g3
        ^ "_su" ^ string_of_sfm m1 ^ "-" ^ string_of_int g1 ^ "-sd"
        ^ string_of_sfm m2 ^ "-" ^ string_of_int g2)
    | G_SU4 (m1, m2, m3, m4, g) → "gsu" ^ string_of_sfm m1 ^ "-"
        ^ "_su" ^ string_of_sfm m2 ^ "-" ^ "_su" ^ string_of_sfm m3 ^ "-" ^
        "_su" ^ string_of_sfm m4 ^ "-" ^ string_of_int g
    | G_SU4_2 (m1, m2, m3, m4, g1, g2) → "gsu" ^ string_of_sfm m1 ^ "-"
        ^ "_su" ^ string_of_sfm m2 ^ "-" ^ "_su" ^ string_of_sfm m3 ^ "-" ^
        "_su" ^ string_of_sfm m4 ^ "-" ^ string_of_int g1 ^ "-" ^
        string_of_int g2
    | G_SD4 (m1, m2, m3, m4, g) → "gsd" ^ string_of_sfm m1 ^ "-"
        ^ "_sd" ^ string_of_sfm m2 ^ "-" ^ "_sd" ^ string_of_sfm m3 ^ "-"
        ^ "_sd" ^ string_of_sfm m4 ^ "-" ^ string_of_int g
    | G_SD4_2 (m1, m2, m3, m4, g1, g2) → "gsd" ^ string_of_sfm m1 ^ "-"
        ^ "_sd" ^ string_of_sfm m2 ^ "-" ^ "_sd" ^ string_of_sfm m3 ^ "-"
        ^ "_sd" ^ string_of_sfm m4 ^ "-" ^ string_of_int g1 ^ "-" ^
        string_of_int g2
    | G_SU2SD2 (m1, m2, m3, m4, g1, g2, g3, g4) → "gsu" ^ string_of_sfm m1
        ^ "-" ^ string_of_int g1 ^ "-su" ^ string_of_sfm m2 ^ "-"
        ^ string_of_int g2 ^ "-sd" ^ string_of_sfm m3 ^ "-" ^ string_of_int g3
        ^ "-sd" ^ string_of_sfm m4 ^ "-" ^ string_of_int g4
    | M f → "mass" ^ flavor_symbol f
    | W f → "width" ^ flavor_symbol f
    | G_Grav → "ggrav" | G_Gr_Ch C1 → "ggrch1" | G_Gr_Ch C2 →
    "ggrch2"
    | G_Gr_Ch C1c → "ggrch1c" | G_Gr_Ch C2c → "ggrch2c"
    | G_Gr_Z_Neu n → "ggrzneu" ^ string_of_neu n
    | G_Gr_A_Neu n → "ggraneu" ^ string_of_neu n
    
```



```

| G_Gr4_Neu n → "ggr4neu" ^ string_of_neu n
| G_Gr4_A_Ch C1 → "ggr4ach1" | G_Gr4_A_Ch C2 → "ggr4ach2"
| G_Gr4_A_Ch C1c → "ggr4ach1c" | G_Gr4_A_Ch C2c →
"ggr4ach2c"
| G_Gr4_Z_Ch C1 → "ggr4zch1" | G_Gr4_Z_Ch C2 → "ggr4zch2"
| G_Gr4_Z_Ch C1c → "ggr4zch1c" | G_Gr4_Z_Ch C2c →
"ggr4zch2c"
| G_Grav_N → "ggravn"
| G_GravGl → "gs□*□ggrav"
| G_Grav_L (g, m) → "ggravl" ^ string_of_int g ^ string_of_sfm m
| G_Grav_Lc (g, m) → "ggravl" ^ string_of_int g ^ string_of_sfm m ^ "c"
| G_Grav_U (g, m) → "ggravu" ^ string_of_int g ^ string_of_sfm m
| G_Grav_Uc (g, m) → "ggravu" ^ string_of_int g ^ string_of_sfm m ^ "c"
| G_Grav_D (g, m) → "ggravd" ^ string_of_int g ^ string_of_sfm m
| G_Grav_Dc (g, m) → "ggravd" ^ string_of_int g ^ string_of_sfm m ^ "c"
| G_Gr_H_Ch C1 → "ggrhch1" | G_Gr_H_Ch C2 → "ggrhch2"
| G_Gr_H_Ch C1c → "ggrhch1c" | G_Gr_H_Ch C2c → "ggrhch2c"
| G_Gr_H1_Neu n → "ggrh1neu" ^ string_of_neu n
| G_Gr_H2_Neu n → "ggrh2neu" ^ string_of_neu n
| G_Gr_H3_Neu n → "ggrh3neu" ^ string_of_neu n
| G_Gr4A_Sl (g, m) → "ggr4asl" ^ string_of_int g ^ string_of_sfm m
| G_Gr4A_Slc (g, m) → "ggr4asl" ^ string_of_int g ^ string_of_sfm m ^ "c"
| G_Gr4A_Su (g, m) → "ggr4asu" ^ string_of_int g ^ string_of_sfm m
| G_Gr4A_Suc (g, m) → "ggr4asu" ^ string_of_int g ^ string_of_sfm m ^ "c"
| G_Gr4A_Sd (g, m) → "ggr4asd" ^ string_of_int g ^ string_of_sfm m
| G_Gr4A_Sdc (g, m) → "ggr4asd" ^ string_of_int g ^ string_of_sfm m ^ "c"
| G_Gr4Z_Sn → "ggr4zsn" | G_Gr4Z_Snc → "ggr4zsn"
| G_Gr4Z_Sl (g, m) → "ggr4zsl" ^ string_of_int g ^ string_of_sfm m
| G_Gr4Z_Slc (g, m) → "ggr4zsl" ^ string_of_int g ^ string_of_sfm m ^ "c"
| G_Gr4Z_Su (g, m) → "ggr4zsu" ^ string_of_int g ^ string_of_sfm m
| G_Gr4Z_Suc (g, m) → "ggr4zsu" ^ string_of_int g ^ string_of_sfm m ^ "c"
| G_Gr4Z_Sd (g, m) → "ggr4zsd" ^ string_of_int g ^ string_of_sfm m
| G_Gr4Z_Sdc (g, m) → "ggr4zsd" ^ string_of_int g ^ string_of_sfm m ^ "c"
| G_Gr4W_Sl (g, m) → "ggr4ws1" ^ string_of_int g ^ string_of_sfm m
| G_Gr4W_Slc (g, m) → "ggr4ws1" ^ string_of_int g ^ string_of_sfm m ^ "c"
| G_Gr4W_Su (g, m) → "ggr4wsu" ^ string_of_int g ^ string_of_sfm m
| G_Gr4W_Suc (g, m) → "ggr4wsu" ^ string_of_int g ^ string_of_sfm m ^ "c"
| G_Gr4W_Sd (g, m) → "ggr4wsd" ^ string_of_int g ^ string_of_sfm m
| G_Gr4W_Sdc (g, m) → "ggr4wsd" ^ string_of_int g ^ string_of_sfm m ^ "c"
| G_Gr4Gl_Su (g, m) → "ggr4glsu" ^ string_of_int g ^ string_of_sfm m
| G_Gr4Gl_Suc (g, m) → "ggr4glsu" ^ string_of_int g ^ string_of_sfm m ^ "c"
| G_Gr4Gl_Sd (g, m) → "ggr4glsd" ^ string_of_int g ^ string_of_sfm m
| G_Gr4Gl_Sdc (g, m) → "ggr4glsd" ^ string_of_int g ^ string_of_sfm m ^ "c"
| G_Gr4_Z_H1 n → "ggr4zh1-" ^ string_of_neu n
| G_Gr4_Z_H2 n → "ggr4zh2-" ^ string_of_neu n
| G_Gr4_Z_H3 n → "ggr4zh3-" ^ string_of_neu n
| G_Gr4_W_H n → "ggr4wh-" ^ string_of_neu n
| G_Gr4_W_Hc n → "ggr4whc-" ^ string_of_neu n
| G_Gr4_H_A C1 → "ggr4ha1" | G_Gr4_H_A C2 → "ggr4ha2"
| G_Gr4_H_A C1c → "ggr4ha1c" | G_Gr4_H_A C2c → "ggr4ha2c"

```

```

| G_Gr4_H_Z C1 → "ggr4hz1" | G_Gr4_H_Z C2 → "ggr4hz2"
| G_Gr4_H_Z C1c → "ggr4hz1c" | G_Gr4_H_Z C2c → "ggr4hz2c"
| G_Gr4W_Sn → "ggr4wsn"
| G_Gr4W_Snc → "ggr4wsnc"
end

```

## 13.9 Interface of *Modellib\_NMSSM*

### 13.9.1 Extended Supersymmetric Models

We do not introduce the possibility here of using four point couplings or not. We simply add the relevant and leave the rest out. No possibility for Goldstone bosons is given. But we allow for CKM mixing.

```

module type NMSSM_flags =
sig
  val ckm_present : bool
  val higgs_triangle : bool (* Hγγ, Hgγ and Hggcouplings*)
end

module NMSSM : NMSSM_flags
module NMSSM_CKM : NMSSM_flags
module NMSSM_Hgg : NMSSM_flags
module NMSSM_func : functor (F : NMSSM_flags) → Model.T with mod-
ule Ch = Charges.QQ

```

## 13.10 Implementation of *Modellib\_NMSSM*

```

let rcs_file = RCS.parse "Modellib_NMSSM" ["NMSSM"]
{ RCS.revision = "$Revision: 4926$";
  RCS.date = "$Date: 2013-12-04 13:35:06 +0100 (Wed, 04 Dec 2013)$";
  RCS.author = "$Author: jr-reuter$";
  RCS.source
    = "$URL: svn+ssh://jr-reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/s

```

### 13.10.1 Next-to-Minimal Supersymmetric Standard Model

This is based on the NMSSM implementation by Felix Braam. Note that for the Higgs sector vertices the conventions of the Franke/Fraas paper have been used.

```

module type NMSSM_flags =
sig
  val ckm_present : bool
  val higgs_triangle : bool
end

module NMSSM : NMSSM_flags =
struct
  let ckm_present = false

```

```

    let higgs_triangle = false
  end

module NMSSM_CKM : NMSSM_flags =
  struct
    let ckm_present = true
    let higgs_triangle = false
  end

module NMSSM_Hgg : NMSSM_flags =
  struct
    let ckm_present = false
    let higgs_triangle = true
  end

module NMSSM_func (Flags : NMSSM_flags) =
  struct
    let rcs = RCS.rename rcs_file "Modellib_NMSSM.NMSSM"
      [ "NMSSM" ]

    open Coupling

    let default_width = ref Timelike
    let use_fudged_width = ref false

    let options = Options.create
      [ "constant_width", Arg.Unit (fun () → default_width := Constant),
        "use_constant_width_also_in_t-channel";
        "fudged_width", Arg.Set use_fudged_width,
        "use_fudge_factor_for_charge_particle_width";
        "custom_width", Arg.String (fun f → default_width := Custom f),
        "use_custom_width";
        "cancel_widths", Arg.Unit (fun () → default_width := Vanishing),
        "use_vanishing_width" ]
  end

```

Yields a list of tuples consistig of the off-diag combinations of the elements in "set".

```

let choose2 set =
  List.map (function [x; y] → (x, y) | _ → failwith "choose2")
    (Combinatorics.choose 2 set)

```

*pairs* appends the diagonal combinations to *choose2*.

```

let rec diag = function
| [] → []
| x1 :: rest → (x1, x1) :: diag rest

```

```
let pairs l = choose2 l @ diag l
```

```

let rec cloop set i j k =
  if i > ((List.length set) - 1) then []
  else if j > i then cloop set (succ i) (j - i - 1) (j - i - 1)
  else if k > j then cloop set i (succ j) (k - j - 1)
  else (List.nth set i, List.nth set j, List.nth set k) :: cloop set i j (succ k)

```

```

let triples set = cloop set 0 0 0

let rec two_and_one' l1 z n =
  if n < 0 then []
  else
    ((fst (List.nth (pairs l1) n)), (snd (List.nth (pairs l1) n)), z) :: two_and_one' l1 z (pred n)

let two_and_one l1 l2 =
  let f z = two_and_one' l1 z ((List.length (pairs l1)) - 1)
  in
    List.flatten ( List.map f l2 )

type gen =
  | G of int | GG of gen × gen

let rec string_of_gen = function
  | G n when n > 0 → string_of_int n
  | G n → string_of_int (abs n) ^ "c"
  | GG (g1, g2) → string_of_gen g1 ^ "-" ^ string_of_gen g2

```

With this we distinguish the flavour.

```

type sff =
  | SL | SN | SU | SD

let string_of_sff = function
  | SL → "s1" | SN → "sn" | SU → "su" | SD → "sd"

```

With this we distinguish the mass eigenstates. At the moment we have to cheat a little bit for the sneutrinos. Because we are dealing with massless neutrinos there is only one sort of sneutrino.

```

type sfm =
  | M1 | M2

let string_of_sfm = function
  | M1 → "1" | M2 → "2"

```

We also introduce special types for the charginos and neutralinos.

```

type char =
  | C1 | C2 | C1c | C2c

type neu =
  | N1 | N2 | N3 | N4 | N5

let int_of_char = function
  | C1 → 1 | C2 → 2 | C1c → -1 | C2c → -2

let string_of_char = function
  | C1 → "1" | C2 → "2" | C1c → "-1" | C2c → "-2"

let conj_char = function
  | C1 → C1c | C2 → C2c | C1c → C1 | C2c → C2

let string_of_neu = function
  | N1 → "1" | N2 → "2" | N3 → "3" | N4 → "4" | N5 → "5"

```

For the Higgs bosons, we follow the conventions of Franke/Fraas.

```

type shiggs =
  | S1 | S2 | S3

type phiggs =
  | P1 | P2

let string_of_shiggs = function
  | S1 → "1" | S2 → "2" | S3 → "3"

let string_of_phiggs = function
  | P1 → "1" | P2 → "2"

type flavor =
  | L of int | N of int
  | U of int | D of int
  | Sup of sfm × int | Sdown of sfm × int
  | Ga | Wp | Wm | Z | Gl
  | Slepton of sfm × int | Sneutrino of int
  | Neutralino of neu | Chargino of char
  | Gluino
  | SHiggs of shiggs | Hp | Hm | PHiggs of phiggs

let string_of_fermion_type = function
  | L _ → "l" | U _ → "u" | D _ → "d" | N _ → "n"
  | _ → failwith "Modellib_NMSSM.NMSSM.string_of_fermion_type:␣invalid␣fermion␣type"

let string_of_fermion_gen = function
  | L g | U g | D g | N g → string_of_int (abs (g))
  | _ → failwith "Modellib_NMSSM.NMSSM.string_of_fermion_gen:␣invalid␣fermion␣type"

type gauge = unit

let gauge_symbol () =
  failwith "Modellib_NMSSM.NMSSM.gauge_symbol:␣internal␣error"

```

At this point we will forget graviton and -ino.

```

let family g = [ L g; N g; Slepton (M1, g);
                 Slepton (M2, g); Sneutrino g;
                 U g; D g; Sup (M1, g); Sup (M2, g);
                 Sdown (M1, g); Sdown (M2, g)]

let external_flavors () =
  [ "1st␣Generation␣matter", ThoList.flatmap family [1; -1];
    "2nd␣Generation␣matter", ThoList.flatmap family [2; -2];
    "3rd␣Generation␣matter", ThoList.flatmap family [3; -3];
    "Gauge␣Bosons", [Ga; Z; Wp; Wm; Gl];
    "Charginos", [Chargino C1; Chargino C2; Chargino C1c; Chargino C2c];
    "Neutralinos", [Neutralino N1; Neutralino N2; Neutralino N3;
                    Neutralino N4; Neutralino N5];
    "Higgs␣Bosons", [SHiggs S1; SHiggs S2; SHiggs S3; Hp; Hm; PHiggs P1; PHiggs P2];
    "Gluino", [Gluino]]

let flavors () = ThoList.flatmap snd (external_flavors ())

let spinor n m =
  if n ≥ 0 ∧ m ≥ 0 then

```

```

    Spinor
  else if
     $n \leq 0 \wedge m \leq 0$  then
      ConjSpinor
    else
      invalid_arg "Modellib_NMSSM.NMSSM.spinor:␣internal␣error"

let lorentz = function
| L g → spinor g 0 | N g → spinor g 0
| U g → spinor g 0 | D g → spinor g 0
| Chargino c → spinor (int_of_char c) 0
| Ga | Gl → Vector
| Wp | Wm | Z → Massive_Vector
| SHiggs _ | PHiggs _ | Hp | Hm
| Sup _ | Sdown _ | Slepton _ | Sneutrino _ → Scalar
| Neutralino _ | Gluino → Majorana

let color = function
| U g → Color.SUN (if g > 0 then 3 else -3)
| Sup (m, g) → Color.SUN (if g > 0 then 3 else -3)
| D g → Color.SUN (if g > 0 then 3 else -3)
| Sdown (m, g) → Color.SUN (if g > 0 then 3 else -3)
| Gl | Gluino → Color.AdjSUN 3
| _ → Color.Singlet

let prop_spinor n m =
  if  $n \geq 0 \wedge m \geq 0$  then
    Prop_Spinor
  else if
     $n \leq 0 \wedge m \leq 0$  then
      Prop_ConjSpinor
    else
      invalid_arg "Modellib_NMSSM.NMSSM.prop_spinor:␣internal␣error"

let propagator = function
| L g → prop_spinor g 0 | N g → prop_spinor g 0
| U g → prop_spinor g 0 | D g → prop_spinor g 0
| Chargino c → prop_spinor (int_of_char c) 0
| Ga | Gl → Prop_Feynman
| Wp | Wm | Z → Prop_Unitarity
| SHiggs _ | PHiggs _ → Prop_Scalar
| Hp | Hm → Prop_Scalar
| Sup _ | Sdown _ | Slepton _ | Sneutrino _ → Prop_Scalar
| Gluino → Prop_Majorana
| Neutralino _ → Prop_Majorana

```

Optionally, ask for the fudge factor treatment for the widths of charged particles. Currently, this only applies to  $W^\pm$  and top.

```

let width f =
  if !use_fudged_width then
    match f with
    | Wp | Wm | U 3 | U (-3) → Fudged

```

```

    | _ → !default_width
  else
    !default_width
let goldstone _ = None
let conjugate = function
| L g → L (-g) | N g → N (-g)
| U g → U (-g) | D g → D (-g)
| Sup (m, g) → Sup (m, -g)
| Sdown (m, g) → Sdown (m, -g)
| Slepton (m, g) → Slepton (m, -g)
| Sneutrino g → Sneutrino (-g)
| Gl → Gl | Ga → Ga | Z → Z
| Wp → Wm | Wm → Wp
| SHiggs s → SHiggs s
| PHiggs p → PHiggs p
| Hp → Hm | Hm → Hp
| Gluino → Gluino
| Neutralino n → Neutralino n | Chargino c → Chargino (conj_char c)
let fermion = function
| L g → if g > 0 then 1 else -1
| N g → if g > 0 then 1 else -1
| U g → if g > 0 then 1 else -1
| D g → if g > 0 then 1 else -1
| Gl | Ga | Z | Wp | Wm → 0
| SHiggs _ | Hp | Hm | PHiggs _ → 0
| Neutralino _ → 2
| Chargino c → if (int_of_char c) > 0 then 1 else -1
| Sup _ → 0 | Sdown _ → 0
| Slepton _ → 0 | Sneutrino _ → 0
| Gluino → 2
module Ch = Charges.QQ
let ( // ) = Algebra.Small_Rational.make
let generation' = function
| 1 → [ 1//1; 0//1; 0//1]
| 2 → [ 0//1; 1//1; 0//1]
| 3 → [ 0//1; 0//1; 1//1]
| -1 → [-1//1; 0//1; 0//1]
| -2 → [ 0//1; -1//1; 0//1]
| -3 → [ 0//1; 0//1; -1//1]
| n → invalid_arg ("NMSSM.generation':␣" ^ string_of_int n)
let generation f =
  if Flags.ckm_present then
    []
  else
    match f with
    | L n | N n | U n | D n | Sup (_, n)
    | Sdown (_, n) | Slepton (_, n)

```

```

| Sneutrino n → generation' n
| - → [0//1; 0//1; 0//1]

let charge = function
| L n → if n > 0 then -1//1 else 1//1
| Slepton (_, n) → if n > 0 then -1//1 else 1//1
| N n → 0//1
| Sneutrino n → 0//1
| U n → if n > 0 then 2//3 else -2//3
| Sup (_, n) → if n > 0 then 2//3 else -2//3
| D n → if n > 0 then -1//3 else 1//3
| Sdown (_, n) → if n > 0 then -1//3 else 1//3
| Gl | Ga | Z | Neutralino - | Gluino → 0//1
| Wp → 1//1
| Wm → -1//1
| SHiggs - | PHiggs - → 0//1
| Hp → 1//1
| Hm → -1//1
| Chargino (C1 | C2) → 1//1
| Chargino (C1c | C2c) → -1//1

let lepton = function
| L n | N n → if n > 0 then 1//1 else -1//1
| Slepton (_, n)
| Sneutrino n → if n > 0 then 1//1 else -1//1
| - → 0//1

let baryon = function
| U n | D n → if n > 0 then 1//1 else -1//1
| Sup (_, n) | Sdown (_, n) → if n > 0 then 1//1 else -1//1
| - → 0//1

let charges f =
[ charge f; lepton f; baryon f ] @ generation f

```

We introduce a Boolean type *vc* as a pseudonym for Vertex Conjugator to distinguish between vertices containing complex mixing matrices like the CKM-matrix or the sfermion or neutralino/chargino-mixing matrices, which have to become complex conjugated. The true-option stands for the conjugated vertex, the false-option for the unconjugated vertex.

```

type vc = bool

type constant =
| E | G
| Mu (*lambda*|s|*) | Lambda
| Q_lepton | Q_up | Q_down | Q_charg
| G_Z | G_CC | G_CCQ of vc × int × int
| G_NC_neutrino | G_NC_lepton | G_NC_up | G_NC_down
| I_Q_W | I_G_ZWW | G_WWWW | G_ZZWW | G_PZWW |
G_PPWW
| G_SS | I_G_S | Gs
| G_NZN of neu × neu | G_CZC of char × char
| G_YUK_FFS of flavor × flavor × shiggs

```



```

| G_YUK_FFP of flavor  $\times$  flavor  $\times$  phiggs
| G_YUK_LCN of int
| G_YUK_UCD of int $\times$ int | G_YUK_DCU of int $\times$ int
| G_NHC of vc  $\times$  neu  $\times$  char
| G_YUK_C of vc  $\times$  flavor  $\times$  char $\times$ sff  $\times$  sfm
| G_YUK_Q of vc  $\times$  int $\times$ flavor  $\times$  char $\times$ sff  $\times$  sfm
| G_YUK_N of vc  $\times$  flavor  $\times$  neu  $\times$  sff  $\times$  sfm
| G_YUK_G of vc  $\times$  flavor  $\times$  sff  $\times$  sfm
| G_NWC of neu  $\times$  char | G_CWN of char $\times$ neu
| G_CSC of char $\times$ char $\times$ shiggs
| G_CPC of char $\times$ char $\times$ phiggs
| G_WSQ of vc  $\times$  int $\times$ int $\times$ sfm  $\times$  sfm
| G_SLSNW of vc  $\times$  int $\times$ sfm
| G_ZSF of sff  $\times$  int $\times$ sfm  $\times$  sfm
| G_CICIS of neu  $\times$  neu  $\times$  shiggs
| G_CICIP of neu  $\times$  neu  $\times$  phiggs
| G_GH_WPC of phiggs | G_GH_WSC of shiggs
| G_GH_ZSP of shiggs  $\times$  phiggs | G_GH_WWS of shiggs
| G_GH_ZZS of shiggs | G_GH_ZCC
| G_GH_GaCC
| G_GH4_ZZPP of phiggs  $\times$  phiggs
| G_GH4_ZZSS of shiggs  $\times$  shiggs
| G_GH4_ZZCC | G_GH4_GaGaCC
| G_GH4_ZGaCC | G_GH4_WWCC
| G_GH4_WWPP of phiggs  $\times$  phiggs
| G_GH4_WWSS of shiggs  $\times$  shiggs
| G_GH4_ZWSC of shiggs
| G_GH4_GaWSC of shiggs
| G_GH4_ZWPC of phiggs
| G_GH4_GaWPC of phiggs
| G_WWSFSF of sff  $\times$  int $\times$ sfm  $\times$  sfm
| G_WPSLSN of vc  $\times$  int $\times$ sfm
| G_H3_SCC of shiggs
| G_H3_SSS of shiggs  $\times$  shiggs  $\times$  shiggs
| G_H3_SPP of shiggs  $\times$  phiggs  $\times$  phiggs
| G_SFSFS of shiggs  $\times$  sff  $\times$  int $\times$ sfm  $\times$  sfm
| G_SFSFP of phiggs  $\times$  sff  $\times$  int $\times$ sfm  $\times$  sfm
| G_HSNSL of vc  $\times$  int $\times$ sfm
| G_HSUSD of vc  $\times$  sfm  $\times$  sfm  $\times$  int $\times$ int
| G_WPSUSD of vc  $\times$  sfm  $\times$  sfm  $\times$  int $\times$ int
| G_WZSUSD of vc  $\times$  sfm  $\times$  sfm  $\times$  int $\times$ int
| G_WZSLSN of vc  $\times$  int $\times$ sfm | G_GlGlSQSQ
| G_PPSFSF of sff
| G_ZZSFSF of sff  $\times$  int $\times$ sfm  $\times$  sfm | G_ZPSFSF of sff  $\times$  int $\times$ sfm  $\times$  sfm
| G_GlZSFSF of sff  $\times$  int $\times$ sfm  $\times$  sfm | G_GlPSQSQ
| G_GlWSUSD of vc  $\times$  sfm  $\times$  sfm  $\times$  int $\times$ int
| G_GLUGLUA0 of phiggs | G_GLUGLUH0 of shiggs

```

Two integer counters for the QCD and EW order of the couplings.

type *orders* = *int*  $\times$  *int*

```
let orders = function
| - → (0,0)
```

$$\alpha_{\text{QED}} = \frac{1}{137.0359895} \quad (13.83a)$$

$$\sin^2 \theta_w = 0.23124 \quad (13.83b)$$

Here we must perhaps allow for complex input parameters. So split them into their modulus and their phase. At first, we leave them real; the generalization to complex parameters is obvious.

```
let parameters () =
{ input = [];
  derived = [];
  derived_arrays = [] }

module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)
```

For the couplings there are generally two possibilities concerning the sign of the covariant derivative.

$$CD^\pm = \partial_\mu \pm igT^a A_\mu^a \quad (13.84)$$

The particle data group defines the signs consistently to be positive. Since the convention for that signs also influence the phase definitions of the gaugino/higgsino fields via the off-diagonal entries in their mass matrices it would be the best to adopt that convention.

\*\* REVISED: Compatible with CD+. FB \*\*

```
let electromagnetic_currents_3 g =
[ ((L (-g), Ga, L g), FBF (1, Psibar, V, Psi), Q_lepton);
  ((U (-g), Ga, U g), FBF (1, Psibar, V, Psi), Q_up);
  ((D (-g), Ga, D g), FBF (1, Psibar, V, Psi), Q_down)]
```

\*\* REVISED: Compatible with CD+. FB\*\*

```
let electromagnetic_sfermion_currents g m =
[ ((Ga, Slepton (m, -g), Slepton (m, g)), Vector_Scalar_Scalar 1, Q_lepton);
  ((Ga, Sup (m, -g), Sup (m, g)), Vector_Scalar_Scalar 1, Q_up);
  ((Ga, Sdown (m, -g), Sdown (m, g)), Vector_Scalar_Scalar 1, Q_down)]
```

\*\* REVISED: Compatible with CD+. FB\*\*

```
let electromagnetic_currents_2 c =
let cc = conj_char c in
[ ((Chargino cc, Ga, Chargino c), FBF (1, Psibar, V, Psi), Q_charg)]
```

\*\* REVISED: Compatible with CD+. FB\*\*

```
let neutral_currents g =
[ ((L (-g), Z, L g), FBF (1, Psibar, VA, Psi), G_NC_lepton);
```

```

((N (-g), Z, N g), FBF (1, Psibar, VA, Psi), G_NC_neutrino);
((U (-g), Z, U g), FBF (1, Psibar, VA, Psi), G_NC_up);
((D (-g), Z, D g), FBF (1, Psibar, VA, Psi), G_NC_down)]

```

$$\mathcal{L}_{CC} = \mp \frac{g}{2\sqrt{2}} \sum_i \bar{\psi}_i \gamma^\mu (1 - \gamma_5) (T^+ W_\mu^+ + T^- W_\mu^-) \psi_i, \quad (13.85)$$

where the sign corresponds to  $CD_\pm$ , respectively.

\*\* REVISED: Compatible with  $CD_+$ . \*\*

Remark: The definition with the other sign compared to the SM files comes from the fact that  $g_{cc} = 1/(2\sqrt{2})$  is used overwhelmingly often in the SUSY Feynman rules, so that JR decided to use a different definition for  $g_{cc}$  in SM and MSSM.

\* FB \*

```

let charged_currents g =
  [ ((L (-g), Wm, N g), FBF ((-1), Psibar, VL, Psi), G_CC);
    ((N (-g), Wp, L g), FBF ((-1), Psibar, VL, Psi), G_CC) ]

```

The quark with the inverted generation (the antiparticle) is the outgoing one, the other the incoming. The vertex attached to the outgoing up-quark contains the CKM matrix element *not* complex conjugated, while the vertex with the outgoing down-quark has the conjugated CKM matrix element.

\*\* REVISED: Compatible with  $CD_+$ . FB \*\*

```

let charged_quark_currents g h =
  [ ((D (-g), Wm, U h), FBF ((-1), Psibar, VL, Psi), G_CCQ (true,g,h));
    ((U (-g), Wp, D h), FBF ((-1), Psibar, VL, Psi), G_CCQ (false,h,g))]

```

\*\* REVISED: Compatible with  $CD_+$ . FB \*\*

```

let charged_chargino_currents n c =
  let cc = conj_char c in
  [ ((Chargino cc, Wp, Neutralino n),
      FBF (1, Psibar, VLR, Chi), G_CWN (c,n));
    ((Neutralino n, Wm, Chargino c),
      FBF (1, Chibar, VLR, Psi), G_NWC (n,c)) ]

```

\*\* REVISED: Compatible with  $CD_+$ . FB\*\*

```

let charged_slepton_currents g m =
  [ ((Wm, Slepton (m, -g), Sneutrino g), Vector_Scalar_Scalar (-1), G_SLSNW
      (true,g,m));
    ((Wp, Slepton (m, g), Sneutrino (-g)), Vector_Scalar_Scalar 1, G_SLSNW
      (false,g,m)) ]

```

\*\* REVISED: Compatible with  $CD_+$ . FB\*\*

```

let charged_squark_currents' g h m1 m2 =
  [ ((Wm, Sup (m1, g), Sdown (m2, -h)), Vector_Scalar_Scalar (-1), G_WSQ
      (true,g,h,m1,m2));
    ((Wp, Sup (m1, -g), Sdown (m2, h)), Vector_Scalar_Scalar 1, G_WSQ
      (false,g,h,m1,m2)) ]
let charged_squark_currents g h =
  List.flatten (Product.list2 (charged_squark_currents' g h) [M1; M2] [M1; M2])

```

\*\* REVISED: Compatible with CD+. FB \*\*

```

let neutral_sfermion_currents' g m1 m2 =
  [ ((Z, Slepton (m1, -g), Slepton (m2, g)), Vector_Scalar_Scalar (-1),
      G_ZSF (SL, g, m1, m2));
    ((Z, Sup (m1, -g), Sup (m2, g)), Vector_Scalar_Scalar (-1),
      G_ZSF (SU, g, m1, m2));
    ((Z, Sdown (m1, -g), Sdown (m2, g)), Vector_Scalar_Scalar (-1),
      G_ZSF (SD, g, m1, m2))]
let neutral_sfermion_currents g =
  List.flatten (Product.list2 (neutral_sfermion_currents'
    g) [M1; M2] [M1; M2]) @
  [ ((Z, Sneutrino (-g), Sneutrino g), Vector_Scalar_Scalar (-1),
      G_ZSF (SN, g, M1, M1)) ]

```

\*\* REVISED: Compatible with CD+. FB\*\*

```

let neutral_Z (n, m) =
  [ ((Neutralino n, Z, Neutralino m), FBF (1, Chibar, VLR, Chi),
      (G_NZN (n, m))) ]

```

\*\* REVISED: Compatible with CD+. FB\*\*

```

let charged_Z c1 c2 =
  let cc1 = conj_char c1 in
  ((Chargino cc1, Z, Chargino c2), FBF ((-1), Psibar, VA, Psi),
    G_CZC (c1, c2))

```

\*\* REVISED: Compatible with CD+. Remark: This is pure octet. FB\*\*

```

let yukawa_v =
  [ (Gluino, Gl, Gluino), FBF (1, Chibar, V, Chi), Gs]

```

\*\* REVISED: Independent of the sign of CD. \*\*

\*\* REVISED: Felix Braam: Compact version using new COMBOS + FF-Couplings

```

let yukawa_higgs_FFS f s =
  [ ((conjugate f, SHiggs s, f), FBF (1, Psibar, S, Psi),
      G_YUK_FFS (conjugate f, f, s))]
let yukawa_higgs_FFP f p =
  [ ((conjugate f, PHiggs p, f), FBF (1, Psibar, P, Psi),
      G_YUK_FFP (conjugate f, f, p))]
let yukawa_higgs_NLC g =
  [ ((N (-g), Hp, L g), FBF (1, Psibar, Coupling.SR, Psi), G_YUK_LCN g);
    ((L (-g), Hm, N g), FBF (1, Psibar, Coupling.SL, Psi), G_YUK_LCN g)]
let yukawa_higgs g =
  yukawa_higgs_NLC g @
  List.flatten (Product.list2 yukawa_higgs_FFS [L g; U g; D g] [S1; S2; S3]) @
  List.flatten (Product.list2 yukawa_higgs_FFP [L g; U g; D g] [P1; P2])

```

\*\* REVISED: Independent of the sign of CD. FB\*\*

```

let yukawa_higgs_quark (g, h) =
  [ ((U (-g), Hp, D h), FBF (1, Psibar, SLR, Psi), G_YUK_UCD (g, h));

```

```

      ((D (-h), Hm, U g), FBF (1, Psibar, SLR, Psi), G_YUK_DCU (g, h)) ]

** REVISED: Compatible with CD+. **
** REVISED: Felix Braam: Compact version using new COMBOS

let yukawa_shiggs_2 c1 c2 s =
  let cc1 = conj_char c1 in
    ((Chargino cc1, SHiggs s, Chargino c2), FBF (1, Psibar, SLR, Psi),
     G_CSC (c1, c2, s))

let yukawa_phiggs_2 c1 c2 p =
  let cc1 = conj_char c1 in
    ((Chargino cc1, PHiggs p, Chargino c2), FBF (1, Psibar, SLR, Psi),
     G_CPC (c1, c2, p))

let yukawa_higgs_2 =
  Product.list3 yukawa_shiggs_2 [C1; C2] [C1; C2] [S1; S2; S3] @
  Product.list3 yukawa_phiggs_2 [C1; C2] [C1; C2] [P1; P2]

** REVISED: Compatible with CD+.FB **

let higgs_charg_neutr n c =
  let cc = conj_char c in
    [ ((Neutralino n, Hm, Chargino c), FBF (-1, Chibar, SLR, Psi),
       G_NHC (false, n, c));
      ((Chargino cc, Hp, Neutralino n), FBF (-1, Psibar, SLR, Chi),
       G_NHC (true, n, c)) ]

** REVISED: Compatible with CD+. **
** REVISED: Felix Braam: Compact version using new COMBOS

let shiggs_neutr (n, m, s) =
  ((Neutralino n, SHiggs s, Neutralino m), FBF (1, Chibar, SLR, Chi),
   G_CICIS (n, m, s))
let phiggs_neutr (n, m, p) =
  ((Neutralino n, PHiggs p, Neutralino m), FBF (1, Chibar, SLR, Chi),
   G_CICIP (n, m, p))

let higgs_neutr =
  List.map shiggs_neutr (two_and_one [N1; N2; N3; N4; N5] [S1; S2; S3]) @
  List.map phiggs_neutr (two_and_one [N1; N2; N3; N4; N5] [P1; P2])

** REVISED: Compatible with CD+. FB**

let yukawa_n_2 n m g =
  [ ((Neutralino n, Slepton (m, -g), L g), FBF (1, Chibar, SLR, Psi),
     G_YUK_N (true, L g, n, SL, m));
    ((L (-g), Slepton (m, g), Neutralino n), FBF (1, Psibar, SLR, Chi),
     G_YUK_N (false, L g, n, SL, m));
    ((Neutralino n, Sup (m, -g), U g), FBF (1, Chibar, SLR, Psi),
     G_YUK_N (true, U g, n, SU, m));
    ((U (-g), Sup (m, g), Neutralino n), FBF (1, Psibar, SLR, Chi),
     G_YUK_N (false, U g, n, SU, m));
    ((Neutralino n, Sdown (m, -g), D g), FBF (1, Chibar, SLR, Psi),
     G_YUK_N (true, D g, n, SD, m));
    ((D (-g), Sdown (m, g), Neutralino n), FBF (1, Psibar, SLR, Chi),

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      G_YUK_N (false,D g,n,SD,m)) ]
let yukawa_n_3 n g =
  [ ((Neutralino n, Sneutrino (-g), N g), FBF (1, Chibar, SLR, Psi),
      G_YUK_N (true,N g,n,SN,M1));
    ((N (-g), Sneutrino g, Neutralino n), FBF (1, Psibar, SLR, Chi),
      G_YUK_N (false,N g, n,SN,M1)) ]
let yukawa_n_5 g m =
  [ ((U (-g), Sup (m,g), Gluino), FBF (1, Psibar, SLR, Chi),
      G_YUK_G (false,U g,SU,m));
    ((D (-g), Sdown (m,g), Gluino), FBF (1, Psibar, SLR, Chi),
      G_YUK_G (false,D g,SD,m));
    ((Gluino, Sup (m,-g), U g), FBF (1, Chibar, SLR, Psi),
      G_YUK_G (true,U g,SU,m));
    ((Gluino, Sdown (m,-g), D g), FBF (1, Chibar, SLR, Psi),
      G_YUK_G (true,D g,SD,m))]
let yukawa_n =
  List.flatten (Product.list3 yukawa_n_2 [N1;N2;N3;N4;N5] [M1;M2] [1;2;3]) @
  List.flatten (Product.list2 yukawa_n_3 [N1;N2;N3;N4;N5] [1;2;3]) @
  List.flatten (Product.list2 yukawa_n_5 [1;2;3] [M1;M2])

** REVISED: Compatible with CD+.FB **

let yukawa_c_2 c g =
  let cc = conj_char c in
  [ ((L (-g), Sneutrino g, Chargino cc), BBB (1, Psibar, SLR,
      Psibar), G_YUK_C (true,L g,c,SN,M1));
    ((Chargino c, Sneutrino (-g), L g), PBP (1, Psi, SLR, Psi),
      G_YUK_C (false,L g,c,SN,M1)) ]
let yukawa_c_3 c m g =
  let cc = conj_char c in
  [ ((N (-g), Slepton (m,g), Chargino c), FBF (1, Psibar, SLR,
      Psi), G_YUK_C (true,N g,c,SL,m));
    ((Chargino cc, Slepton (m,-g), N g), FBF (1, Psibar, SLR,
      Psi), G_YUK_C (false,N g,c,SL,m)) ]
let yukawa_c c =
  ThoList.flatmap (yukawa_c_2 c) [1;2;3] @
  List.flatten (Product.list2 (yukawa_c_3 c) [M1;M2] [1;2;3])

** REVISED: Compatible with CD+. FB**

let yukawa_cq' c (g,h) m =
  let cc = conj_char c in
  [ ((Chargino c, Sup (m,-g), D h), PBP (1, Psi, SLR, Psi),
      G_YUK_Q (false,g,D h,c,SU,m));
    ((D (-h), Sup (m,g), Chargino cc), BBB (1, Psibar, SLR, Psibar),
      G_YUK_Q (true,g,D h,c,SU,m));
    ((Chargino cc, Sdown (m,-g), U h), FBF (1, Psibar, SLR, Psi),
      G_YUK_Q (true,g,U h,c,SD,m));
    ((U (-h), Sdown (m,g), Chargino c), FBF (1, Psibar, SLR, Psi),
      G_YUK_Q (false,g,U h,c,SD,m)) ]
let yukawa_cq c =
  if Flags.ckm_present then

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List.flatten (Product.list2 (yukawa_cq' c) [(1, 1); (1, 2); (2, 1); (2, 2); (1, 3); (2, 3); (3, 3); (3, 2); (3, 1)] [M
else
List.flatten (Product.list2 (yukawa_cq' c) [(1, 1); (2, 2); (3, 3)] [M1; M2])

** REVISÉD: Compatible with CD+. Remark: Singlet and octet gluon ex-
change. The coupling is divided by sqrt(2) to account for the correct normal-
ization of the Lie algebra generators. **FB

let col_currents g =
[ ((D (-g), Gl, D g), FBF ((-1), Psibar, V, Psi), Gs);
  ((U (-g), Gl, U g), FBF ((-1), Psibar, V, Psi), Gs)]

** REVISÉD: Compatible with CD+. Remark: Singlet and octet gluon ex-
change. The coupling is divided by sqrt(2) to account for the correct normal-
ization of the Lie algebra generators. **FB

let chg = function
| M1 → M2 | M2 → M1

let col_sfermion_currents g m =
[ ((Gl, Sup (m, -g), Sup (m, g)), Vector_Scalar_Scalar (-1), Gs);
  ((Gl, Sdown (m, -g), Sdown (m, g)), Vector_Scalar_Scalar (-1), Gs)]

** REVISÉD: Compatible with CD+. **FB

let triple_gauge =
[ ((Ga, Wm, Wp), Gauge_Gauge_Gauge 1, I_Q_W);
  ((Z, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_ZWW);
  ((Gl, Gl, Gl), Gauge_Gauge_Gauge 1, I_G_S)]

** REVISÉD: Independent of the sign of CD. **FB

let gauge4 = Vector4 [(2, C_13_42); (-1, C_12_34); (-1, C_14_23)]
let minus_gauge4 = Vector4 [(-2, C_13_42); (1, C_12_34); (1, C_14_23)]
let quartic_gauge =
[ (Wm, Wp, Wm, Wp), gauge4, G_WWWW;
  (Wm, Z, Wp, Z), minus_gauge4, G_ZZWW;
  (Wm, Z, Wp, Ga), minus_gauge4, G_PZWW;
  (Wm, Ga, Wp, Ga), minus_gauge4, G_PPWW;
  (Gl, Gl, Gl, Gl), gauge4, G_SS]

The Scalar_Vector_Vector couplings do not depend on the choice of the sign of
the covariant derivative since they are quadratic in the gauge couplings.
* Effective Higgs-Gluon-Gluon coupling. *

let gauge_higgs_GlGlS s =
((SHiggs s, Gl, Gl), Dim5_Scalar_Gauge2 1, G_GLUGLUH0 s)
let gauge_higgs_GlGlP p =
((PHiggs p, Gl, Gl), Dim5_Scalar_Gauge2_Skew 1, G_GLUGLUA0 p)

** REVISÉD: Compatible with CD+. FB**
** Revision: 2005-03-10: first two vertices corrected. **
** REVISÉD: Compact version using new COMBOS
** REVISÉD: Couplings adjusted to FF-convention

let gauge_higgs_WPC p =
[ ((Wm, Hp, PHiggs p), Vector_Scalar_Scalar 1, G_GH_WPC p);

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      ((Wp, Hm, PHiggs p), Vector_Scalar_Scalar 1, G_GH_WPC p)]
let gauge_higgs_WSC s =
  [((Wm, Hp, SHiggs s), Vector_Scalar_Scalar 1, G_GH_WSC s);
   ((Wp, Hm, SHiggs s), Vector_Scalar_Scalar (-1), G_GH_WSC s)]
let gauge_higgs_ZSP s p =
  [((Z, SHiggs s, PHiggs p), Vector_Scalar_Scalar 1, G_GH_ZSP (s, p))]
let gauge_higgs_WWS s =
  ((SHiggs s, Wp, Wm), Scalar_Vector_Vector 1, G_GH_WWS s)
let gauge_higgs_ZZS s =
  ((SHiggs s, Z, Z), Scalar_Vector_Vector 1, G_GH_ZZS s)
let gauge_higgs_ZCC =
  ((Z, Hp, Hm), Vector_Scalar_Scalar 1, G_GH_ZCC )
let gauge_higgs_GaCC =
  ((Ga, Hp, Hm), Vector_Scalar_Scalar 1, G_GH_GaCC )

let gauge_higgs =
  ThoList.flatmap gauge_higgs_WPC [P1; P2] @
  ThoList.flatmap gauge_higgs_WSC [S1; S2; S3] @
  List.flatten (Product.list2 gauge_higgs_ZSP [S1; S2; S3] [P1; P2]) @
  List.map gauge_higgs_WWS [S1; S2; S3] @
  List.map gauge_higgs_ZZS [S1; S2; S3] @
  [gauge_higgs_ZCC] @ [gauge_higgs_GaCC] @
  (if Flags.higgs_triangle then
    List.map gauge_higgs_GIGIS [S1; S2; S3] @
    List.map gauge_higgs_GIGIP [P1; P2]
  else
    [])

** REVISED: Compact version using new COMBOS
** REVISED: Couplings adjusted to FF-convention

let gauge_higgs4_ZZPP (p1, p2) =
  ((PHiggs p1, PHiggs p2, Z, Z), Scalar2_Vector2 1, G_GH4_ZZPP (p1, p2))

let gauge_higgs4_ZZSS (s1, s2) =
  ((SHiggs s1, SHiggs s2, Z, Z), Scalar2_Vector2 1, G_GH4_ZZSS (s1, s2))

let gauge_higgs4_ZZCC =
  ((Hp, Hm, Z, Z), Scalar2_Vector2 1, G_GH4_ZZCC)

let gauge_higgs4_GaGaCC =
  ((Hp, Hm, Ga, Ga), Scalar2_Vector2 1, G_GH4_GaGaCC)

let gauge_higgs4_ZGaCC =
  ((Hp, Hm, Ga, Z), Scalar2_Vector2 1, G_GH4_ZGaCC )

let gauge_higgs4_WWCC =
  ((Hp, Hm, Wp, Wm), Scalar2_Vector2 1, G_GH4_WWCC )

let gauge_higgs4_WWPP (p1, p2) =
  ((PHiggs p1, PHiggs p2, Wp, Wm), Scalar2_Vector2 1, G_GH4_WWPP (p1, p2))

let gauge_higgs4_WWSS (s1, s2) =
  ((SHiggs s1, SHiggs s2, Wp, Wm), Scalar2_Vector2 1, G_GH4_WWSS (s1, s2))

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let gauge_higgs4_ZWSC s =
  [ ((Hp, SHiggs s, Wm, Z), Scalar2_Vector2 1, G_GH4_ZWSC s);
    ((Hm, SHiggs s, Wp, Z), Scalar2_Vector2 1, G_GH4_ZWSC s)]

let gauge_higgs4_GaWSC s =
  [ ((Hp, SHiggs s, Wm, Ga), Scalar2_Vector2 1, G_GH4_GaWSC s);
    ((Hm, SHiggs s, Wp, Ga), Scalar2_Vector2 1, G_GH4_GaWSC s)]

let gauge_higgs4_ZWPC p =
  [ ((Hp, PHiggs p, Wm, Z), Scalar2_Vector2 1, G_GH4_ZWPC p);
    ((Hm, PHiggs p, Wp, Z), Scalar2_Vector2 (-1), G_GH4_ZWPC p)]

let gauge_higgs4_GaWPC p =
  [ ((Hp, PHiggs p, Wm, Ga), Scalar2_Vector2 1, G_GH4_GaWPC p);
    ((Hm, PHiggs p, Wp, Ga), Scalar2_Vector2 (-1), G_GH4_GaWPC p)]

let gauge_higgs4 =
  List.map gauge_higgs4_ZZPP (pairs [P1; P2]) @
  List.map gauge_higgs4_ZZSS (pairs [S1; S2; S3]) @
  [gauge_higgs4_ZZCC] @ [gauge_higgs4_GaGaCC] @
  [gauge_higgs4_ZGaCC] @ [gauge_higgs4_WWCC] @
  List.map gauge_higgs4_WWPP (pairs [P1; P2]) @
  List.map gauge_higgs4_WWSS (pairs [S1; S2; S3]) @
  ThoList.flatmap gauge_higgs4_ZWSC [S1; S2; S3] @
  ThoList.flatmap gauge_higgs4_GaWSC [S1; S2; S3] @
  ThoList.flatmap gauge_higgs4_ZWPC [P1; P2] @
  ThoList.flatmap gauge_higgs4_GaWPC [P1; P2]
*****FB***

let gauge_sfermion4' g m1 m2 =
  [ ((Wp, Wm, Slepton (m1, g), Slepton (m2, -g)), Scalar2_Vector2 1,
    G_WWSFSF (SL, g, m1, m2));
    ((Z, Ga, Slepton (m1, g), Slepton (m2, -g)), Scalar2_Vector2 1,
    G_ZPSFSF (SL, g, m1, m2));
    ((Z, Z, Slepton (m1, g), Slepton (m2, -g)), Scalar2_Vector2 1,
    G_ZZSFSF (SL, g, m1, m2));
    ((Wp, Wm, Sup (m1, g), Sup (m2, -g)), Scalar2_Vector2 1, G_WWSFSF
    (SU, g, m1, m2));
    ((Wp, Wm, Sdown (m1, g), Sdown (m2, -g)), Scalar2_Vector2 1,
    G_WWSFSF (SD, g, m1, m2));
    ((Z, Z, Sup (m1, g), Sup (m2, -g)), Scalar2_Vector2 1, G_ZZSFSF
    (SU, g, m1, m2));
    ((Z, Z, Sdown (m1, g), Sdown (m2, -g)), Scalar2_Vector2 1, G_ZZSFSF
    (SD, g, m1, m2));
    ((Z, Ga, Sup (m1, g), Sup (m2, -g)), Scalar2_Vector2 1, G_ZPSFSF
    (SU, g, m1, m2));
    ((Z, Ga, Sdown (m1, g), Sdown (m2, -g)), Scalar2_Vector2 1, G_ZPSFSF
    (SD, g, m1, m2)) ]

let gauge_sfermion4'' g m =
  [ ((Wp, Ga, Slepton (m, g), Sneutrino (-g)), Scalar2_Vector2 1,
    G_WPSLSN (false, g, m));
    ((Wm, Ga, Slepton (m, -g), Sneutrino g), Scalar2_Vector2 1,

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      G_WPSLSN (true,g,m));
    ((Wp, Z, Slepton (m,g), Sneutrino (-g)), Scalar2_Vector2 1,
      G_WZSLSN(false,g,m));
    ((Wm, Z, Slepton (m,-g), Sneutrino g), Scalar2_Vector2 1,
      G_WZSLSN (true,g,m));
    ((Ga, Ga, Slepton (m,g), Slepton (m,-g)), Scalar2_Vector2 1,
      G_PPSFSF SL);
    ((Ga, Ga, Sup (m,g), Sup (m,-g)), Scalar2_Vector2 1, G_PPSFSF SU);
    ((Ga, Ga, Sdown (m,g), Sdown (m,-g)), Scalar2_Vector2 1, G_PPSFSF SD)]

let gauge_sfermion4 g =
  List.flatten (Product.list2 (gauge_sfermion4' g) [M1;M2] [M1;M2]) @
  ThoList.flatmap (gauge_sfermion4'' g) [M1;M2] @
  [ ((Wp, Wm, Sneutrino g, Sneutrino (-g)), Scalar2_Vector2 1, G_WWSFSF
    (SN,g,M1,M1));
    ((Z, Z, Sneutrino g, Sneutrino (-g)), Scalar2_Vector2 1, G_ZZSFSF
    (SN,g,M1,M1)) ]

** Added by Felix Braam. **

let gauge_squark4'' g h m1 m2 =
  [ ((Wp, Ga, Sup (m1,-g), Sdown (m2,h)), Scalar2_Vector2 1, G_WPSUSD
    (false,m1,m2,g,h));
    ((Wm, Ga, Sup (m1,g), Sdown (m2,-h)), Scalar2_Vector2 1, G_WPSUSD
    (true,m1,m2,g,h));
    ((Wp, Z, Sup (m1,-g), Sdown (m2,h)), Scalar2_Vector2 1, G_WZSUSD
    (false,m1,m2,g,h));
    ((Wm, Z, Sup (m1,g), Sdown (m2,-h)), Scalar2_Vector2 1, G_WZSUSD
    (true,m1,m2,g,h)) ]
let gauge_squark4' g h = List.flatten (Product.list2 (gauge_squark4'' g h)
  [M1;M2] [M1;M2])

let gauge_squark4 =
  if Flags.ckm_present then
    List.flatten (Product.list2 gauge_squark4' [1;2;3] [1;2;3])
  else
    ThoList.flatmap (fun g → gauge_squark4' g g) [1;2;3]

*****FB*****

let gluon_w_squark'' g h m1 m2 =
  [ ((Gl, Wp, Sup (m1,-g), Sdown (m2,h)),
    Scalar2_Vector2 1, G_GlWSUSD (false,m1,m2,g,h));
    ((Gl, Wm, Sup (m1,g), Sdown (m2,-h)),
    Scalar2_Vector2 1, G_GlWSUSD (true,m1,m2,g,h)) ]
let gluon_w_squark' g h =
  List.flatten (Product.list2 (gluon_w_squark'' g h) [M1;M2] [M1;M2])
let gluon_w_squark =
  if Flags.ckm_present then
    List.flatten (Product.list2 gluon_w_squark' [1;2;3] [1;2;3])
  else
    ThoList.flatmap (fun g → gluon_w_squark' g g) [1;2;3]

*****FB*****

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let gluon_gauge_squark' g m1 m2 =
  [ ((Gl, Z, Sup (m1, g), Sup (m2, -g)),
      Scalar2_Vector2 2, G_GLZSFSF (SU, g, m1, m2));
    ((Gl, Z, Sdown (m1, g), Sdown (m2, -g)),
      Scalar2_Vector2 2, G_GLZSFSF (SD, g, m1, m2)) ]
let gluon_gauge_squark'' g m =
  [ ((Gl, Ga, Sup (m, g), Sup (m, -g)), Scalar2_Vector2 2, G_GLPSQSQ);
    ((Gl, Ga, Sdown (m, g), Sdown (m, -g)), Scalar2_Vector2 (-1), G_GLPSQSQ) ]
let gluon_gauge_squark g =
  List.flatten (Product.list2 (gluon_gauge_squark' g) [M1; M2] [M1; M2]) @
  ThoList.flatmap (gluon_gauge_squark'' g) [M1; M2]
(******FB******)
let gluon2_squark2' g m =
  [ ((Gl, Gl, Sup (m, g), Sup (m, -g)), Scalar2_Vector2 2, G_GLGLSQSQ);
    ((Gl, Gl, Sdown (m, g), Sdown (m, -g)), Scalar2_Vector2 2, G_GLGLSQSQ) ]
let gluon2_squark2 g =
  ThoList.flatmap (gluon2_squark2' g) [M1; M2]
** REVISED: Independent of the sign of CD. *FB*
** REVISED: Compact version using new COMBOS
** REVISED: Couplings adjusted to FF-convention

let higgs_SCC s =
  ((Hp, Hm, SHiggs s), Scalar_Scalar_Scalar 1, G_H3_SCC s)
let higgs_SSS (s1, s2, s3) =
  ((SHiggs s1, SHiggs s2, SHiggs s3), Scalar_Scalar_Scalar 1,
    G_H3_SSS (s1, s2, s3))
let higgs_SPP (p1, p2, s) =
  ((SHiggs s, PHiggs p1, PHiggs p2), Scalar_Scalar_Scalar 1,
    G_H3_SPP (s, p1, p2))

let higgs =
  List.map higgs_SCC [S1; S2; S3] @
  List.map higgs_SSS (triples [S1; S2; S3]) @
  List.map higgs_SPP (two_and_one [P1; P2] [S1; S2; S3])

let higgs4 = []
(* The vertices of the type Higgs - Sfermion - Sfermion are independent of the
choice of the CD sign since they are quadratic in the gauge coupling. *)
** REVISED: Independent of the sign of CD. **

let higgs_sneutrino' s g =
  ((SHiggs s, Sneutrino g, Sneutrino (-g)), Scalar_Scalar_Scalar 1,
    G_SFSSFS (s, SN, g, M1, M1))
let higgs_sneutrino'' g m =
  [ ((Hp, Sneutrino (-g), Slepton (m, g)), Scalar_Scalar_Scalar 1,
      G_HSNSL (false, g, m));
    ((Hm, Sneutrino g, Slepton (m, -g)), Scalar_Scalar_Scalar 1,
      G_HSNSL (true, g, m))]
let higgs_sneutrino =
  Product.list2 higgs_sneutrino' [S1; S2; S3] [1; 2; 3] @

```

*List.flatten ( Product.list2 higgs\_sneutrino'' [1; 2; 3] [M1; M2] )*

Under the assumption that there is no mixing between the left- and right-handed sfermions for the first two generations there is only a coupling of the form Higgs - sfermion1 - sfermion2 for the third generation. All the others are suppressed by  $m_f/M_W$ .

\*\* REVISED: Independent of the sign of CD. \*\*

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let higgs_sfermion_S s g m1 m2 =
  [ ((SHiggs s, Slepton (m1, g), Slepton (m2, -g)), Scalar_Scalar_Scalar 1,
      G_SFSFS (s, SL, g, m1, m2));
    ((SHiggs s, Sup (m1, g), Sup (m2, -g)), Scalar_Scalar_Scalar 1,
      G_SFSFS (s, SU, g, m1, m2));
    ((SHiggs s, Sdown (m1, g), Sdown (m2, -g)), Scalar_Scalar_Scalar 1,
      G_SFSFS (s, SD, g, m1, m2))]

let higgs_sfermion' g m1 m2 =
  (higgs_sfermion_S S1 g m1 m2) @ (higgs_sfermion_S S2 g m1 m2) @ (higgs_sfermion_S S3 g m1 m2)

let higgs_sfermion_P p g m1 m2 =
  [ ((PHiggs p, Slepton (m1, g), Slepton (m2, -g)), Scalar_Scalar_Scalar 1,
      G_SFSFP (p, SL, g, m1, m2));
    ((PHiggs p, Sup (m1, g), Sup (m2, -g)), Scalar_Scalar_Scalar 1,
      G_SFSFP (p, SU, g, m1, m2));
    ((PHiggs p, Sdown (m1, g), Sdown (m2, -g)), Scalar_Scalar_Scalar 1,
      G_SFSFP (p, SD, g, m1, m2)) ]

let higgs_sfermion'' g m1 m2 =
  (higgs_sfermion_P P1 g m1 m2) @ (higgs_sfermion_P P2 g m1 m2)
let higgs_sfermion = List.flatten (Product.list3 higgs_sfermion' [1; 2; 3] [M1; M2] [M1; M2]) @
  List.flatten (Product.list3 higgs_sfermion'' [1; 2; 3] [M1; M2] [M1; M2])

** REVISED: Independent of the sign of CD. **

let higgs_squark' g h m1 m2 =
  [ ((Hp, Sup (m1, -g), Sdown (m2, h)), Scalar_Scalar_Scalar 1,
      G_HSUSD (false, m1, m2, g, h));
    ((Hm, Sup (m1, g), Sdown (m2, -h)), Scalar_Scalar_Scalar 1,
      G_HSUSD (true, m1, m2, g, h)) ]

let higgs_squark_a g h = higgs_squark' g h M1 M1
let higgs_squark_b (g, h) = List.flatten (Product.list2 (higgs_squark' g h)
  [M1; M2] [M1; M2])

let higgs_squark =
  if Flags.ckm_present then
    List.flatten (Product.list2 higgs_squark_a [1; 2] [1; 2]) @
    ThoList.flatmap higgs_squark_b [(1, 3); (2, 3); (3, 3); (3, 1); (3, 2)]
  else
    higgs_squark_a 1 1 @ higgs_squark_a 2 2 @ higgs_squark_b (3, 3)

let vertices3 =
  (ThoList.flatmap electromagnetic_currents_3 [1; 2; 3] @
    ThoList.flatmap electromagnetic_currents_2 [C1; C2] @
    List.flatten (Product.list2 electromagnetic_sfermion_currents [1; 2; 3]
  [M1; M2]) @

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    ThoList.flatmap neutral_currents [1; 2; 3] @
    ThoList.flatmap neutral_sfermion_currents [1; 2; 3] @
    ThoList.flatmap charged_currents [1; 2; 3] @
    List.flatten (Product.list2 charged_slepton_currents [1; 2; 3]
                  [M1; M2]) @
  (if Flags.ckm-present then
    List.flatten (Product.list2 charged_quark_currents [1; 2; 3]
                      [1; 2; 3]) @
    List.flatten (Product.list2 charged_squark_currents [1; 2; 3]
                      [1; 2; 3]) @
    ThoList.flatmap yukawa_higgs_quark [(1, 3); (2, 3); (3, 3); (3, 1); (3, 2)]
  else
    charged_quark_currents 1 1 @
    charged_quark_currents 2 2 @
    charged_quark_currents 3 3 @
    charged_squark_currents 1 1 @
    charged_squark_currents 2 2 @
    charged_squark_currents 3 3 @
    ThoList.flatmap yukawa_higgs_quark [(3, 3)] @
    yukawa_higgs 3 @ yukawa_n @
    ThoList.flatmap yukawa_c [C1; C2] @
    ThoList.flatmap yukawa_cq [C1; C2] @
    List.flatten (Product.list2 charged_chargino_currents [N1; N2; N3; N4; N5]
                  [C1; C2]) @ triple_gauge @
    ThoList.flatmap neutral_Z (pairs [N1; N2; N3; N4; N5]) @
    Product.list2 charged_Z [C1; C2] [C1; C2] @
    gauge_higgs @ higgs @ yukawa_higgs_2 @
    List.flatten (Product.list2 higgs_charg_neutr [N1; N2; N3; N4; N5] [C1; C2]) @
    higgs_neutr @ higgs_sneutrino @ higgs_sfermion @
    higgs_squark @ yukawa_v @
    ThoList.flatmap col_currents [1; 2; 3] @
    List.flatten (Product.list2 col_sfermion_currents [1; 2; 3] [M1; M2]))

let vertices4 =
  (quartic_gauge @ higgs4 @ gauge_higgs4 @
   ThoList.flatmap gauge_sfermion4 [1; 2; 3] @
   gauge_squark4 @ gluon_w_squark @
   ThoList.flatmap gluon2_squark2 [1; 2; 3] @
   ThoList.flatmap gluon_gauge_squark [1; 2; 3])

let vertices () = (vertices3, vertices4, [])

let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 4

```

SLHA2-Nomenclature for neutral Higgses

```

let flavor_of_string s =
  match s with
  | "e-" → L 1 | "e+" → L (-1)

```

```

| "mu-" → L 2 | "mu+" → L (-2)
| "tau-" → L 3 | "tau+" → L (-3)
| "nue" → N 1 | "nuebar" → N (-1)
| "numu" → N 2 | "numubar" → N (-2)
| "nutau" → N 3 | "nutaubar" → N (-3)
| "se1-" → Slepton (M1,1) | "se1+" → Slepton (M1,-1)
| "smu1-" → Slepton (M1,2) | "smu1+" → Slepton (M1,-2)
| "stau1-" → Slepton (M1,3) | "stau1+" → Slepton (M1,-3)
| "se2-" → Slepton (M2,1) | "se2+" → Slepton (M2,-1)
| "smu2-" → Slepton (M2,2) | "smu2+" → Slepton (M2,-2)
| "stau2-" → Slepton (M2,3) | "stau2+" → Slepton (M2,-3)
| "snue" → Sneutrino 1 | "snue*" → Sneutrino (-1)
| "snumu" → Sneutrino 2 | "snumu*" → Sneutrino (-2)
| "snutau" → Sneutrino 3 | "snutau*" → Sneutrino (-3)
| "u" → U 1 | "ubar" → U (-1)
| "c" → U 2 | "cbar" → U (-2)
| "t" → U 3 | "tbar" → U (-3)
| "d" → D 1 | "dbar" → D (-1)
| "s" → D 2 | "sbar" → D (-2)
| "b" → D 3 | "bbar" → D (-3)
| "A" → Ga | "Z" | "Z0" → Z
| "W+" → Wp | "W-" → Wm
| "g1" | "g" → Gl
| "h01" → SHiggs S1 | "h02" → SHiggs S2 | "h03" →
SHiggs S3
| "A01" → PHiggs P1 | "A02" → PHiggs P2
| "H+" → Hp | "H-" → Hm
| "su1" → Sup (M1,1) | "su1c" → Sup (M1,-1)
| "sc1" → Sup (M1,2) | "sc1c" → Sup (M1,-2)
| "st1" → Sup (M1,3) | "st1c" → Sup (M1,-3)
| "su2" → Sup (M2,1) | "su2c" → Sup (M2,-1)
| "sc2" → Sup (M2,2) | "sc2c" → Sup (M2,-2)
| "st2" → Sup (M2,3) | "st2c" → Sup (M2,-3)
| "sg1" | "sg" → Gluino
| "sd1" → Sdown (M1,1) | "sd1c" → Sdown (M1,-1)
| "ss1" → Sdown (M1,2) | "ss1c" → Sdown (M1,-2)
| "sb1" → Sdown (M1,3) | "sb1c" → Sdown (M1,-3)
| "sd2" → Sdown (M2,1) | "sd2c" → Sdown (M2,-1)
| "ss2" → Sdown (M2,2) | "ss2c" → Sdown (M2,-2)
| "sb2" → Sdown (M2,3) | "sb2c" → Sdown (M2,-3)
| "neu1" → Neutralino N1 | "neu2" → Neutralino N2
| "neu3" → Neutralino N3 | "neu4" → Neutralino N4
| "neu5" → Neutralino N5
| "ch1+" → Chargino C1 | "ch2+" → Chargino C2
| "ch1-" → Chargino C1c | "ch2-" → Chargino C2c
| s → invalid_arg ("Fatal error: %s\Modellib_NMSSM.NMSSM.flavor_of_string:" ^ s)

let flavor_to_string = function
| L 1 → "e-" | L (-1) → "e+"
| L 2 → "mu-" | L (-2) → "mu+"

```

```

| L 3 → "tau-" | L (-3) → "tau+"
| N 1 → "nue" | N (-1) → "nuebar"
| N 2 → "numu" | N (-2) → "numubar"
| N 3 → "nutau" | N (-3) → "nutaubar"
| U 1 → "u" | U (-1) → "ubar"
| U 2 → "c" | U (-2) → "cbar"
| U 3 → "t" | U (-3) → "tbar"
| U _ → invalid_arg
| "Modellib_NMSSM.NMSSM.flavor_to_string:_invalid_up_type_quark"
| D 1 → "d" | D (-1) → "dbar"
| D 2 → "s" | D (-2) → "sbar"
| D 3 → "b" | D (-3) → "bbar"
| D _ → invalid_arg
| "Modellib_NMSSM.NMSSM.flavor_to_string:_invalid_down_type_quark"
| Gl → "gl" | Gluino → "sgl"
| Ga → "A" | Z → "Z"
| Wp → "W+" | Wm → "W-"
| SHiggs S1 → "h01" | SHiggs S2 → "h02" | SHiggs S3 → "h03"
| PHiggs P1 → "A01" | PHiggs P2 → "A02"
| Hp → "H+" | Hm → "H-"
| Slepton (M1,1) → "se1-" | Slepton (M1,-1) → "se1+"
| Slepton (M1,2) → "smu1-" | Slepton (M1,-2) → "smu1+"
| Slepton (M1,3) → "stau1-" | Slepton (M1,-3) → "stau1+"
| Slepton (M2,1) → "se2-" | Slepton (M2,-1) → "se2+"
| Slepton (M2,2) → "smu2-" | Slepton (M2,-2) → "smu2+"
| Slepton (M2,3) → "stau2-" | Slepton (M2,-3) → "stau2+"
| Sneutrino 1 → "snue" | Sneutrino (-1) → "snue*"
| Sneutrino 2 → "snumu" | Sneutrino (-2) → "snumu*"
| Sneutrino 3 → "snutau" | Sneutrino (-3) → "snutau*"
| Sup (M1,1) → "su1" | Sup (M1,-1) → "su1c"
| Sup (M1,2) → "sc1" | Sup (M1,-2) → "sc1c"
| Sup (M1,3) → "st1" | Sup (M1,-3) → "st1c"
| Sup (M2,1) → "su2" | Sup (M2,-1) → "su2c"
| Sup (M2,2) → "sc2" | Sup (M2,-2) → "sc2c"
| Sup (M2,3) → "st2" | Sup (M2,-3) → "st2c"
| Sdown (M1,1) → "sd1" | Sdown (M1,-1) → "sd1c"
| Sdown (M1,2) → "ss1" | Sdown (M1,-2) → "ss1c"
| Sdown (M1,3) → "sb1" | Sdown (M1,-3) → "sb1c"
| Sdown (M2,1) → "sd2" | Sdown (M2,-1) → "sd2c"
| Sdown (M2,2) → "ss2" | Sdown (M2,-2) → "ss2c"
| Sdown (M2,3) → "sb2" | Sdown (M2,-3) → "sb2c"
| Neutralino N1 → "neu1"
| Neutralino N2 → "neu2"
| Neutralino N3 → "neu3"
| Neutralino N4 → "neu4"
| Neutralino N5 → "neu5"
| Chargino C1 → "ch1+" | Chargino C1c → "ch1-"
| Chargino C2 → "ch2+" | Chargino C2c → "ch2-"
| _ → invalid_arg "Modellib_NMSSM.NMSSM.flavor_to_string"

```

```

let flavor_to_TeX = function
| L 1 → "e^--" | L (-1) → "e^+"
| L 2 → "\\mu^--" | L (-2) → "\\mu^+"
| L 3 → "\\tau^--" | L (-3) → "\\tau^+"
| N 1 → "\\nu_e" | N (-1) → "\\bar{\\nu}_e"
| N 2 → "\\nu_\\mu" | N (-2) → "\\bar{\\nu}_\\mu"
| N 3 → "\\nu_\\tau" | N (-3) → "\\bar{\\nu}_\\tau"
| U 1 → "u" | U (-1) → "\\bar{u}"
| U 2 → "c" | U (-2) → "\\bar{c}"
| U 3 → "t" | U (-3) → "\\bar{t}"
| D 1 → "d" | D (-1) → "\\bar{d}"
| D 2 → "s" | D (-2) → "\\bar{s}"
| D 3 → "b" | D (-3) → "\\bar{b}"
| L _ → invalid_arg
      "Modellib_NMSSM.flavor_to_TeX: invalid lepton"
| N _ → invalid_arg
      "Modellib_NMSSM.flavor_to_TeX: invalid neutrino"
| U _ → invalid_arg
      "Modellib_NMSSM.flavor_to_TeX: invalid up type quark"
| D _ → invalid_arg
      "Modellib_NMSSM.flavor_to_TeX: invalid down type quark"
| Gl → "g" | Gluino → "\\widetilde{g}"
| Ga → "\\gamma" | Z → "Z" | Wp → "W^+" | Wm → "W^- "
| SHiggs S1 → "S_1" | SHiggs S2 → "S_2" | SHiggs S3 → "S_3"
| PHiggs P1 → "P_1" | PHiggs P2 → "P_2"
| Hp → "H^+" | Hm → "H^- "
| Slepton (M1,1) → "\\widetilde{e}_1^- "
| Slepton (M1,-1) → "\\widetilde{e}_1^+ "
| Slepton (M1,2) → "\\widetilde{\\mu}_1^- "
| Slepton (M1,-2) → "\\widetilde{\\mu}_1^+ "
| Slepton (M1,3) → "\\widetilde{\\tau}_1^- "
| Slepton (M1,-3) → "\\widetilde{\\tau}_1^+ "
| Slepton (M2,1) → "\\widetilde{e}_2^- "
| Slepton (M2,-1) → "\\widetilde{e}_2^+ "
| Slepton (M2,2) → "\\widetilde{\\mu}_2^- "
| Slepton (M2,-2) → "\\widetilde{\\mu}_2^+ "
| Slepton (M2,3) → "\\widetilde{\\tau}_2^- "
| Slepton (M2,-3) → "\\widetilde{\\tau}_2^+ "
| Sneutrino 1 → "\\widetilde{\\nu}_e"
| Sneutrino (-1) → "\\widetilde{\\nu}_e^*"
| Sneutrino 2 → "\\widetilde{\\nu}_\\mu"
| Sneutrino (-2) → "\\widetilde{\\nu}_\\mu^*"
| Sneutrino 3 → "\\widetilde{\\nu}_\\tau"
| Sneutrino (-3) → "\\widetilde{\\nu}_\\tau^*"
| Sup (M1,1) → "\\widetilde{u}_1"
| Sup (M1,-1) → "\\widetilde{u}_1^*"
| Sup (M1,2) → "\\widetilde{c}_1"
| Sup (M1,-2) → "\\widetilde{c}_1^*"
| Sup (M1,3) → "\\widetilde{t}_1"
| Sup (M1,-3) → "\\widetilde{t}_1^*"

```



---

```

| Sup (M2,1) → "\\widetilde{u}_{-2}"
| Sup (M2,-1) → "\\widetilde{u}_{-2}*"
| Sup (M2,2) → "\\widetilde{c}_{-2}"
| Sup (M2,-2) → "\\widetilde{c}_{-2}*"
| Sup (M2,3) → "\\widetilde{t}_{-2}"
| Sup (M2,-3) → "\\widetilde{t}_{-2}*"
| Sdown (M1,1) → "\\widetilde{d}_{-1}"
| Sdown (M1,-1) → "\\widetilde{d}_{-1}*"
| Sdown (M1,2) → "\\widetilde{s}_{-1}"
| Sdown (M1,-2) → "\\widetilde{s}_{-1}*"
| Sdown (M1,3) → "\\widetilde{b}_{-1}"
| Sdown (M1,-3) → "\\widetilde{b}_{-1}*"
| Sdown (M2,1) → "\\widetilde{d}_{-2}"
| Sdown (M2,-1) → "\\widetilde{d}_{-2}*"
| Sdown (M2,2) → "\\widetilde{s}_{-2}"
| Sdown (M2,-2) → "\\widetilde{s}_{-2}*"
| Sdown (M2,3) → "\\widetilde{b}_{-2}"
| Sdown (M2,-3) → "\\widetilde{b}_{-2}*"
| Neutralino N1 → "\\widetilde{\\chi}^0_1"
| Neutralino N2 → "\\widetilde{\\chi}^0_2"
| Neutralino N3 → "\\widetilde{\\chi}^0_3"
| Neutralino N4 → "\\widetilde{\\chi}^0_4"
| Neutralino N5 → "\\widetilde{\\chi}^0_5"
| Slepton _ → invalid_arg
| "Modellib_NMSSM.NMSSM.flavor_to_TeX:_invalid_slepton"
| Sneutrino _ → invalid_arg
| "Modellib_NMSSM.NMSSM.flavor_to_TeX:_invalid_sneutrino"
| Sup _ → invalid_arg
| "Modellib_NMSSM.NMSSM.flavor_to_TeX:_invalid_up_type_squark"
| Sdown _ → invalid_arg
| "Modellib_NMSSM.NMSSM.flavor_to_TeX:_invalid_down_type_squark"
| Chargino C1 → "\\widetilde{\\chi}^{-1}_+"
| Chargino C1c → "\\widetilde{\\chi}^{-1}_-"
| Chargino C2 → "\\widetilde{\\chi}^{-2}_+"
| Chargino C2c → "\\widetilde{\\chi}^{-2}_-"

```

```
let flavor_symbol = function
```

```

| L g when g > 0 → "l" ^ string_of_int g
| L g → "l" ^ string_of_int (abs g) ^ "b"
| N g when g > 0 → "n" ^ string_of_int g
| N g → "n" ^ string_of_int (abs g) ^ "b"
| U g when g > 0 → "u" ^ string_of_int g
| U g → "u" ^ string_of_int (abs g) ^ "b"
| D g when g > 0 → "d" ^ string_of_int g
| D g → "d" ^ string_of_int (abs g) ^ "b"
| Gl → "gl"
| Ga → "a" | Z → "z"
| Wp → "wp" | Wm → "wm"
| Slepton (M1,g) when g > 0 → "s1l" ^ string_of_int g
| Slepton (M1,g) → "s1lc" ^ string_of_int (abs g)

```

```

| Slepton (M2, g) when g > 0 → "s12" ^ string_of_int g
| Slepton (M2, g) → "s12c" ^ string_of_int (abs g)
| Sneutrino g when g > 0 → "sn" ^ string_of_int g
| Sneutrino g → "snc" ^ string_of_int (abs g)
| Sup (M1, g) when g > 0 → "su1" ^ string_of_int g
| Sup (M1, g) → "su1c" ^ string_of_int (abs g)
| Sup (M2, g) when g > 0 → "su2" ^ string_of_int g
| Sup (M2, g) → "su2c" ^ string_of_int (abs g)
| Sdown (M1, g) when g > 0 → "sd1" ^ string_of_int g
| Sdown (M1, g) → "sd1c" ^ string_of_int (abs g)
| Sdown (M2, g) when g > 0 → "sd2" ^ string_of_int g
| Sdown (M2, g) → "sd2c" ^ string_of_int (abs g)
| Neutralino n → "neu" ^ (string_of_neu n)
| Chargino c when (int_of_char c) > 0 → "cp" ^ string_of_char c
| Chargino c → "cm" ^ string_of_int (abs (int_of_char c))
| Gluino → "sg1"
| SHiggs s → "h0" ^ (string_of_shiggs s)
| PHiggs p → "A0" ^ (string_of_phiggs p)
| Hp → "hp" | Hm → "hm"

let pdg = function
| L g when g > 0 → 9 + 2 × g
| L g → - 9 + 2 × g
| N g when g > 0 → 10 + 2 × g
| N g → - 10 + 2 × g
| U g when g > 0 → 2 × g
| U g → 2 × g
| D g when g > 0 → - 1 + 2 × g
| D g → 1 + 2 × g
| Gl → 21
| Ga → 22 | Z → 23
| Wp → 24 | Wm → (-24)
| SHiggs S1 → 25 | SHiggs S2 → 35 | SHiggs S3 → 45
| PHiggs P1 → 36 | PHiggs P2 → 46
| Hp → 37 | Hm → (-37)
| Slepton (M1, g) when g > 0 → 1000009 + 2 × g
| Slepton (M1, g) → - 1000009 + 2 × g
| Slepton (M2, g) when g > 0 → 2000009 + 2 × g
| Slepton (M2, g) → - 2000009 + 2 × g
| Sneutrino g when g > 0 → 1000010 + 2 × g
| Sneutrino g → - 1000010 + 2 × g
| Sup (M1, g) when g > 0 → 1000000 + 2 × g
| Sup (M1, g) → - 1000000 + 2 × g
| Sup (M2, g) when g > 0 → 2000000 + 2 × g
| Sup (M2, g) → - 2000000 + 2 × g
| Sdown (M1, g) when g > 0 → 999999 + 2 × g
| Sdown (M1, g) → - 999999 + 2 × g
| Sdown (M2, g) when g > 0 → 1999999 + 2 × g
| Sdown (M2, g) → - 1999999 + 2 × g
| Gluino → 1000021

```

	<i>Chargino C1</i>	→	1000024		<i>Chargino C1c</i>	→	(−1000024)
	<i>Chargino C2</i>	→	1000037		<i>Chargino C2c</i>	→	(−1000037)
	<i>Neutralino N1</i>	→	1000022		<i>Neutralino N2</i>	→	1000023
	<i>Neutralino N3</i>	→	1000025		<i>Neutralino N4</i>	→	1000035
	<i>Neutralino N5</i>	→	1000045				

We must take care of the pdg numbers for the two different kinds of sfermions in the MSSM. The particle data group in its Monte Carlo particle numbering scheme takes only into account mixtures of the third generation squarks and the stau. For the other sfermions we will use the number of the lefthanded field for the lighter mixed state and the one for the righthanded for the heavier. Below are the official pdg numbers from the Particle Data Group. In order not to produce arrays with some million entries in the Fortran code for the masses and the widths we introduce our private pdg numbering scheme which only extends not too far beyond 42. Our private scheme then has the following pdf numbers (for the sparticles the subscripts  $L/R$  and  $1/2$  are taken synonymously):

$d$	down-quark	1
$u$	up-quark	2
$s$	strange-quark	3
$c$	charm-quark	4
$b$	bottom-quark	5
$t$	top-quark	6
$e^-$	electron	11
$\nu_e$	electron-neutrino	12
$\mu^-$	muon	13
$\nu_\mu$	muon-neutrino	14
$\tau^-$	tau	15
$\nu_\tau$	tau-neutrino	16
$g$	gluon	(9) 21
$\gamma$	photon	22
$Z^0$	Z-boson	23
$W^+$	W-boson	24
$h^0$	light Higgs boson	25
$H^0$	heavy Higgs boson	35
$A^0$	pseudoscalar Higgs	36
$H^\pm$	charged Higgs	37
$\tilde{d}_L$	down-squark 1	41
$\tilde{u}_L$	up-squark 1	42
$\tilde{s}_L$	strange-squark 1	43
$\tilde{c}_L$	charm-squark 1	44
$\tilde{b}_L$	bottom-squark 1	45
$\tilde{t}_L$	top-squark 1	46
$\tilde{d}_R$	down-squark 2	47
$\tilde{u}_R$	up-squark 2	48
$\tilde{s}_R$	strange-squark 2	49
$\tilde{c}_R$	charm-squark 2	50
$\tilde{b}_R$	bottom-squark 2	51
$\tilde{t}_R$	top-squark 2	52
$\tilde{e}_L$	selectron 1	53
$\tilde{\nu}_{e,L}$	electron-sneutrino	54
$\tilde{\mu}_L$	smuon 1	55
$\tilde{\nu}_{\mu,L}$	muon-sneutrino	56
$\tilde{\tau}_L$	stau 1	57
$\tilde{\nu}_{\tau,L}$	tau-sneutrino	58
$\tilde{e}_R$	selectron 2	59
$\tilde{\mu}_R$	smuon 2	61
$\tilde{\tau}_R$	stau 2	63
$\tilde{g}$	gluino 521	64
$\tilde{\chi}_1^0$	neutralino 1	65
$\tilde{\chi}_2^0$	neutralino 2	66
$\tilde{\chi}_3^0$	neutralino 3	67
$\tilde{\chi}_4^0$	neutralino 4	68
$\tilde{\chi}_5^0$	neutralino 5	69
$\tilde{\chi}_1^\pm$	chargino 1	70

```

let pdg_mw = function
| L g when g > 0 → 9 + 2 × g
| L g → - 9 + 2 × g
| N g when g > 0 → 10 + 2 × g
| N g → - 10 + 2 × g
| U g when g > 0 → 2 × g
| U g → 2 × g
| D g when g > 0 → - 1 + 2 × g
| D g → 1 + 2 × g
| Gl → 21
| Ga → 22 | Z → 23
| Wp → 24 | Wm → (-24)
| SHiggs S1 → 25 | SHiggs S2 → 35 | PHiggs P1 → 36
| Hp → 37 | Hm → (-37)
| Sup (M1, g) when g > 0 → 40 + 2 × g
| Sup (M1, g) → - 40 + 2 × g
| Sup (M2, g) when g > 0 → 46 + 2 × g
| Sup (M2, g) → - 46 + 2 × g
| Sdown (M1, g) when g > 0 → 39 + 2 × g
| Sdown (M1, g) → - 39 + 2 × g
| Sdown (M2, g) when g > 0 → 45 + 2 × g
| Sdown (M2, g) → - 45 + 2 × g
| Slepton (M1, g) when g > 0 → 51 + 2 × g
| Slepton (M1, g) → - 51 + 2 × g
| Slepton (M2, g) when g > 0 → 57 + 2 × g
| Slepton (M2, g) → - 57 + 2 × g
| Sneutrino g when g > 0 → 52 + 2 × g
| Sneutrino g → - 52 + 2 × g
| Gluino → 64
| Chargino C1 → 70 | Chargino C1c → (-70)
| Chargino C2 → 71 | Chargino C2c → (-71)
| Neutralino N1 → 65 | Neutralino N2 → 66
| Neutralino N3 → 67 | Neutralino N4 → 68
| Neutralino N5 → 69
| PHiggs P2 → 72 | SHiggs S3 → 73

let mass_symbol f =
  "mass(" ^ string_of_int (abs (pdg_mw f)) ^ ")"

let width_symbol f =
  "width(" ^ string_of_int (abs (pdg_mw f)) ^ ")"

let conj_symbol = function
| false, str → str
| true, str → str ^ "_c"

let constant_symbol = function
| E → "e" | G → "g"
| Mu → "mu" | Lambda → "lambda" | G_Z → "gz"
| Q_lepton → "qlep" | Q_up → "qup" | Q_down → "qdown"
| Q_charg → "qchar"
| G_NC_lepton → "gnclep" | G_NC_neutrino → "gncneu"

```

---

```

| G_NC_up → "gncup" | G_NC_down → "gncdwn"
| G_CC → "gcc"
| G_CCQ (vc, g1, g2) → conj_symbol (vc, "g-ccq") ^ "(" ^
  string_of_int g1 ^ ", " ^ string_of_int g2 ^ ")"
| I_Q_W → "iqw" | I_G_ZWW → "igzww"
| G_WWWW → "gw4" | G_ZZWW → "gzzww"
| G_PZWW → "gpzww" | G_PPWW → "gppww"
| G_GH4_ZZPP (p1, p2) → "g-ZZAOAO(" ^ string_of_phiggs p1 ^ ", " ^
  string_of_phiggs p2 ^ ")"
| G_GH4_ZZSS (s1, s2) → "g-ZZh0h0(" ^ string_of_shiggs s1 ^ ", " ^
  string_of_shiggs s2 ^ ")"
| G_GH4_ZZCC → "g-zzhphm"
| G_GH4_GaGaCC → "g-AAhphm"
| G_GH4_ZGaCC → "g-zAhphm"
| G_GH4_WWCC → "g-wwhphm"
| G_GH4_WWPP (p1, p2) → "g-WWAOAO(" ^ string_of_phiggs p1 ^ ", " ^
  string_of_phiggs p2 ^ ")"
| G_GH4_WWSS (s1, s2) → "g-WWh0h0(" ^ string_of_shiggs s1 ^ ", " ^
  string_of_shiggs s2 ^ ")"
| G_GH4_ZWSC s → "g-ZWhph0(" ^ string_of_shiggs s ^ ")"
| G_GH4_GaWSC s → "g-AWhph0(" ^ string_of_shiggs s ^ ")"
| G_GH4_ZWPC p → "g-ZWhpA0(" ^ string_of_phiggs p ^ ")"
| G_GH4_GaWPC p → "g-AWhpA0(" ^ string_of_phiggs p ^ ")"
| G_CICIS (n1, n2, s) → "g-neuneuh0(" ^ string_of_neu n1 ^ ", " ^
  string_of_neu n2 ^ ", " ^ string_of_shiggs s ^ ")"
| G_CICIP (n1, n2, p) → "g-neuneuA0(" ^ string_of_neu n1 ^ ", " ^
  string_of_neu n2 ^ ", " ^ string_of_phiggs p ^ ")"
| G_H3_SCC s → "g-h0hphm(" ^ string_of_shiggs s ^ ")"
| G_H3_SPP (s, p1, p2) → "g-h0AOAO(" ^ string_of_shiggs s ^ ", " ^
  string_of_phiggs p1 ^ ", " ^ string_of_phiggs p2 ^ ")"
| G_H3_SSS (s1, s2, s3) → "g-h0h0h0(" ^ string_of_shiggs s1 ^ ", " ^
  string_of_shiggs s2 ^ ", " ^ string_of_shiggs s3 ^ ")"
| G_CSC (c1, c2, s) → "g-chchh0(" ^ string_of_char c1 ^ ", " ^
  string_of_char c2 ^ ", " ^ string_of_shiggs s ^ ")"
| G_CPC (c1, c2, p) → "g-chchA0(" ^ string_of_char c1 ^ ", " ^
  string_of_char c2 ^ ", " ^ string_of_phiggs p ^ ")"
| G_YUK_FFS (f1, f2, s) → "g-yuk_h0-" ^ string_of_fermion_type f1 ^
  string_of_fermion_type f2 ^ "(" ^ string_of_shiggs s ^ ", " ^
  string_of_fermion_gen f1 ^ ")"
| G_YUK_FFP (f1, f2, p) → "g-yuk_A0-" ^ string_of_fermion_type f1 ^
  string_of_fermion_type f2 ^ "(" ^ string_of_phiggs p ^ ", " ^
  string_of_fermion_gen f1 ^ ")"
| G_YUK_LCN g → "g-yuk_hp-ln(" ^ string_of_int g ^ ")"
| G_NWC (n, c) → "g-nwc(" ^ string_of_char c ^ ", " ^ string_of_neu n
  ^ ")"
| G_CWN (c, n) → "g-cwn(" ^ string_of_char c ^ ", " ^ string_of_neu n
  ^ ")"
| G_SLSNW (vc, g, m) → conj_symbol (vc, "g-wslsn") ^ "(" ^
  string_of_int g ^ ", " ^ string_of_sfm m ^ ")"
| G_NZN (n1, n2) → "g-zneuneu(" ^ string_of_neu n1 ^ ", "

```

```

      ^ string_of_neu n2 ^ ") "
| G_CZC (c1, c2) → "g-zchch(" ^ string_of_char c1 ^ ", " ^
      string_of_char c2 ^ ") "
| Gs → "gs"
| G_YUK_UCD (n, m) → "g-yuk-hp-ud(" ^ string_of_int n ^ ", " ^
      string_of_int m ^ ") "
| G_YUK_DCU (n, m) → "g-yuk-hm-du(" ^ string_of_int n ^ ", " ^
      string_of_int m ^ ") "
| G_YUK_N (vc, f, n, sf, m) → conj_symbol (vc, "g-yuk-neu-" ^
      string_of_fermion_type f ^ string_of_sff sf) ^ "(" ^
      string_of_fermion_gen f ^ ", " ^ string_of_neu n ^ ", " ^
      string_of_sfm m ^ ") "
| G_YUK_G (vc, f, sf, m) → conj_symbol (vc, "g-yuk-gluino-" ^
      string_of_fermion_type f ^ string_of_sff sf) ^ "(" ^
      string_of_fermion_gen f ^ ", " ^ string_of_sfm m ^ ") "
| G_YUK_C (vc, f, c, sf, m) → conj_symbol (vc, "g-yuk-char-" ^
      string_of_fermion_type f ^ string_of_sff sf) ^ "(" ^
      string_of_fermion_gen f ^ ", " ^ string_of_char c ^ ", " ^
      string_of_sfm m ^ ") "
| G_YUK_Q (vc, g1, f, c, sf, m) → conj_symbol (vc, "g-yuk-char-" ^
      string_of_fermion_type f ^ string_of_sff sf) ^ "(" ^ string_of_int
      g1 ^ ", " ^ string_of_fermion_gen f ^ ", " ^ string_of_char c ^ ", " ^
      string_of_sfm m ^ ") "
| G_WPSUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "g-wA-susd") ^ "(" ^
      string_of_int g1 ^ ", " ^ string_of_int g2 ^ ", " ^ string_of_sfm m1 ^
      ", " ^ string_of_sfm m2 ^ ") "
| G_WZSUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "g-wz-susd") ^ "(" ^
      string_of_int g1 ^ ", " ^ string_of_int g2 ^ ", " ^ string_of_sfm m1 ^
      ", " ^ string_of_sfm m2 ^ ") "
| G_GH_ZSP (s, p) → "g-zh0a0(" ^ string_of_shiggs s ^ ", " ^
      string_of_phiggs p ^ ") "
| G_GH_WSC s → "g-Whph0(" ^ string_of_shiggs s ^ ") "
| G_GH_WPC p → "g-WhpA0(" ^ string_of_phiggs p ^ ") "
| G_GH_ZZS s → "g-ZZh0(" ^ string_of_shiggs s ^ ") "
| G_GH_WWS s → "g-WWh0(" ^ string_of_shiggs s ^ ") "
| G_GLUGLUH0 s → "g-glugluh0(" ^ string_of_shiggs s ^ ") "
| G_GLUGLUA0 p → "g-gluglua0(" ^ string_of_phiggs p ^ ") "
| G_GH_ZCC → "g-Zhmhp"
| G_GH_GaCC → "g-Ahmhp"
| G_ZSF (f, g, m1, m2) → "g-z" ^ string_of_sff f ^ string_of_sff f ^ "(" ^
      string_of_int g ^ ", " ^ string_of_sfm m1 ^ ", " ^ string_of_sfm m2
      ^ ") "
| G_HSNSL (vc, g, m) → conj_symbol (vc, "g-hp-s1" ^ string_of_sfm m ^
      "sn1") ^ "(" ^ string_of_int g ^ ") "
| G_GLISQSQ → "g-gg-sqsq"
| G_PPSFSF f → "g-AA-" ^ string_of_sff f ^ string_of_sff f
| G_ZZSFSF (f, g, m1, m2) → "g-zz-" ^ string_of_sff f ^ string_of_sff f ^
      "(" ^ string_of_int g ^ ", " ^ string_of_sfm m1
      ^ ", " ^ string_of_sfm m2 ^ ") "
| G_ZPSFSF (f, g, m1, m2) → "g-zA-" ^ string_of_sff f ^ string_of_sff f ^

```

```

      "(" ^ string_of_int g ^ "," ^ string_of_sfm m1
      ^ "," ^ string_of_sfm m2 ^ ")"
| G_GLPSQSQ → "g-gA-sqsq"
| G_GLZSFSF (f, g, m1, m2) → "g-gz-" ^ string_of_sff f ^ string_of_sff f ^
      "(" ^ string_of_int g ^ "," ^ string_of_sfm m1 ^ "," ^ string_of_sfm
      m2 ^ ")"
| G_GLWSUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "g-gw-susd") ^ "(" ^
      string_of_int g1 ^ "," ^ string_of_int g2 ^ "," ^ string_of_sfm m1 ^
      "," ^ string_of_sfm m2 ^ ")"
| G_SS → "gs**2"
| I_G_S → "igs"
| G_NHC (vc, n, c) → conj_symbol (vc, "g-neuhmchar") ^ "(" ^
      string_of_neu n ^ "," ^ string_of_char c ^ ")"
| G_WWSFSF (f, g, m1, m2) → "g-ww-" ^ string_of_sff f
      ^ string_of_sff f ^ "(" ^ string_of_int g ^ "," ^ string_of_sfm m1 ^
      "," ^ string_of_sfm m2 ^ ")"
| G_WPSLSN (vc, g, m) → conj_symbol (vc, "g-wA-slsn") ^ "(" ^
      string_of_int g ^ "," ^ string_of_sfm m ^ ")"
| G_WZSLSN (vc, g, m) → conj_symbol (vc, "g-wz-slsn") ^ "(" ^ string_of_int
      g ^ "," ^ string_of_sfm m ^ ")"
| G_SFSFS (s, f, g, m1, m2) → "g-h0-" ^ string_of_sff f ^ string_of_sfm m1
      ^ string_of_sff f ^ string_of_sfm m2 ^ "(" ^ string_of_shiggs s ^ ","
      ^ string_of_int g ^ ")"
| G_SFSFP (p, f, g, m1, m2) → "g-A0-" ^ string_of_sff f ^ string_of_sfm m1
      ^ string_of_sff f ^ string_of_sfm m2 ^ "(" ^ string_of_phiggs p ^ ","
      ^ string_of_int g ^ ")"
| G_HSUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "g-hp-su" ^ string_of_sfm
      m1 ^ "sd" ^ string_of_sfm m2) ^ "(" ^ string_of_int g1 ^ ","
      ^ string_of_int g2 ^ ")"
| G_WSQ (vc, g1, g2, m1, m2) → conj_symbol (vc, "g-wsusd") ^ "(" ^
      string_of_int g1 ^ "," ^ string_of_int g2 ^ "," ^ string_of_sfm m1
      ^ "," ^ string_of_sfm m2 ^ ")"

```

end

## 13.11 Interface of *Modellib\_PSSSM*

### 13.11.1 Extended Supersymmetric Models

We do not introduce the possibility here of using four point couplings or not. We simply add the relevant and leave the rest out. No possibility for Goldstone bosons is given. But we allow for CKM mixing.

```

module type extMSSM_flags =
  sig
    val ckm_present : bool
  end

module PSSSM : extMSSM_flags
module PSSSM_QCD : extMSSM_flags

```



```
module ExtMSSM : functor (F : extMSSM_flags) → Model.T with mod-
ule Ch = Charges.QQ
```

### 13.12 Implementation of *Modellib\_PSSSM*

```
let rcs_file = RCS.parse "Modellib_PSSSM" ["Extended_SUSY_models"]
{ RCS.revision = "$Revision: 4926$";
  RCS.date = "$Date: 2013-12-04 13:35:06 +0100 (Wed, 04 Dec 2013)$";
  RCS.author = "$Author: jr-reuter$";
  RCS.source
    = "$URL: svn+ssh://jr-reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/s"
```

#### 13.12.1 Extended Supersymmetric Standard Model(s)

This is based on the NMSSM implementation by Felix Braam, and extended to the exotica – leptoquarks, leptoquarkinos, additional Higgses etc. – by Daniel Wiesler. Note that for the Higgs sector vertices the conventions of the Franke/Fraas paper have been used.

```
module type extMSSM_flags =
sig
  val ckm_present : bool
end

module PSSSM : extMSSM_flags =
struct
  let ckm_present = false
end

module PSSSM_QCD : extMSSM_flags =
struct
  let ckm_present = false
end

module ExtMSSM (Flags : extMSSM_flags) =
struct
  let rcs = RCS.rename rcs_file "Modellib_PSSSM.NMSSM"
    [ "Extended_SUSY_models" ]

  open Coupling

  let default_width = ref Timelike
  let use_fudged_width = ref false

  let options = Options.create
    [ "constant_width", Arg.Unit (fun () → default_width := Constant),
      "use_constant_width(also_in_t-channel)";
      "fudged_width", Arg.Set use_fudged_width,
      "use_fudge_factor_for_charge_particle_width";
      "custom_width", Arg.String (fun f → default_width := Custom f),
      "use_custom_width";
      "cancel_widths", Arg.Unit (fun () → default_width := Vanishing),
```

```
"use_vanishing_width"]
```

additional combinatorics

yields a list of tuples consistig of the off-diag combinations of the elements in "set"

```
let choose2 set =
  List.map (function [x;y] → (x,y) | _ → failwith "choose2")
    (Combinatorics.choose 2 set)
```

*pairs*

*pairs* appends the diagonal combinations to *choose2*

```
let rec diag = function
| [] → []
| x1 :: rest → (x1, x1) :: diag rest

let pairs l = choose2 l @ diag l
```

*triples*

rank 3 generalization of *pairs*

```
let rec cloop set i j k =
  if i > ((List.length set) - 1) then []
  else if j > i then cloop set (succ i) (j - i - 1) (j - i - 1)
  else if k > j then cloop set i (succ j) (k - j - 1)
  else (List.nth set i, List.nth set j, List.nth set k) :: cloop set i j (succ k)

let triples set = cloop set 0 0 0
(* two_and_one *)

let rec two_and_one' l1 z n =
  if n < 0 then []
  else
    ((fst (List.nth (pairs l1) n)), (snd (List.nth (pairs l1) n)), z) :: two_and_one' l1 z (pred n)

let two_and_one l1 l2 =
  let f z = two_and_one' l1 z ((List.length (pairs l1)) - 1)
  in
    List.flatten ( List.map f l2 )

type gen =
| G of int | GG of gen × gen

let rec string_of_gen = function
| G n when n > 0 → string_of_int n
| G n → string_of_int (abs n) ^ "c"
| GG (g1,g2) → string_of_gen g1 ^ "-" ^ string_of_gen g2
```

With this we distinguish the flavour.

```
type sff =
| SL | SN | SU | SD

let string_of_sff = function
| SL → "s1" | SN → "sn" | SU → "su" | SD → "sd"
```

With this we distinguish the mass eigenstates. At the moment we have to cheat a little bit for the sneutrinos. Because we are dealing with massless neutrinos there is only one sort of sneutrino.

```

type sfm =
  | M1 | M2

let string_of_sfm = function
  | M1 → "1" | M2 → "2"

```

We also introduce special types for the charginos and neutralinos.

```

type char =
  | C1 | C2 | C1c | C2c | C3 | C3c | C4 | C4c

type neu =
  | N1 | N2 | N3 | N4 | N5 | N6 | N7 | N8 | N9 | N10 | N11

let int_of_char = function
  | C1 → 1 | C2 → 2 | C1c → -1 | C2c → -2
  | C3 → 3 | C4 → 4 | C3c → -3 | C4c → -4

let string_of_char c = string_of_int (int_of_char c)

let conj_char = function
  | C1 → C1c | C2 → C2c | C1c → C1 | C2c → C2
  | C3 → C3c | C4 → C4c | C3c → C3 | C4c → C4

let string_of_neu = function
  | N1 → "1" | N2 → "2" | N3 → "3" | N4 → "4" | N5 →
"5" | N6 → "6"
  | N7 → "7" | N8 → "8" | N9 → "9" | N10 → "10" | N11 → "11"

```

For NMSSM-like the Higgs bosons, we follow the conventions of Franke/Fraas. Daniel Wiesler: extended to E6 models.

```

type shiggs =
  | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9

type phiggs =
  | P1 | P2 | P3 | P4 | P5 | P6 | P7

HCx is always the  $H^+$ , HCxc the  $H^-$ .

type chiggs =
  | HC1 | HC2 | HC3 | HC4 | HC5 | HC1c | HC2c | HC3c |
HC4c | HC5c

let conj_chiggs = function
  | HC1 → HC1c | HC2 → HC2c | HC1c → HC1 | HC2c → HC2
  | HC3 → HC3c | HC4 → HC4c | HC3c → HC3 | HC4c → HC4
  | HC5 → HC5c | HC5c → HC5

let string_of_shiggs = function
  | S1 → "1" | S2 → "2" | S3 → "3" | S4 → "4" | S5 → "5"
  | S6 → "6" | S7 → "7" | S8 → "8" | S9 → "9"

let string_of_phiggs = function
  | P1 → "1" | P2 → "2" | P3 → "3" | P4 → "4" | P5 → "5"

```

```

| P6 → "6" | P7 → "7"

let nlist = [ N1; N2; N3; N4; N5; N6; N7; N8; N9; N10; N11 ]
let slist = [ S1; S2; S3; S4; S5; S6; S7; S8; S9 ]
let plist = [ P1; P2; P3; P4; P5; P6; P7 ]
let clist = [ HC1; HC2; HC3; HC4; HC5; HC1c; HC2c; HC3c; HC4c; HC5c ]
let charlist = [ C1; C2; C3; C4; C1c; C2c; C3c; C4c ]

type flavor =
| L of int | N of int
| U of int | D of int
| Sup of sfm × int | Sdown of sfm × int
| Ga | Wp | Wm | Z | Gl
| Slepton of sfm × int | Sneutrino of int
| Neutralino of neu | Chargino of char
| Gluino | SHiggs of shiggs | PHiggs of phiggs
| CHiggs of chiggs
| LQ of sfm × int
| LQino of int

let string_of_fermion_type = function
| L _ → "l" | U _ → "u" | D _ → "d" | N _ → "n"
| _ → failwith
      "Modellib_PSSSM.ExtMSSM.string_of_fermion_type:␣invalid␣fermion␣type"

let string_of_fermion_gen = function
| L g | U g | D g | N g → string_of_int (abs (g))
| _ → failwith
      "Modellib_PSSSM.ExtMSSM.string_of_fermion_gen:␣invalid␣fermion␣type"

type gauge = unit

let gauge_symbol () =
  failwith "Modellib_PSSSM.ExtMSSM.gauge_symbol:␣internal␣error"

```

At this point we will forget graviton and -ino.

```

let family g = [ L g; N g; Slepton (M1, g);
                 Slepton (M2, g); Sneutrino g;
                 U g; D g; Sup (M1, g); Sup (M2, g);
                 Sdown (M1, g); Sdown (M2, g);
                 LQ (M1, g); LQ (M2, g); LQino g ]

let external_flavors () =
[ "1st␣Generation␣matter", ThoList.flatmap family [1; -1];
  "2nd␣Generation␣matter", ThoList.flatmap family [2; -2];
  "3rd␣Generation␣matter", ThoList.flatmap family [3; -3];
  "Gauge␣Bosons", [Ga; Z; Wp; Wm; Gl];
  "Charginos", List.map (fun a → Chargino a) charlist;
  "Neutralinos", List.map (fun a → Neutralino a) nlist;
  "Higgs␣Bosons", List.map (fun a → SHiggs a) slist @
    List.map (fun a → PHiggs a) plist @
    List.map (fun a → CHiggs a) clist;
  "Gluino", [Gluino]]

```

```

let flavors () = ThoList.flatmap snd (external_flavors ())

let spinor n m =
  if n ≥ 0 ∧ m ≥ 0 then
    Spinor
  else if
    n ≤ 0 ∧ m ≤ 0 then
    ConjSpinor
  else
    invalid_arg "Modellib_PSSSM.ExtMSSM.spinor:␣internal␣error"

let lorentz = function
| L g → spinor g 0 | N g → spinor g 0
| U g → spinor g 0 | D g → spinor g 0
| LQino g → spinor g 0
| Chargino c → spinor (int_of_char c) 0
| Ga | Gl → Vector
| Wp | Wm | Z → Massive_Vector
| SHiggs - | PHiggs - | CHiggs -
| Sup - | Sdown - | Slepton - | Sneutrino - | LQ - → Scalar
| Neutralino - | Gluino → Majorana

let color = function
| U g → Color.SUN (if g > 0 then 3 else -3)
| Sup (m, g) → Color.SUN (if g > 0 then 3 else -3)
| D g → Color.SUN (if g > 0 then 3 else -3)
| Sdown (m, g) → Color.SUN (if g > 0 then 3 else -3)
| LQ (m, g) → Color.SUN (if g > 0 then 3 else -3)
| LQino g → Color.SUN (if g > 0 then 3 else -3)
| Gl | Gluino → Color.AdjSUN 3
| - → Color.Singlet

let prop_spinor n m =
  if n ≥ 0 ∧ m ≥ 0 then
    Prop_Spinor
  else if
    n ≤ 0 ∧ m ≤ 0 then
    Prop_ConjSpinor
  else
    invalid_arg "Modellib_PSSSM.ExtMSSM.prop_spinor:␣internal␣error"

let propagator = function
| L g → prop_spinor g 0 | N g → prop_spinor g 0
| U g → prop_spinor g 0 | D g → prop_spinor g 0
| LQino g → prop_spinor g 0
| Chargino c → prop_spinor (int_of_char c) 0
| Ga | Gl → Prop_Feynman
| Wp | Wm | Z → Prop_Unitarity
| SHiggs - | PHiggs - | CHiggs - → Prop_Scalar
| Sup - | Sdown - | Slepton - | Sneutrino - → Prop_Scalar
| LQ - → Prop_Scalar
| Gluino → Prop_Majorana
| Neutralino - → Prop_Majorana

```

Optionally, ask for the fudge factor treatment for the widths of charged particles. Currently, this only applies to  $W^\pm$  and top.

```

let width f =
  if !use_fudged_width then
    match f with
    | Wp | Wm | U 3 | U (-3) → Fudged
    | _ → !default_width
  else
    !default_width

let goldstone _ = None

let conjugate = function
| L g → L (-g) | N g → N (-g)
| U g → U (-g) | D g → D (-g)
| Sup (m, g) → Sup (m, -g)
| Sdown (m, g) → Sdown (m, -g)
| Slepton (m, g) → Slepton (m, -g)
| Sneutrino g → Sneutrino (-g)
| Gl → Gl | Ga → Ga | Z → Z
| Wp → Wm | Wm → Wp
| SHiggs s → SHiggs s
| PHiggs p → PHiggs p
| CHiggs c → CHiggs (conj_chiggs c)
| Gluino → Gluino
| Neutralino n → Neutralino n | Chargino c → Chargino (conj_char c)
| LQino g → LQino (-g)
| LQ (m, g) → LQ (m, -g)

let fermion = function
| L g → if g > 0 then 1 else -1
| N g → if g > 0 then 1 else -1
| U g → if g > 0 then 1 else -1
| D g → if g > 0 then 1 else -1
| Gl | Ga | Z | Wp | Wm → 0
| SHiggs _ | PHiggs _ | CHiggs _ → 0
| Neutralino _ → 2
| Chargino c → if (int_of_char c) > 0 then 1 else -1
| Sup _ → 0 | Sdown _ → 0
| Slepton _ → 0 | Sneutrino _ → 0
| Gluino → 2
| LQ _ → 0
| LQino g → if g > 0 then 1 else -1

```

This model does NOT have a conserved generation quantum number.

```

module Ch = Charges.QQ

let ( // ) = Algebra.Small_Rational.make

let charge = function
| L n → if n > 0 then -1//1 else 1//1
| Slepton (_, n) → if n > 0 then -1//1 else 1//1

```

```

|  $N\ n \rightarrow 0//1$ 
|  $Sneutrino\ n \rightarrow 0//1$ 
|  $U\ n \rightarrow \text{if } n > 0 \text{ then } 2//3 \text{ else } -2//3$ 
|  $Sup\ (-, n) \rightarrow \text{if } n > 0 \text{ then } 2//3 \text{ else } -2//3$ 
|  $D\ n \mid LQ\ (-, n) \mid LQino\ n \rightarrow \text{if } n > 0 \text{ then } -1//3 \text{ else } 1//3$ 
|  $Sdown\ (-, n) \rightarrow \text{if } n > 0 \text{ then } -1//3 \text{ else } 1//3$ 
|  $Gl \mid Ga \mid Z \mid Neutralino\ - \mid Gluino \rightarrow 0//1$ 
|  $Wp \rightarrow 1//1$ 
|  $Wm \rightarrow -1//1$ 
|  $SHiggs\ - \mid PHiggs\ - \rightarrow 0//1$ 
|  $CHiggs\ (HC1 \mid HC2 \mid HC3 \mid HC4 \mid HC5) \rightarrow 1//1$ 
|  $CHiggs\ (HC1c \mid HC2c \mid HC3c \mid HC4c \mid HC5c) \rightarrow -1//1$ 
|  $Chargino\ (C1 \mid C2 \mid C3 \mid C4) \rightarrow 1//1$ 
|  $Chargino\ (C1c \mid C2c \mid C3c \mid C4c) \rightarrow -1//1$ 

let lepton = function
|  $L\ n \mid N\ n \rightarrow \text{if } n > 0 \text{ then } 1//1 \text{ else } -1//1$ 
|  $Slepton\ (-, n)$ 
|  $Sneutrino\ n \rightarrow \text{if } n > 0 \text{ then } 1//1 \text{ else } -1//1$ 
|  $LQ\ (-, n) \mid LQino\ n \rightarrow \text{if } n > 0 \text{ then } 1//1 \text{ else } -1//1$ 
|  $- \rightarrow 0//1$ 

let baryon = function
|  $U\ n \mid D\ n \rightarrow \text{if } n > 0 \text{ then } 1//1 \text{ else } -1//1$ 
|  $Sup\ (-, n) \mid Sdown\ (-, n) \rightarrow \text{if } n > 0 \text{ then } 1//1 \text{ else } -1//1$ 
|  $LQ\ (-, n) \mid LQino\ n \rightarrow \text{if } n > 0 \text{ then } 1//1 \text{ else } -1//1$ 
|  $- \rightarrow 0//1$ 

let charges f =
[ charge f; lepton f; baryon f]

```

We introduce a Boolean type *vc* as a pseudonym for Vertex Conjugator to distinguish between vertices containing complex mixing matrices like the CKM-matrix or the sfermion or neutralino/chargino-mixing matrices, which have to become complex conjugated. The true-option stands for the conjugated vertex, the false-option for the unconjugated vertex.

```

type vc = bool

type constant =
|  $E \mid G$ 
|  $Q\_lepton \mid Q\_up \mid Q\_down \mid Q\_charg$ 
|  $G\_Z \mid G\_CC \mid G\_CCQ\ \text{of } vc \times int \times int$ 
|  $G\_NC\_neutrino \mid G\_NC\_lepton \mid G\_NC\_up \mid G\_NC\_down$ 
|  $I\_Q\_W \mid I\_G\_ZWW \mid G\_WWWW \mid G\_ZZWW \mid G\_PZWW \mid$ 
 $G\_PPWW$ 
|  $G\_strong \mid G\_SS \mid I\_G\_S$ 
|  $G_s$ 
|  $G\_NZN\ \text{of } neu \times neu \mid G\_CZC\ \text{of } char \times char$ 
|  $G\_YUK\_FFS\ \text{of } flavor \times flavor \times shiggs$ 
|  $G\_YUK\_FFP\ \text{of } flavor \times flavor \times phiggs$ 
|  $G\_YUK\_LCN\ \text{of } int$ 
|  $G\_YUK\_UCD\ \text{of } int \times int \mid G\_YUK\_DCU\ \text{of } int \times int$ 

```

$G\_NHC$  of  $vc \times neu \times char$   
 $G\_YUK\_C$  of  $vc \times flavor \times char \times sff \times sfm$   
 $G\_YUK\_Q$  of  $vc \times int \times flavor \times char \times sff \times sfm$   
 $G\_YUK\_N$  of  $vc \times flavor \times neu \times sff \times sfm$   
 $G\_YUK\_G$  of  $vc \times flavor \times sff \times sfm$   
 $G\_NWC$  of  $neu \times char$  |  $G\_CWN$  of  $char \times neu$   
 $G\_CSC$  of  $char \times char \times shiggs$   
 $G\_CPC$  of  $char \times char \times phiggs$   
 $G\_WSQ$  of  $vc \times int \times int \times sfm \times sfm$   
 $G\_SLSNW$  of  $vc \times int \times sfm$   
 $G\_ZSF$  of  $sff \times int \times sfm \times sfm$   
 $G\_CICIS$  of  $neu \times neu \times shiggs$   
 $G\_CICIP$  of  $neu \times neu \times phiggs$   
 $G\_GH\_WPC$  of  $phiggs$  |  $G\_GH\_WSC$  of  $shiggs$   
 $G\_GH\_ZSP$  of  $shiggs \times phiggs$  |  $G\_GH\_WWS$  of  $shiggs$   
 $G\_GH\_ZZS$  of  $shiggs$  |  $G\_GH\_ZCC$   
 $G\_GH\_GaCC$   
 $G\_GH4\_ZZPP$  of  $phiggs \times phiggs$   
 $G\_GH4\_ZZSS$  of  $shiggs \times shiggs$   
 $G\_GH4\_ZZCC$  |  $G\_GH4\_GaGaCC$   
 $G\_GH4\_ZGaCC$  |  $G\_GH4\_WWCC$   
 $G\_GH4\_WWPP$  of  $phiggs \times phiggs$   
 $G\_GH4\_WWSS$  of  $shiggs \times shiggs$   
 $G\_GH4\_ZWSC$  of  $shiggs$   
 $G\_GH4\_GaWSC$  of  $shiggs$   
 $G\_GH4\_ZWPC$  of  $phiggs$   
 $G\_GH4\_GaWPC$  of  $phiggs$   
 $G\_WWSFSF$  of  $sff \times int \times sfm \times sfm$   
 $G\_WPSLSN$  of  $vc \times int \times sfm$   
 $G\_H3\_SCC$  of  $shiggs$   
 $G\_H3\_SSS$  of  $shiggs \times shiggs \times shiggs$   
 $G\_H3\_SPP$  of  $shiggs \times phiggs \times phiggs$   
 $G\_SFSFS$  of  $shiggs \times sff \times int \times sfm \times sfm$   
 $G\_SFSFP$  of  $phiggs \times sff \times int \times sfm \times sfm$   
 $G\_HSNSL$  of  $vc \times int \times sfm$   
 $G\_HSUSD$  of  $vc \times sfm \times sfm \times int \times int$   
 $G\_WPSUSD$  of  $vc \times sfm \times sfm \times int \times int$   
 $G\_WZSUSD$  of  $vc \times sfm \times sfm \times int \times int$   
 $G\_WZSLSN$  of  $vc \times int \times sfm$  |  $G\_GLISQSQ$   
 $G\_PPSFSF$  of  $sff$   
 $G\_ZZSFSF$  of  $sff \times int \times sfm \times sfm$  |  $G\_ZPSFSF$  of  $sff \times int \times sfm \times sfm$   
 $G\_GLZSFSF$  of  $sff \times int \times sfm \times sfm$  |  $G\_GLPSQSQ$   
 $G\_GLWSUSD$  of  $vc \times sfm \times sfm \times int \times int$   
 $G\_YUK\_LQ\_S$  of  $int \times shiggs \times int$   
 $G\_YUK\_LQ\_P$  of  $int \times phiggs \times int$   
 $G\_LQ\_NEU$  of  $sfm \times int \times int \times neu$   
 $G\_LQ\_EC\_UC$  of  $vc \times sfm \times int \times int \times int$   
 $G\_LQ\_GG$  of  $sfm \times int \times int$   
 $G\_LQ\_SSU$  of  $sfm \times sfm \times sfm \times int \times int \times int$   
 $G\_LQ\_SSD$  of  $sfm \times sfm \times int \times int \times int$



```

| G_LQ_S of sfm × sfm × int × shiggs × int
| G_LQ_P of sfm × sfm × int × phiggs × int
| G_ZLQ of int × sfm × sfm
| G_ZZLQLQ | G_ZPLQLQ | G_PPLQLQ | G_ZGILQLQ |
G_PGILQLQ | G_NLQC | G_GILQLQ

```

Two integer counters for the QCD and EW order of the couplings.

```

type orders = int × int
let orders = function
| _ → (0,0)

```

$$\alpha_{\text{QED}} = \frac{1}{137.0359895} \quad (13.86a)$$

$$\sin^2 \theta_w = 0.23124 \quad (13.86b)$$

Here we must perhaps allow for complex input parameters. So split them into their modulus and their phase. At first, we leave them real; the generalization to complex parameters is obvious.

```

let parameters () =
{ input = [];
  derived = [];
  derived_arrays = [] }

module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)

```

For the couplings there are generally two possibilities concerning the sign of the covariant derivative.

$$\text{CD}^\pm = \partial_\mu \pm ig T^a A_\mu^a \quad (13.87)$$

The particle data group defines the signs consistently to be positive. Since the convention for that signs also influence the phase definitions of the gaugino/higgsino fields via the off-diagonal entries in their mass matrices it would be the best to adopt that convention.

\*\* REVISED: Compatible with CD+. FB \*\*

```

let electromagnetic_currents_3 g =
[ ((L (-g), Ga, L g), FBF (1, Psibar, V, Psi), Q_lepton);
  ((U (-g), Ga, U g), FBF (1, Psibar, V, Psi), Q_up);
  ((D (-g), Ga, D g), FBF (1, Psibar, V, Psi), Q_down)]

```

\*\* REVISED: Compatible with CD+. FB\*\*

```

let electromagnetic_sfermion_currents g m =
[ ((Ga, Slepton (m, -g), Slepton (m, g)), Vector_Scalar_Scalar 1, Q_lepton);
  ((Ga, Sup (m, -g), Sup (m, g)), Vector_Scalar_Scalar 1, Q_up);
  ((Ga, Sdown (m, -g), Sdown (m, g)), Vector_Scalar_Scalar 1, Q_down)]

```

\*\* REVISED: Compatible with CD+. FB\*\*

```
let electromagnetic_currents_2 c =
  let cc = conj_char c in
  [ ((Chargino cc, Ga, Chargino c), FBF (1, Psibar, V, Psi), Q_charg) ]
```

\*\* REVISED: Compatible with CD+. FB\*\*

```
let neutral_currents g =
  [ ((L (-g), Z, L g), FBF (1, Psibar, VA, Psi), G_NC_lepton);
    ((N (-g), Z, N g), FBF (1, Psibar, VA, Psi), G_NC_neutrino);
    ((U (-g), Z, U g), FBF (1, Psibar, VA, Psi), G_NC_up);
    ((D (-g), Z, D g), FBF (1, Psibar, VA, Psi), G_NC_down)]
```

$$\mathcal{L}_{CC} = \mp \frac{g}{2\sqrt{2}} \sum_i \bar{\psi}_i \gamma^\mu (1 - \gamma_5) (T^+ W_\mu^+ + T^- W_\mu^-) \psi_i, \quad (13.88)$$

where the sign corresponds to  $CD_\pm$ , respectively.

\*\* REVISED: Compatible with CD+. \*\*

Remark: The definition with the other sign compared to the SM files comes from the fact that  $g_{cc} = 1/(2\sqrt{2})$  is used overwhelmingly often in the SUSY Feynman rules, so that JR decided to use a different definition for  $g_{cc}$  in SM and MSSM.

\* FB \*

```
let charged_currents g h =
  [ ((L (-g), Wm, N g), FBF ((-1), Psibar, VL, Psi), G_CC);
    ((N (-g), Wp, L g), FBF ((-1), Psibar, VL, Psi), G_CC) ]
```

The quark with the inverted generation (the antiparticle) is the outgoing one, the other the incoming. The vertex attached to the outgoing up-quark contains the CKM matrix element *not* complex conjugated, while the vertex with the outgoing down-quark has the conjugated CKM matrix element.

\*\* REVISED: Compatible with CD+. FB \*\*

```
let charged_quark_currents g h =
  [ ((D (-g), Wm, U h), FBF ((-1), Psibar, VL, Psi), G_CCQ (true, g, h));
    ((U (-g), Wp, D h), FBF ((-1), Psibar, VL, Psi), G_CCQ (false, h, g))] 
```

\*\* REVISED: Compatible with CD+.FB \*\*

```
let charged_chargino_currents n c =
  let cc = conj_char c in
  [ ((Chargino cc, Wp, Neutralino n),
      FBF (1, Psibar, VLR, Chi), G_CWN (c, n));
    ((Neutralino n, Wm, Chargino c),
      FBF (1, Chibar, VLR, Psi), G_NWC (n, c)) ]
```

\*\* REVISED: Compatible with CD+. FB\*\*

```
let charged_slepton_currents g m =
  [ ((Wm, Slepton (m, -g), Sneutrino g), Vector_Scalar_Scalar (-1), G_SLSNW
      (true, g, m));
    ((Wp, Slepton (m, g), Sneutrino (-g)), Vector_Scalar_Scalar 1, G_SLSNW
      (false, g, m)) ]
```

\*\* REVISED: Compatible with CD+. FB\*\*

```
let charged_squark_currents' g h m1 m2 =
  [ ((Wm, Sup (m1, g), Sdown (m2, -h)), Vector_Scalar_Scalar (-1), G_WSQ
    (true, g, h, m1, m2));
    ((Wp, Sup (m1, -g), Sdown (m2, h)), Vector_Scalar_Scalar 1, G_WSQ
    (false, g, h, m1, m2)) ]
let charged_squark_currents g h =
  List.flatten (Product.list2 (charged_squark_currents' g h) [M1; M2] [M1; M2] )
```

\*\* REVISED: Compatible with CD+. FB \*\*

```
let neutral_sfermion_currents' g m1 m2 =
  [ ((Z, Slepton (m1, -g), Slepton (m2, g)), Vector_Scalar_Scalar (-1),
    G_ZSF (SL, g, m1, m2));
    ((Z, Sup (m1, -g), Sup (m2, g)), Vector_Scalar_Scalar (-1),
    G_ZSF (SU, g, m1, m2));
    ((Z, Sdown (m1, -g), Sdown (m2, g)), Vector_Scalar_Scalar (-1),
    G_ZSF (SD, g, m1, m2))]
let neutral_sfermion_currents g =
  List.flatten (Product.list2 (neutral_sfermion_currents'
    g) [M1; M2] [M1; M2]) @
  [ ((Z, Sneutrino (-g), Sneutrino g), Vector_Scalar_Scalar (-1),
    G_ZSF (SN, g, M1, M1)) ]
```

The reality of the coupling of the Z-boson to two identical neutralinos makes the vector part of the coupling vanish. So we distinguish them not by the name but by the structure of the couplings.

\*\* REVISED: Compatible with CD+. FB\*\*

```
let neutral_Z (n, m) =
  [ ((Neutralino n, Z, Neutralino m), FBF (1, Chibar, VA, Chi),
    (G_NZN (n, m))) ]
```

\*\* REVISED: Compatible with CD+. FB\*\*

```
let charged_Z c1 c2 =
  let cc1 = conj_char c1 in
  ((Chargino cc1, Z, Chargino c2), FBF ((-1), Psibar, VA, Psi),
    G_CZC (c1, c2))
```

\*\* REVISED: Compatible with CD+. Remark: This is pure octet. FB\*\*

```
let yukawa_v =
  [ (Gluino, Gl, Gluino), FBF (1, Chibar, V, Chi), Gs]
```

\*\* REVISED: Independent of the sign of CD. \*\*

\*\* REVISED: Felix Braam: Compact version using new COMBOS + FF-Couplings

```
let yukawa_higgs_FFS f s =
  [ ((conjgate f, SHiggs s, f), FBF (1, Psibar, S, Psi),
    G_YUK_FFS (conjgate f, f, s))]
let yukawa_higgs_FFP f p =
  [ ((conjgate f, PHiggs p, f), FBF (1, Psibar, P, Psi),
    G_YUK_FFP (conjgate f, f, p))]
```

JR: Only the first charged Higgs.

```

let yukawa_higgs_NLC g =
  [ ((N (-g), CHiggs HC1, L g), FBF (1, Psibar, Coupling.SR, Psi),
      G_YUK_LCN g);
    ((L (-g), CHiggs HC1c, N g), FBF (1, Psibar, Coupling.SL, Psi),
      G_YUK_LCN g) ]

let yukawa_higgs g =
  yukawa_higgs_NLC g @
  List.flatten ( Product.list2 yukawa_higgs_FFS [L g; U g; D g] [S1; S2; S3] ) @
  List.flatten ( Product.list2 yukawa_higgs_FFP [L g; U g; D g] [P1; P2] )

```

JR: Only the first charged Higgs.

\*\* REVISED: Independent of the sign of CD. FB\*\*

```

let yukawa_higgs_quark (g, h) =
  [ ((U (-g), CHiggs HC1, D h), FBF (1, Psibar, SLR, Psi),
      G_YUK_UCD (g, h));
    ((D (-h), CHiggs HC1c, U g), FBF (1, Psibar, SLR, Psi),
      G_YUK_DCU (g, h)) ]

```

\*\* REVISED: Compatible with CD+.FB

\*\* REVISED: Compact version using new COMBOS

```

let yukawa_shiggs_2 c1 c2 s =
  let cc1 = conj_char c1 in
  ((Chargino cc1, SHiggs s, Chargino c2), FBF (1, Psibar, SLR, Psi),
    G_CSC (c1, c2, s))

let yukawa_phiggs_2 c1 c2 p =
  let cc1 = conj_char c1 in
  ((Chargino cc1, PHiggs p, Chargino c2), FBF (1, Psibar, SLR, Psi),
    G_CPC (c1, c2, p))

let yukawa_higgs_2 =
  Product.list3 yukawa_shiggs_2 [C1; C2] [C1; C2] [S1; S2; S3] @
  Product.list3 yukawa_phiggs_2 [C1; C2] [C1; C2] [P1; P2]

```

JR: Only the first charged Higgs.

\*\* REVISED: Compatible with CD+.FB \*\*

```

let higgs_charg_neutr n c =
  let cc = conj_char c in
  [ ((Neutralino n, CHiggs HC1c, Chargino c), FBF (-1, Chibar, SLR, Psi),
      G_NHC (false, n, c));
    ((Chargino cc, CHiggs HC1, Neutralino n), FBF (-1, Psibar, SLR, Chi),
      G_NHC (true, n, c)) ]

```

\*\* REVISED: Compatible with CD+. FB\*\*

\*\* REVISED: Compact version using new COMBOS

```

let shiggs_neutr (n, m, s) =
  ((Neutralino n, SHiggs s, Neutralino m), FBF (1, Chibar, SP, Chi),
    G_CICIS (n, m, s))

let phiggs_neutr (n, m, p) =

```

```

((Neutralino n, PHiggs p, Neutralino m), FBF (1, Chibar, SP, Chi),
  G_CICIP (n, m, p))

let higgs_neutr =
  List.map shiggs_neutr (two_and_one [N1; N2; N3; N4; N5] [S1; S2; S3]) @
  List.map phiggs_neutr (two_and_one [N1; N2; N3; N4; N5] [P1; P2])

** REVISED: Compatible with CD+. FB**

let yukawa_n_2 n m g =
  [ ((Neutralino n, Slepton (m, -g), L g), FBF (1, Chibar, SLR, Psi),
      G_YUK_N (true, L g, n, SL, m));
    ((L (-g), Slepton (m, g), Neutralino n), FBF (1, Psibar, SLR, Chi),
      G_YUK_N (false, L g, n, SL, m));
    ((Neutralino n, Sup (m, -g), U g), FBF (1, Chibar, SLR, Psi),
      G_YUK_N (true, U g, n, SU, m));
    ((U (-g), Sup (m, g), Neutralino n), FBF (1, Psibar, SLR, Chi),
      G_YUK_N (false, U g, n, SU, m));
    ((Neutralino n, Sdown (m, -g), D g), FBF (1, Chibar, SLR, Psi),
      G_YUK_N (true, D g, n, SD, m));
    ((D (-g), Sdown (m, g), Neutralino n), FBF (1, Psibar, SLR, Chi),
      G_YUK_N (false, D g, n, SD, m)) ]

let yukawa_n_3 n g =
  [ ((Neutralino n, Sneutrino (-g), N g), FBF (1, Chibar, SLR, Psi),
      G_YUK_N (true, N g, n, SN, M1));
    ((N (-g), Sneutrino g, Neutralino n), FBF (1, Psibar, SLR, Chi),
      G_YUK_N (false, N g, n, SN, M1)) ]

let yukawa_n_5 g m =
  [ ((U (-g), Sup (m, g), Gluino), FBF (1, Psibar, SLR, Chi),
      G_YUK_G (false, U g, SU, m));
    ((D (-g), Sdown (m, g), Gluino), FBF (1, Psibar, SLR, Chi),
      G_YUK_G (false, D g, SD, m));
    ((Gluino, Sup (m, -g), U g), FBF (1, Chibar, SLR, Psi),
      G_YUK_G (true, U g, SU, m));
    ((Gluino, Sdown (m, -g), D g), FBF (1, Chibar, SLR, Psi),
      G_YUK_G (true, D g, SD, m))]

let yukawa_n =
  List.flatten (Product.list3 yukawa_n_2 [N1; N2; N3; N4; N5] [M1; M2] [1; 2; 3]) @
  List.flatten (Product.list2 yukawa_n_3 [N1; N2; N3; N4; N5] [1; 2; 3]) @
  List.flatten (Product.list2 yukawa_n_5 [1; 2; 3] [M1; M2])

** REVISED: Compatible with CD+.FB **

let yukawa_c_2 c g =
  let cc = conj_char c in
  [ ((L (-g), Sneutrino g, Chargino cc), BBB (1, Psibar, SLR,
      Psibar), G_YUK_C (true, L g, c, SN, M1));
    ((Chargino c, Sneutrino (-g), L g), PBP (1, Psi, SLR, Psi),
      G_YUK_C (false, L g, c, SN, M1)) ]

let yukawa_c_3 c m g =
  let cc = conj_char c in
  [ ((N (-g), Slepton (m, g), Chargino c), FBF (1, Psibar, SLR,

```

```

      Psi), G_YUK_C (true, N g, c, SL, m));
      ((Chargino cc, Slepton (m, -g), N g), FBF (1, Psibar, SLR,
      Psi), G_YUK_C (false, N g, c, SL, m)) ]
let yukawa_c c =
  ThoList.flatmap (yukawa_c-2 c) [1; 2; 3] @
  List.flatten (Product.list2 (yukawa_c-3 c) [M1; M2] [1; 2; 3])
** REVISED: Compatible with CD+. FB**

let yukawa_cq' c (g, h) m =
  let cc = conj_char c in
  [ ((Chargino c, Sup (m, -g), D h), PBP (1, Psi, SLR, Psi),
    G_YUK_Q (false, g, D h, c, SU, m));
    ((D (-h), Sup (m, g), Chargino cc), BBB (1, Psibar, SLR, Psibar),
    G_YUK_Q (true, g, D h, c, SU, m));
    ((Chargino cc, Sdown (m, -g), U h), FBF (1, Psibar, SLR, Psi),
    G_YUK_Q (true, g, U h, c, SD, m));
    ((U (-h), Sdown (m, g), Chargino c), FBF (1, Psibar, SLR, Psi),
    G_YUK_Q (false, g, U h, c, SD, m)) ]
let yukawa_cq c =
  if Flags.ckm_present then
    List.flatten (Product.list2 (yukawa_cq' c) [(1, 1); (1, 2); (2, 1); (2, 2); (1, 3); (2, 3); (3, 3); (3, 2); (3, 1)] [M
  else
    List.flatten (Product.list2 (yukawa_cq' c) [(1, 1); (2, 2); (3, 3)] [M1; M2])

** REVISED: Compatible with CD+. Remark: Singlet and octet gluon ex-
change. The coupling is divided by sqrt(2) to account for the correct normal-
ization of the Lie algebra generators. **FB

let col_currents g =
  [ ((D (-g), Gl, D g), FBF ((-1), Psibar, V, Psi), Gs);
    ((U (-g), Gl, U g), FBF ((-1), Psibar, V, Psi), Gs)]

** REVISED: Compatible with CD+. Remark: Singlet and octet gluon ex-
change. The coupling is divided by sqrt(2) to account for the correct normal-
ization of the Lie algebra generators. **FB
* LQ-coupl. **DW*

let chg = function
  | M1 → M2 | M2 → M1

* LQ - Yuk's *

let yuk_lqino_se_uc1' g1 g2 g3 m =
  let cm = chg m in
  [ ((U (-g3), Slepton (m, -g2), LQino g1), FBF (1, Psibar, SLR, Psi),
    G_LQ_EC_UC (true, cm, g1, g2, g3)) ]

let yuk_lqino_se_uc1 g1 g2 g3 =
  ThoList.flatmap (yuk_lqino_se_uc1' g1 g2 g3) [M1; M2]

let yuk_lqino_se_uc2' g1 g2 g3 m =
  let cm = chg m in
  [ ((LQino (-g1), Slepton (m, g2), U g3), FBF (1, Psibar, SLR, Psi),
    G_LQ_EC_UC (false, cm, g1, g2, g3)) ]

```

```

let yuk_lqino_se_uc2 g1 g2 g3 =
  ThoList.flatmap (yuk_lqino_se_uc2' g1 g2 g3) [M1; M2]

let yuk_lqino_sn_dc1 g1 g2 g3 =
  [ ((D (-g3), Sneutrino (-g2), LQino g1), FBF (-1, Psibar, SLR, Psi),
    G_LQ_EC_UC (true, M2, g1, g2, g3)) ]

let yuk_lqino_sn_dc2 g1 g2 g3 =
  [ ((LQino (-g1), Sneutrino g2, D g3), FBF (-1, Psibar, SLR, Psi),
    G_LQ_EC_UC (false, M2, g1, g2, g3)) ]

let yuk_lqino_ec_su1' g1 g2 g3 m =
  let cm = chg m in
  [ ((LQino (-g1), Sup (m, g3), L g2), FBF (1, Psibar, SLR, Psi),
    G_LQ_EC_UC (true, cm, g1, g2, g3)) ]

let yuk_lqino_ec_su1 g1 g2 g3 =
  ThoList.flatmap (yuk_lqino_ec_su1' g1 g2 g3) [M1; M2]

let yuk_lqino_ec_su2' g1 g2 g3 m =
  let cm = chg m in
  [ ((L (-g2), Sup (m, -g3), LQino (g1)), FBF (1, Psibar, SLR, Psi),
    G_LQ_EC_UC (false, cm, g1, g2, g3)) ]

let yuk_lqino_ec_su2 g1 g2 g3 =
  ThoList.flatmap (yuk_lqino_ec_su2' g1 g2 g3) [M1; M2]

let yuk_lqino_nc_sd1 g1 g2 g3 =
  [ ((LQino (-g1), Sdown (M1, g3), N g2), FBF (-1, Psibar, SLR, Psi),
    G_LQ_EC_UC (true, M2, g1, g2, g3)) ]

let yuk_lqino_nc_sd2 g1 g2 g3 =
  [ ((N (-g2), Sdown (M1, -g3), LQino (g1)), FBF (-1, Psibar, SLR, Psi),
    G_LQ_EC_UC (false, M2, g1, g2, g3)) ]

let yuk_lq_ec_uc' g1 g2 g3 m =
  [ ((L (-g2), LQ (m, g1), U (-g3)), BBB (1, Psibar, SLR, Psibar),
    G_LQ_EC_UC (false, m, g1, g2, g3)) ]

let yuk_lq_ec_uc g1 g2 g3 =
  ThoList.flatmap (yuk_lq_ec_uc' g1 g2 g3) [M1; M2]

let yuk_lq_ec_uc2' g1 g2 g3 m =
  [ ((L (g2), LQ (m, -g1), U (g3)), PBP (1, Psi, SLR, Psi),
    G_LQ_EC_UC (true, m, g1, g2, g3)) ]

let yuk_lq_ec_uc2 g1 g2 g3 =
  ThoList.flatmap (yuk_lq_ec_uc2' g1 g2 g3) [M1; M2]

let yuk_lq_nc_dc g1 g2 g3 =
  [ ((N (-g2), LQ (M2, g1), D (-g3)), BBB (-1, Psibar, SLR, Psibar),
    G_LQ_EC_UC (false, M2, g1, g2, g3)) ]

let yuk_lq_nc_dc2 g1 g2 g3 =
  [ ((N (g2), LQ (M2, -g1), D (g3)), PBP (-1, Psi, SLR, Psi),
    G_LQ_EC_UC (true, M2, g1, g2, g3)) ]

```

\*\* Daniel Wiesler: LQ - F-Term w/ vev \*\*

```

let lq_se_su' g1 g2 g3 m1 m2 m3 =
  [ ((LQ (m1, g1), Slepton (m2, -g2), Sup (m3, -g3)), Scalar_Scalar_Scalar 1,
    G_LQ_SSU (m1, m2, m3, g1, g2, g3)) ]

let lq_se_su g1 g2 g3 =
  List.flatten (Product.list3 (lq_se_su' g1 g2 g3) [M1; M2] [M1; M2] [M1; M2] )

let lq_snu_sd' g1 g2 g3 m1 m2 =
  [ ((LQ (m1, g1), Sdown (m2, -g2), Sneutrino (-g3)), Scalar_Scalar_Scalar 1,
    G_LQ_SSD (m1, m2, g1, g2, g3)) ]

let lq_snu_sd g1 g2 g3 =
  List.flatten (Product.list2 (lq_snu_sd' g1 g2 g3) [M1; M2] [M1; M2] )

** Daniel Wiesler: LQ - Higgs **

let lq_shiggs' g1 s g2 m1 m2 =
  [ ((LQ (m1, g1), SHiggs s, LQ (m2, -g2)), Scalar_Scalar_Scalar 1, G_LQ_S (m1, m2, g1, s, g2))]

let lq_shiggs g1 s g2 =
  List.flatten ( Product.list2 (lq_shiggs' g1 s g2) [M1; M2] [M1; M2])

let lq_phiggs' g1 p g2 m1 m2 =
  [ ((LQ (m1, g1), PHiggs p, LQ (m2, -g2)), Scalar_Scalar_Scalar 1, G_LQ_P (m1, m2, g1, p, g2))]

let lq_phiggs g1 p g2 =
  List.flatten ( Product.list2 (lq_phiggs' g1 p g2) [M1; M2] [M1; M2])

let yuk_lqino_shiggs g1 s g2 =
  [ ((LQino (-g1), SHiggs s, LQino g2), FBF (1, Psibar, SLR, Psi),
    G_YUK_LQ_S (g1, s, g2)) ]

let yuk_lqino_phiggs g1 p g2 =
  [ ((LQino (-g1), PHiggs p, LQino g2), FBF (1, Psibar, SLR, Psi),
    G_YUK_LQ_P (g1, p, g2)) ]

** Daniel Wiesler: LQ - Neutralinos. **

let lqino_lq_neu' n g1 g2 m =
  [ ((Neutralino n, LQ (m, -g1), LQino g2), FBF (1, Chibar, SLR, Psi),
    G_LQ_NEU (m, g1, g2, n)) ]

let lqino_lq_neu n g1 g2 =
  ThoList.flatmap (lqino_lq_neu' n g1 g2) [M1; M2]

let lqino_lq_neu2' n g1 g2 m =
  [ ((LQino (-g2), LQ (m, g1), Neutralino n), FBF (1, Psibar, SLR, Chi),
    G_LQ_NEU (m, g1, g2, n)) ]

let lqino_lq_neu2 n g1 g2 =
  ThoList.flatmap (lqino_lq_neu2' n g1 g2) [M1; M2]

** Daniel Wiesler: LQ-LQino-Gluino **

let lqino_lq_gg' g1 g2 m =
  [ ((Gluino, LQ (m, -g1), LQino g2), FBF (1, Chibar, SLR, Psi),
    G_LQ_GG (m, g1, g2)) ]

let lqino_lq_gg g1 g2 =

```



```

    ThoList.flatmap (lqino_lq_gg' g1 g2) [M1; M2]
** Daniel Wiesler: LQ - Gauge **
let col_lqino_currents g =
  [ ((LQino (-g), Gl, LQino g), FBF ((-1), Psibar, V, Psi), Gs)]
let neutr_lqino_current g =
  [ ((LQino (-g), Z, LQino g), FBF (1, Psibar, V, Psi), G_NLQC)]
let col_lq_currents m g =
  [ ((Gl, LQ (m, -g), LQ (m, g)), Vector_Scalar_Scalar (-1), Gs)]
let lq_neutr_Z g m1 m2 =
  [ ((Z, LQ (m1, -g), LQ (m2, g)), Vector_Scalar_Scalar (-1), G_ZLQ (g, m1, m2))]
let em_lq_currents g m =
  [ ((Ga, LQ (m, -g), LQ (m, g)), Vector_Scalar_Scalar 1, Q_down)]
let em_lqino_currents g =
  [ ((LQino (-g), Ga, LQino g), FBF (1, Psibar, V, Psi), Q_down)]
let gluon2_lq2' g m =
  [ ((LQ (m, g), LQ (m, -g), Gl, Gl), Scalar2_Vector2 2, G_GlGlLQLQ)]
let gluon2_lq2 g =
  ThoList.flatmap (gluon2_lq2' g) [M1; M2]
let lq_gauge4' g m =
  [ ((Z, Z, LQ (m, g), LQ (m, -g)), Scalar2_Vector2 1, G_ZZLQLQ);
    ((Z, Ga, LQ (m, g), LQ (m, -g)), Scalar2_Vector2 1, G_ZPLQLQ);
    ((Ga, Ga, LQ (m, g), LQ (m, -g)), Scalar2_Vector2 1, G_PPLQLQ)]
let lq_gauge4 g =
  ThoList.flatmap (lq_gauge4' g) [M1; M2]
let lq_gg_gauge2' g m =
  [ ((Z, Gl, LQ (m, g), LQ (m, -g)), Scalar2_Vector2 1, G_ZGILQLQ);
    ((Ga, Gl, LQ (m, g), LQ (m, -g)), Scalar2_Vector2 1, G_PGILQLQ)]
let lq_gg_gauge2 g =
  ThoList.flatmap (lq_gg_gauge2' g) [M1; M2]
let col_sfermion_currents g m =
  [ ((Gl, Sup (m, -g), Sup (m, g)), Vector_Scalar_Scalar (-1), Gs);
    ((Gl, Sdown (m, -g), Sdown (m, g)), Vector_Scalar_Scalar (-1), Gs)]
** REVISED: Compatible with CD+. **FB
let triple_gauge =
  [ ((Ga, Wm, Wp), Gauge_Gauge_Gauge 1, I_Q_W);
    ((Z, Wm, Wp), Gauge_Gauge_Gauge 1, I_G_ZWW);
    ((Gl, Gl, Gl), Gauge_Gauge_Gauge 1, I_G_S)]
** REVISED: Independent of the sign of CD. **FB
let gauge4 = Vector4 [(2, C_13_42); (-1, C_12_34); (-1, C_14_23)]
let minus_gauge4 = Vector4 [(-2, C_13_42); (1, C_12_34); (1, C_14_23)]
let quartic_gauge =
  [ (Wm, Wp, Wm, Wp), gauge4, G_WWWW;

```

```

(Wm, Z, Wp, Z), minus_gauge4, G_ZZWW;
(Wm, Z, Wp, Ga), minus_gauge4, G_PZWW;
(Wm, Ga, Wp, Ga), minus_gauge4, G_PPWW;
(Gl, Gl, Gl, Gl), gauge4, G_SS]

```

The *Scalar\_Vector\_Vector* couplings do not depend on the choice of the sign of the covariant derivative since they are quadratic in the gauge couplings.

JR: Only the first charged Higgs.

\*\* REVISED: Compatible with CD+. \*\*

\*\* Revision: 2005-03-10: first two vertices corrected. \*\*

\*\* REVISED: Felix Braam: Compact version using new COMBOS

\*\* REVISED: Felix Braam: Couplings adjusted to FF-convention

```

let gauge_higgs_WPC p =
  [((Wm, CHiggs HC1, PHiggs p), Vector_Scalar_Scalar 1, G_GH_WPC p);
   ((Wp, CHiggs HC1c, PHiggs p), Vector_Scalar_Scalar 1, G_GH_WPC p)]
let gauge_higgs_WSC s =
  [((Wm, CHiggs HC1, SHiggs s), Vector_Scalar_Scalar 1, G_GH_WSC s);
   ((Wp, CHiggs HC1c, SHiggs s), Vector_Scalar_Scalar (-1), G_GH_WSC s)]
let gauge_higgs_ZSP s p =
  [((Z, SHiggs s, PHiggs p), Vector_Scalar_Scalar 1, G_GH_ZSP (s, p))]
let gauge_higgs_WWS s =
  ((SHiggs s, Wp, Wm), Scalar_Vector_Vector 1, G_GH_WWS s)
let gauge_higgs_ZZS s =
  ((SHiggs s, Z, Z), Scalar_Vector_Vector 1, G_GH_ZZS s)
let gauge_higgs_ZCC =
  ((Z, CHiggs HC1, CHiggs HC1c), Vector_Scalar_Scalar 1, G_GH_ZCC)
let gauge_higgs_GaCC =
  ((Ga, CHiggs HC1, CHiggs HC1c), Vector_Scalar_Scalar 1, G_GH_GaCC)

let gauge_higgs =
  ThoList.flatmap gauge_higgs_WPC [P1; P2] @
  ThoList.flatmap gauge_higgs_WSC [S1; S2; S3] @
  List.flatten (Product.list2 gauge_higgs_ZSP [S1; S2; S3] [P1; P2]) @
  List.map gauge_higgs_WWS [S1; S2; S3] @
  List.map gauge_higgs_ZZS [S1; S2; S3] @
  [gauge_higgs_ZCC] @ [gauge_higgs_GaCC]

```

\*\* REVISED: Compact version using new COMBOS

\*\* REVISED: Couplings adjusted to FF-convention

```

let gauge_higgs4_ZZPP (p1, p2) =
  ((PHiggs p1, PHiggs p2, Z, Z), Scalar2_Vector2 1, G_GH4_ZZPP (p1, p2))
let gauge_higgs4_ZZSS (s1, s2) =
  ((SHiggs s1, SHiggs s2, Z, Z), Scalar2_Vector2 1, G_GH4_ZZSS (s1, s2))

```

JR: Only the first charged Higgs.

```

let gauge_higgs4_ZZCC =
  ((CHiggs HC1, CHiggs HC1c, Z, Z), Scalar2_Vector2 1, G_GH4_ZZCC)
let gauge_higgs4_GaGaCC =
  ((CHiggs HC1, CHiggs HC1c, Ga, Ga), Scalar2_Vector2 1, G_GH4_GaGaCC)

```

```

let gauge_higgs4_ZGaCC =
  ((CHiggs HC1, CHiggs HC1c, Ga, Z), Scalar2_Vector2 1, G_GH4_ZGaCC)
let gauge_higgs4_WWCC =
  ((CHiggs HC1, CHiggs HC1c, Wp, Wm), Scalar2_Vector2 1, G_GH4_WWCC)
let gauge_higgs4_WWPP (p1, p2) =
  ((PHiggs p1, PHiggs p2, Wp, Wm), Scalar2_Vector2 1, G_GH4_WWPP (p1, p2))
let gauge_higgs4_WWSS (s1, s2) =
  ((SHiggs s1, SHiggs s2, Wp, Wm), Scalar2_Vector2 1, G_GH4_WWSS (s1, s2))

```

JR: Only the first charged Higgs.

```

let gauge_higgs4_ZWSC s =
  [((CHiggs HC1, SHiggs s, Wm, Z), Scalar2_Vector2 1, G_GH4_ZWSC s);
   ((CHiggs HC1c, SHiggs s, Wp, Z), Scalar2_Vector2 1, G_GH4_ZWSC s)]
let gauge_higgs4_GaWSC s =
  [((CHiggs HC1, SHiggs s, Wm, Ga), Scalar2_Vector2 1, G_GH4_GaWSC s);
   ((CHiggs HC1c, SHiggs s, Wp, Ga), Scalar2_Vector2 1, G_GH4_GaWSC s)]
let gauge_higgs4_ZWPC p =
  [((CHiggs HC1, PHiggs p, Wm, Z), Scalar2_Vector2 1, G_GH4_ZWPC p);
   ((CHiggs HC1c, PHiggs p, Wp, Z), Scalar2_Vector2 (-1), G_GH4_ZWPC p)]
let gauge_higgs4_GaWPC p =
  [((CHiggs HC1, PHiggs p, Wm, Ga), Scalar2_Vector2 1, G_GH4_GaWPC p);
   ((CHiggs HC1c, PHiggs p, Wp, Ga), Scalar2_Vector2 (-1),
    G_GH4_GaWPC p)]
let gauge_higgs4 =
  List.map gauge_higgs4_ZZPP (pairs [P1; P2]) @
  List.map gauge_higgs4_ZZSS (pairs [S1; S2; S3]) @
  [gauge_higgs4_ZZCC] @ [gauge_higgs4_GaGaCC] @
  [gauge_higgs4_ZGaCC] @ [gauge_higgs4_WWCC] @
  List.map gauge_higgs4_WWPP (pairs [P1; P2]) @
  List.map gauge_higgs4_WWSS (pairs [S1; S2; S3]) @
  ThoList.flatmap gauge_higgs4_ZWSC [S1; S2; S3] @
  ThoList.flatmap gauge_higgs4_GaWSC [S1; S2; S3] @
  ThoList.flatmap gauge_higgs4_ZWPC [P1; P2] @
  ThoList.flatmap gauge_higgs4_GaWPC [P1; P2]

```

\*\* Added by Felix Braam. \*\*

```

let gauge_sfermion4' g m1 m2 =
  [((Wp, Wm, Slepton (m1, g), Slepton (m2, -g)), Scalar2_Vector2 1,
    G_WWSFSF (SL, g, m1, m2));
   ((Z, Ga, Slepton (m1, g), Slepton (m2, -g)), Scalar2_Vector2 1,
    G_ZPSFSF (SL, g, m1, m2));
   ((Z, Z, Slepton (m1, g), Slepton (m2, -g)), Scalar2_Vector2 1,
    G_ZZSFSF (SL, g, m1, m2));
   ((Wp, Wm, Sup (m1, g), Sup (m2, -g)), Scalar2_Vector2 1, G_WWSFSF
    (SU, g, m1, m2));
   ((Wp, Wm, Sdown (m1, g), Sdown (m2, -g)), Scalar2_Vector2 1, G_WWSFSF
    (SD, g, m1, m2));

```

```

((Z, Z, Sup (m1, g), Sup (m2, -g)), Scalar2_Vector2 1, G_ZZSFSSF
  (SU, g, m1, m2));
((Z, Z, Sdown (m1, g), Sdown (m2, -g)), Scalar2_Vector2 1, G_ZZSFSSF
  (SD, g, m1, m2));
((Z, Ga, Sup (m1, g), Sup (m2, -g)), Scalar2_Vector2 1, G_ZPSFSSF
  (SU, g, m1, m2));
((Z, Ga, Sdown (m1, g), Sdown (m2, -g)), Scalar2_Vector2 1, G_ZPSFSSF
  (SD, g, m1, m2)) ]

let gauge_sfermion4'' g m =
[ ((Wp, Ga, Slepton (m, g), Sneutrino (-g)), Scalar2_Vector2 1,
  G_WPSLSN (false, g, m));
  ((Wm, Ga, Slepton (m, -g), Sneutrino g), Scalar2_Vector2 1,
  G_WPSLSN (true, g, m));
  ((Wp, Z, Slepton (m, g), Sneutrino (-g)), Scalar2_Vector2 1,
  G_WZLSN (false, g, m));
  ((Wm, Z, Slepton (m, -g), Sneutrino g), Scalar2_Vector2 1,
  G_WZLSN (true, g, m));
  ((Ga, Ga, Slepton (m, g), Slepton (m, -g)), Scalar2_Vector2 1, G_PPSFSSF SL);
  ((Ga, Ga, Sup (m, g), Sup (m, -g)), Scalar2_Vector2 1, G_PPSFSSF SU);
  ((Ga, Ga, Sdown (m, g), Sdown (m, -g)), Scalar2_Vector2 1, G_PPSFSSF SD)]

let gauge_sfermion4 g =
List.flatten (Product.list2 (gauge_sfermion4' g) [M1; M2] [M1; M2]) @
ThoList.flatmap (gauge_sfermion4'' g) [M1; M2] @
[ ((Wp, Wm, Sneutrino g, Sneutrino (-g)), Scalar2_Vector2 1, G_WWSFSSF
  (SN, g, M1, M1));
  ((Z, Z, Sneutrino g, Sneutrino (-g)), Scalar2_Vector2 1, G_ZZSFSSF
  (SN, g, M1, M1)) ]

** Modified by Felix Braam. **

let gauge_squark4'' g h m1 m2 =
[ ((Wp, Ga, Sup (m1, -g), Sdown (m2, h)), Scalar2_Vector2 1, G_WPSUSD
  (false, m1, m2, g, h));
  ((Wm, Ga, Sup (m1, g), Sdown (m2, -h)), Scalar2_Vector2 1, G_WPSUSD
  (true, m1, m2, g, h));
  ((Wp, Z, Sup (m1, -g), Sdown (m2, h)), Scalar2_Vector2 1, G_WZSUSD
  (false, m1, m2, g, h));
  ((Wm, Z, Sup (m1, g), Sdown (m2, -h)), Scalar2_Vector2 1, G_WZSUSD
  (true, m1, m2, g, h)) ]

let gauge_squark4' g h = List.flatten (Product.list2 (gauge_squark4'' g h)
  [M1; M2] [M1; M2])

let gauge_squark4 =
if Flags.ckm_present then
  List.flatten (Product.list2 gauge_squark4' [1; 2; 3] [1; 2; 3])
else
  ThoList.flatmap (fun g → gauge_squark4' g g) [1; 2; 3]

let gluon_w_squark'' g h m1 m2 =
[ ((Gl, Wp, Sup (m1, -g), Sdown (m2, h)),
  Scalar2_Vector2 1, G_GlWSUSD (false, m1, m2, g, h));
  ((Gl, Wm, Sup (m1, g), Sdown (m2, -h)),
  Scalar2_Vector2 1, G_GlWSUSD (true, m1, m2, g, h)) ]

```

```

      Scalar2_Vector2 1, G_GlWSUSD (true,m1,m2,g,h)) ]
let gluon_w_squark' g h =
  List.flatten (Product.list2 (gluon_w_squark'' g h) [M1;M2] [M1;M2])
let gluon_w_squark =
  if Flags.ckm-present then
    List.flatten (Product.list2 gluon_w_squark' [1;2;3] [1;2;3])
  else
    ThoList.flatmap (fun g → gluon_w_squark' g g) [1;2;3]
** Modified by Felix Braam. **

let gluon_gauge_squark' g m1 m2 =
  [ ((Gl, Z, Sup (m1,g), Sup (m2,-g)),
    Scalar2_Vector2 2, G_GLZSFSF (SU,g,m1,m2));
    ((Gl, Z, Sdown (m1,g), Sdown (m2,-g)),
    Scalar2_Vector2 2, G_GLZSFSF (SD,g,m1,m2)) ]
let gluon_gauge_squark'' g m =
  [ ((Gl, Ga, Sup (m,g), Sup (m,-g)), Scalar2_Vector2 2, G_GLPSQSQ);
    ((Gl, Ga, Sdown (m,g), Sdown (m,-g)), Scalar2_Vector2 (-1), G_GLPSQSQ) ]
** Modified by Felix Braam. **

let gluon_gauge_squark g =
  List.flatten (Product.list2 (gluon_gauge_squark' g) [M1;M2] [M1;M2]) @
  ThoList.flatmap (gluon_gauge_squark'' g) [M1;M2]

let gluon2_squark2' g m =
  [ ((Gl, Gl, Sup (m,g), Sup (m,-g)), Scalar2_Vector2 2, G_GLGLSQSQ);
    ((Gl, Gl, Sdown (m,g), Sdown (m,-g)), Scalar2_Vector2 2, G_GLGLSQSQ) ]
let gluon2_squark2 g =
  ThoList.flatmap (gluon2_squark2' g) [M1;M2]

JR: Only the first charged Higgs.
** REVISED: Independent of the sign of CD. **
** REVISED: Felix Braam: Compact version using new COMBOS
** REVISED: Felix Braam: Couplings adjusted to FF-convention

let higgs_SCC s =
  ((CHiggs HC1, CHiggs HC1c, SHiggs s), Scalar_Scalar_Scalar 1,
   G_H3_SCC s)
let higgs_SSS (s1,s2,s3) =
  ((SHiggs s1, SHiggs s2, SHiggs s3), Scalar_Scalar_Scalar 1,
   G_H3_SSS (s1,s2,s3))
let higgs_SPP (p1,p2,s) =
  ((SHiggs s, PHiggs p1, PHiggs p2), Scalar_Scalar_Scalar 1,
   G_H3_SPP (s,p1,p2))

let higgs =
  List.map higgs_SCC [S1;S2;S3]@
  List.map higgs_SSS (triples [S1;S2;S3])@
  List.map higgs_SPP (two_and_one [P1;P2] [S1;S2;S3])

let higgs4 = []
(* The vertices of the type Higgs - Sfermion - Sfermion are independent of the
choice of the CD sign since they are quadratic in the gauge coupling. *)

```

JR: Only the first charged Higgs.

\*\* REVISED: Independent of the sign of CD. \*\*

```

let higgs_sneutrino' s g =
  ((SHiggs s, Sneutrino g, Sneutrino (-g)), Scalar_Scalar_Scalar 1,
   G_SFSSFS (s, SN, g, M1, M1))
let higgs_sneutrino'' g m =
  [((CHiggs HC1, Sneutrino (-g), Slepton (m, g)),
    Scalar_Scalar_Scalar 1, G_HSNSL (false, g, m));
   ((CHiggs HC1c, Sneutrino g, Slepton (m, -g)), Scalar_Scalar_Scalar 1,
    G_HSNSL (true, g, m))]
let higgs_sneutrino =
  Product.list2 higgs_sneutrino' [S1; S2; S3] [1; 2; 3] @
  List.flatten ( Product.list2 higgs_sneutrino'' [1; 2; 3] [M1; M2] )

```

Under the assumption that there is no mixing between the left- and right-handed sfermions for the first two generations there is only a coupling of the form Higgs - sfermion1 - sfermion2 for the third generation. All the others are suppressed by  $m_f/M_W$ .

\*\* REVISED: Independent of the sign of CD. \*\*

```

let higgs_sfermion_S s g m1 m2 =
  [ ((SHiggs s, Slepton (m1, g), Slepton (m2, -g)), Scalar_Scalar_Scalar 1,
    G_SFSSFS (s, SL, g, m1, m2));
    ((SHiggs s, Sup (m1, g), Sup (m2, -g)), Scalar_Scalar_Scalar 1,
    G_SFSSFS (s, SU, g, m1, m2));
    ((SHiggs s, Sdown (m1, g), Sdown (m2, -g)), Scalar_Scalar_Scalar 1,
    G_SFSSFS (s, SD, g, m1, m2))]
let higgs_sfermion' g m1 m2 =
  (higgs_sfermion_S S1 g m1 m2) @ (higgs_sfermion_S S2 g m1 m2) @ (higgs_sfermion_S S3 g m1 m2)
let higgs_sfermion_P p g m1 m2 =
  [ ((PHiggs p, Slepton (m1, g), Slepton (m2, -g)), Scalar_Scalar_Scalar 1,
    G_SFSSFP (p, SL, g, m1, m2));
    ((PHiggs p, Sup (m1, g), Sup (m2, -g)), Scalar_Scalar_Scalar 1,
    G_SFSSFP (p, SU, g, m1, m2));
    ((PHiggs p, Sdown (m1, g), Sdown (m2, -g)), Scalar_Scalar_Scalar 1,
    G_SFSSFP (p, SD, g, m1, m2)) ]
let higgs_sfermion'' g m1 m2 =
  (higgs_sfermion_P P1 g m1 m2) @ (higgs_sfermion_P P2 g m1 m2)
let higgs_sfermion = List.flatten (Product.list3 higgs_sfermion' [1; 2; 3] [M1; M2] [M1; M2]) @
  List.flatten (Product.list3 higgs_sfermion'' [1; 2; 3] [M1; M2] [M1; M2])

```

JR: Only the first charged Higgs.

\*\* REVISED: Independent of the sign of CD. \*\*

```

let higgs_squark' g h m1 m2 =
  [ ((CHiggs HC1, Sup (m1, -g), Sdown (m2, h)), Scalar_Scalar_Scalar 1,
    G_HSUSD (false, m1, m2, g, h));
    ((CHiggs HC1c, Sup (m1, g), Sdown (m2, -h)), Scalar_Scalar_Scalar 1,
    G_HSUSD (true, m1, m2, g, h)) ]
let higgs_squark_a g h = higgs_squark' g h M1 M1

```

```

let higgs_squark_b (g, h) = List.flatten (Product.list2 (higgs_squark' g h)
                                                         [M1; M2] [M1; M2])

let higgs_squark =
  if Flags.ckm_present then
    List.flatten (Product.list2 higgs_squark_a [1; 2] [1; 2]) @
    ThoList.flatmap higgs_squark_b [(1, 3); (2, 3); (3, 3); (3, 1); (3, 2)]
  else
    higgs_squark_a 1 1 @ higgs_squark_a 2 2 @ higgs_squark_b (3, 3)

let vertices3 =
  (ThoList.flatmap electromagnetic_currents_3 [1; 2; 3] @
   ThoList.flatmap electromagnetic_currents_2 [C1; C2] @
   List.flatten (Product.list2 electromagnetic_sfermion_currents [1; 2; 3]
                                                             [M1; M2]) @
   ThoList.flatmap neutral_currents [1; 2; 3] @
   ThoList.flatmap neutral_sfermion_currents [1; 2; 3] @
   ThoList.flatmap charged_currents [1; 2; 3] @
   List.flatten (Product.list2 charged_slepton_currents [1; 2; 3]
                                                             [M1; M2]) @
   (if Flags.ckm_present then
    List.flatten (Product.list2 charged_quark_currents [1; 2; 3]
                                                             [1; 2; 3]) @
    List.flatten (Product.list2 charged_squark_currents [1; 2; 3]
                                                             [1; 2; 3]) @
    ThoList.flatmap yukawa_higgs_quark [(1, 3); (2, 3); (3, 3); (3, 1); (3, 2)]
  else
    charged_quark_currents 1 1 @
    charged_quark_currents 2 2 @
    charged_quark_currents 3 3 @
    charged_squark_currents 1 1 @
    charged_squark_currents 2 2 @
    charged_squark_currents 3 3 @
    ThoList.flatmap yukawa_higgs_quark [(3, 3)] @
    yukawa_higgs 3 @ yukawa_n @
    ThoList.flatmap yukawa_c [C1; C2] @
    ThoList.flatmap yukawa_cq [C1; C2] @
    List.flatten (Product.list2 charged_chargino_currents [N1; N2; N3; N4; N5]
                                                             [C1; C2]) @ triple_gauge @
    ThoList.flatmap neutral_Z (pairs [N1; N2; N3; N4; N5]) @
    Product.list2 charged_Z [C1; C2] [C1; C2] @
    gauge_higgs @ higgs @ yukawa_higgs_2 @
    List.flatten (Product.list2 higgs_charg_neutr [N1; N2; N3; N4; N5] [C1; C2]) @
    higgs_neutr @ higgs_sneutrino @ higgs_sfermion @
    higgs_squark @ yukawa_v @
    ThoList.flatmap col_currents [1; 2; 3] @
    List.flatten (Product.list2 col_sfermion_currents [1; 2; 3] [M1; M2]) @
    List.flatten (Product.list2 col_lq_currents [M1; M2] [1; 2; 3]) @
    ThoList.flatmap col_lqino_currents [1; 2; 3] @
    ThoList.flatmap em_lqino_currents [1; 2; 3] @
    ThoList.flatmap neutr_lqino_current [1; 2; 3] @

```

```

List.flatten (Product.list3 yuk_lqino_se_uc1 [1; 2; 3] [1; 2; 3] [1; 2; 3]) @
List.flatten (Product.list3 yuk_lqino_se_uc2 [1; 2; 3] [1; 2; 3] [1; 2; 3]) @
List.flatten (Product.list3 yuk_lqino_ec_su1 [1; 2; 3] [1; 2; 3] [1; 2; 3]) @
List.flatten (Product.list3 yuk_lqino_ec_su2 [1; 2; 3] [1; 2; 3] [1; 2; 3]) @
List.flatten (Product.list3 yuk_lqino_sn_dc1 [1; 2; 3] [1; 2; 3] [1; 2; 3]) @
List.flatten (Product.list3 yuk_lqino_sn_dc2 [1; 2; 3] [1; 2; 3] [1; 2; 3]) @
List.flatten (Product.list3 yuk_lqino_nc_sd1 [1; 2; 3] [1; 2; 3] [1; 2; 3]) @
List.flatten (Product.list3 yuk_lqino_nc_sd2 [1; 2; 3] [1; 2; 3] [1; 2; 3]) @
List.flatten (Product.list3 yuk_lq_ec_uc [1; 2; 3] [1; 2; 3] [1; 2; 3]) @
List.flatten (Product.list3 yuk_lq_ec_uc2 [1; 2; 3] [1; 2; 3] [1; 2; 3]) @
List.flatten (Product.list3 yuk_lq_nc_dc [1; 2; 3] [1; 2; 3] [1; 2; 3]) @
List.flatten (Product.list3 yuk_lq_nc_dc2 [1; 2; 3] [1; 2; 3] [1; 2; 3]) @
List.flatten (Product.list3 lq_neutr_Z [1; 2; 3] [M1; M2] [M1; M2]) @
List.flatten (Product.list2 em_lq_currents [1; 2; 3] [M1; M2]) @
List.flatten (Product.list3 lq_shiggs [1; 2; 3] [S1; S2; S3; S4; S5; S6; S7; S8; S9] [1; 2; 3]) @
List.flatten (Product.list3 lq_phiggs [1; 2; 3] [P1; P2; P3; P4; P5; P6; P7] [1; 2; 3]) @
List.flatten (Product.list3 yuk_lqino_shiggs [1; 2; 3] [S1; S2; S3; S4; S5; S6; S7; S8; S9] [1; 2; 3]) @
List.flatten (Product.list3 yuk_lqino_phiggs [1; 2; 3] [P1; P2; P3; P4; P5; P6; P7] [1; 2; 3]) @
List.flatten (Product.list3 lqino_lq_neu_nlist [1; 2; 3] [1; 2; 3]) @
List.flatten (Product.list3 lqino_lq_neu2_nlist [1; 2; 3] [1; 2; 3]) @
List.flatten (Product.list3 lq_se_su [1; 2; 3] [1; 2; 3] [1; 2; 3]) @
List.flatten (Product.list3 lq_snu_sd [1; 2; 3] [1; 2; 3] [1; 2; 3]) @
List.flatten (Product.list2 lqino_lq_gg [1; 2; 3] [1; 2; 3])

let vertices4 =
  (quartic_gauge @ higgs4 @ gauge_higgs4 @
   ThoList.flatmap gauge_sfermion4 [1; 2; 3] @
   gauge_squark4 @ gluon_w_squark @
   ThoList.flatmap gluon2_squark2 [1; 2; 3] @
   ThoList.flatmap gluon_gauge_squark [1; 2; 3] @
   ThoList.flatmap gluon2_lq2 [1; 2; 3] @
   ThoList.flatmap lq_gauge4 [1; 2; 3] @
   ThoList.flatmap lq_gg_gauge2 [1; 2; 3])

let vertices () = (vertices3, vertices4, [])

let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 4

```

SLHA2-Nomenclature for neutral Higgses

```

let flavor_of_string s =
  match s with
  | "e-" → L 1 | "e+" → L (-1)
  | "mu-" → L 2 | "mu+" → L (-2)
  | "tau-" → L 3 | "tau+" → L (-3)
  | "nue" → N 1 | "nuebar" → N (-1)
  | "numu" → N 2 | "numubar" → N (-2)
  | "nutau" → N 3 | "nutaubar" → N (-3)
  | "se1-" → Slepton (M1, 1) | "se1+" → Slepton (M1, -1)

```



	"smu1-" $\rightarrow$ <i>Slepton</i> ( <i>M1</i> , 2)   "smu1+" $\rightarrow$ <i>Slepton</i> ( <i>M1</i> , -2)
	"stau1-" $\rightarrow$ <i>Slepton</i> ( <i>M1</i> , 3)   "stau1+" $\rightarrow$ <i>Slepton</i> ( <i>M1</i> , -3)
	"se2-" $\rightarrow$ <i>Slepton</i> ( <i>M2</i> , 1)   "se2+" $\rightarrow$ <i>Slepton</i> ( <i>M2</i> , -1)
	"smu2-" $\rightarrow$ <i>Slepton</i> ( <i>M2</i> , 2)   "smu2+" $\rightarrow$ <i>Slepton</i> ( <i>M2</i> , -2)
	"stau2-" $\rightarrow$ <i>Slepton</i> ( <i>M2</i> , 3)   "stau2+" $\rightarrow$ <i>Slepton</i> ( <i>M2</i> , -3)
	"snue" $\rightarrow$ <i>Sneutrino</i> 1   "snue*" $\rightarrow$ <i>Sneutrino</i> (-1)
	"snumu" $\rightarrow$ <i>Sneutrino</i> 2   "snumu*" $\rightarrow$ <i>Sneutrino</i> (-2)
	"snutau" $\rightarrow$ <i>Sneutrino</i> 3   "snutau*" $\rightarrow$ <i>Sneutrino</i> (-3)
	"u" $\rightarrow$ <i>U</i> 1   "ubar" $\rightarrow$ <i>U</i> (-1)
	"c" $\rightarrow$ <i>U</i> 2   "cbar" $\rightarrow$ <i>U</i> (-2)
	"t" $\rightarrow$ <i>U</i> 3   "tbar" $\rightarrow$ <i>U</i> (-3)
	"d" $\rightarrow$ <i>D</i> 1   "dbar" $\rightarrow$ <i>D</i> (-1)
	"s" $\rightarrow$ <i>D</i> 2   "sbar" $\rightarrow$ <i>D</i> (-2)
	"b" $\rightarrow$ <i>D</i> 3   "bbar" $\rightarrow$ <i>D</i> (-3)
	"A" $\rightarrow$ <i>Ga</i>   "Z"   "Z0" $\rightarrow$ <i>Z</i>
	"W+" $\rightarrow$ <i>Wp</i>   "W-" $\rightarrow$ <i>Wm</i>
	"gl"   "g" $\rightarrow$ <i>Gl</i>
<i>SHiggs S3</i>	"h01" $\rightarrow$ <i>SHiggs S1</i>   "h02" $\rightarrow$ <i>SHiggs S2</i>   "h03" $\rightarrow$
	"A01" $\rightarrow$ <i>PHiggs P1</i>   "A02" $\rightarrow$ <i>PHiggs P2</i>
<i>SHiggs S6</i>	"h04" $\rightarrow$ <i>SHiggs S4</i>   "h05" $\rightarrow$ <i>SHiggs S5</i>   "h06" $\rightarrow$
	"A03" $\rightarrow$ <i>PHiggs P3</i>   "A04" $\rightarrow$ <i>PHiggs P4</i>
<i>SHiggs S9</i>	"h07" $\rightarrow$ <i>SHiggs S7</i>   "h08" $\rightarrow$ <i>SHiggs S8</i>   "h09" $\rightarrow$
<i>PHiggs P7</i>	"A05" $\rightarrow$ <i>PHiggs P5</i>   "A06" $\rightarrow$ <i>PHiggs P6</i>   "A07" $\rightarrow$

(\* JR: Only the first charged Higgs. \*)

	"H+" $\rightarrow$ <i>CHiggs HC1</i>   "H-" $\rightarrow$ <i>CHiggs HC1c</i>
	"su1" $\rightarrow$ <i>Sup</i> ( <i>M1</i> , 1)   "su1c" $\rightarrow$ <i>Sup</i> ( <i>M1</i> , -1)
	"sc1" $\rightarrow$ <i>Sup</i> ( <i>M1</i> , 2)   "sc1c" $\rightarrow$ <i>Sup</i> ( <i>M1</i> , -2)
	"st1" $\rightarrow$ <i>Sup</i> ( <i>M1</i> , 3)   "st1c" $\rightarrow$ <i>Sup</i> ( <i>M1</i> , -3)
	"su2" $\rightarrow$ <i>Sup</i> ( <i>M2</i> , 1)   "su2c" $\rightarrow$ <i>Sup</i> ( <i>M2</i> , -1)
	"sc2" $\rightarrow$ <i>Sup</i> ( <i>M2</i> , 2)   "sc2c" $\rightarrow$ <i>Sup</i> ( <i>M2</i> , -2)
	"st2" $\rightarrow$ <i>Sup</i> ( <i>M2</i> , 3)   "st2c" $\rightarrow$ <i>Sup</i> ( <i>M2</i> , -3)
	"sgl"   "sg" $\rightarrow$ <i>Gluino</i>
	"sd1" $\rightarrow$ <i>Sdown</i> ( <i>M1</i> , 1)   "sd1c" $\rightarrow$ <i>Sdown</i> ( <i>M1</i> , -1)
	"ss1" $\rightarrow$ <i>Sdown</i> ( <i>M1</i> , 2)   "ss1c" $\rightarrow$ <i>Sdown</i> ( <i>M1</i> , -2)
	"sb1" $\rightarrow$ <i>Sdown</i> ( <i>M1</i> , 3)   "sb1c" $\rightarrow$ <i>Sdown</i> ( <i>M1</i> , -3)
	"sd2" $\rightarrow$ <i>Sdown</i> ( <i>M2</i> , 1)   "sd2c" $\rightarrow$ <i>Sdown</i> ( <i>M2</i> , -1)
	"ss2" $\rightarrow$ <i>Sdown</i> ( <i>M2</i> , 2)   "ss2c" $\rightarrow$ <i>Sdown</i> ( <i>M2</i> , -2)
	"sb2" $\rightarrow$ <i>Sdown</i> ( <i>M2</i> , 3)   "sb2c" $\rightarrow$ <i>Sdown</i> ( <i>M2</i> , -3)
	"neu1" $\rightarrow$ <i>Neutralino N1</i>   "neu2" $\rightarrow$ <i>Neutralino N2</i>
	"neu3" $\rightarrow$ <i>Neutralino N3</i>   "neu4" $\rightarrow$ <i>Neutralino N4</i>
	"neu5" $\rightarrow$ <i>Neutralino N5</i>   "neu6" $\rightarrow$ <i>Neutralino N6</i>
	"neu7" $\rightarrow$ <i>Neutralino N7</i>   "neu8" $\rightarrow$ <i>Neutralino N8</i>
	"neu9" $\rightarrow$ <i>Neutralino N9</i>   "neu10" $\rightarrow$ <i>Neutralino N10</i>
	"neu11" $\rightarrow$ <i>Neutralino N11</i>
	"ch1+" $\rightarrow$ <i>Chargino C1</i>   "ch2+" $\rightarrow$ <i>Chargino C2</i>
	"ch1-" $\rightarrow$ <i>Chargino C1c</i>   "ch2-" $\rightarrow$ <i>Chargino C2c</i>

```

| "ch3+" → Chargino C3 | "ch4+" → Chargino C4
| "ch3-" → Chargino C3c | "ch4-" → Chargino C4c
| "lq11" → LQ (M1,1) | "lq11c" → LQ (M1,-1)
| "lq12" → LQ (M2,1) | "lq12c" → LQ (M2,-1)
| "lq21" → LQ (M1,2) | "lq21c" → LQ (M1,-2)
| "lq22" → LQ (M2,2) | "lq22c" → LQ (M2,-2)
| "lq31" → LQ (M1,3) | "lq31c" → LQ (M1,-3)
| "lq32" → LQ (M2,3) | "lq32c" → LQ (M2,-3)
| "lqino1" → LQino 1 | "lqino1b" → LQino (-1)
| "lqino2" → LQino 2 | "lqino2b" → LQino (-2)
| "lqino3" → LQino 3 | "lqino3b" → LQino (-3)
| s → invalid_arg ("HUBABUBA:_%s_Modellib_PSSSM.ExtMSSM.flavor_of_string:" ^ s)

let flavor_to_string = function
| L 1 → "e-" | L (-1) → "e+"
| L 2 → "mu-" | L (-2) → "mu+"
| L 3 → "tau-" | L (-3) → "tau+"
| N 1 → "nue" | N (-1) → "nuebar"
| N 2 → "numu" | N (-2) → "numubar"
| N 3 → "nutau" | N (-3) → "nutaubar"
| U 1 → "u" | U (-1) → "ubar"
| U 2 → "c" | U (-2) → "cbar"
| U 3 → "t" | U (-3) → "tbar"
| U _ → invalid_arg
      "Modellib_PSSSM.ExtMSSM.flavor_to_string:_invalid_up_type_quark"
| D 1 → "d" | D (-1) → "dbar"
| D 2 → "s" | D (-2) → "sbar"
| D 3 → "b" | D (-3) → "bbar"
| D _ → invalid_arg
      "Modellib_PSSSM.ExtMSSM.flavor_to_string:_invalid_down_type_quark"
| Gl → "g1" | Gluino → "sg1"
| Ga → "A" | Z → "Z"
| Wp → "W+" | Wm → "W-"
| SHiggs S1 → "h01" | SHiggs S2 → "h02" | SHiggs S3 → "h03"
| PHiggs P1 → "A01" | PHiggs P2 → "A02"
| SHiggs S4 → "h04" | SHiggs S5 → "h05" | SHiggs S6 → "h06"
| PHiggs P3 → "A03" | PHiggs P4 → "A04"
| SHiggs S7 → "h07" | SHiggs S8 → "h08" | SHiggs S9 → "h09"
| PHiggs P5 → "A05" | PHiggs P6 → "A06" | PHiggs P7 → "A07"
(* JR: Only the first charged Higgs. *)
| CHiggs HC1 → "H+" | CHiggs HC1c → "H-"
| CHiggs HC2 → "HX_1+" | CHiggs HC2c → "HX_1-"
| CHiggs HC3 → "HX_2+" | CHiggs HC3c → "HX_2-"
| CHiggs HC4 → "HX_3+" | CHiggs HC4c → "HX_3-"
| CHiggs HC5 → "HX_4+" | CHiggs HC5c → "HX_4-"
| Slepton (M1,1) → "se1-" | Slepton (M1,-1) → "se1+"
| Slepton (M1,2) → "smu1-" | Slepton (M1,-2) → "smu1+"
| Slepton (M1,3) → "stau1-" | Slepton (M1,-3) → "stau1+"
| Slepton (M2,1) → "se2-" | Slepton (M2,-1) → "se2+"
| Slepton (M2,2) → "smu2-" | Slepton (M2,-2) → "smu2+"

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| Slepton (M2,3) → "stau2-" | Slepton (M2,-3) → "stau2+"
| Sneutrino 1 → "snue" | Sneutrino (-1) → "snue*"
| Sneutrino 2 → "snumu" | Sneutrino (-2) → "snumu*"
| Sneutrino 3 → "snutau" | Sneutrino (-3) → "snutau*"
| Sup (M1,1) → "su1" | Sup (M1,-1) → "su1c"
| Sup (M1,2) → "sc1" | Sup (M1,-2) → "sc1c"
| Sup (M1,3) → "st1" | Sup (M1,-3) → "st1c"
| Sup (M2,1) → "su2" | Sup (M2,-1) → "su2c"
| Sup (M2,2) → "sc2" | Sup (M2,-2) → "sc2c"
| Sup (M2,3) → "st2" | Sup (M2,-3) → "st2c"
| Sdown (M1,1) → "sd1" | Sdown (M1,-1) → "sd1c"
| Sdown (M1,2) → "ss1" | Sdown (M1,-2) → "ss1c"
| Sdown (M1,3) → "sb1" | Sdown (M1,-3) → "sb1c"
| Sdown (M2,1) → "sd2" | Sdown (M2,-1) → "sd2c"
| Sdown (M2,2) → "ss2" | Sdown (M2,-2) → "ss2c"
| Sdown (M2,3) → "sb2" | Sdown (M2,-3) → "sb2c"
| Neutralino n → "neu" ^ string_of_neu n
| Chargino C1 → "ch1+" | Chargino C1c → "ch1-"
| Chargino C2 → "ch2+" | Chargino C2c → "ch2-"
| Chargino C3 → "ch3+" | Chargino C3c → "ch3-"
| Chargino C4 → "ch4+" | Chargino C4c → "ch4-"
| LQ (M1,1) → "lq11" | LQ (M1,-1) → "lq11c"
| LQ (M2,1) → "lq12" | LQ (M2,-1) → "lq12c"
| LQ (M1,2) → "lq21" | LQ (M1,-2) → "lq21c"
| LQ (M2,2) → "lq22" | LQ (M2,-2) → "lq22c"
| LQ (M1,3) → "lq31" | LQ (M1,-3) → "lq31c"
| LQ (M2,3) → "lq32" | LQ (M2,-3) → "lq32c"
| LQino 1 → "lqino1" | LQino (-1) → "lqino1b"
| LQino 2 → "lqino2" | LQino (-2) → "lqino2b"
| LQino 3 → "lqino3" | LQino (-3) → "lqino3b"
| _ → invalid_arg "Modellib_PSSSM.ExtMSSM.flavor_to_string"

let flavor_to_TeX = function
| L 1 → "e~-" | L (-1) → "e~+"
| L 2 → "\\mu~-" | L (-2) → "\\mu~+"
| L 3 → "\\tau~-" | L (-3) → "\\tau~+"
| N 1 → "\\nu_e" | N (-1) → "\\bar{\\nu}_e"
| N 2 → "\\nu_\\mu" | N (-2) → "\\bar{\\nu}_\\mu"
| N 3 → "\\nu_\\tau" | N (-3) → "\\bar{\\nu}_\\tau"
| U 1 → "u" | U (-1) → "\\bar{u}"
| U 2 → "c" | U (-2) → "\\bar{c}"
| U 3 → "t" | U (-3) → "\\bar{t}"
| D 1 → "d" | D (-1) → "\\bar{d}"
| D 2 → "s" | D (-2) → "\\bar{s}"
| D 3 → "b" | D (-3) → "\\bar{b}"
| L _ → invalid_arg
|         "Modellib_PSSSM.ExtMSSM.flavor_to_TeX:~invalid~lepton"
| N _ → invalid_arg
|         "Modellib_PSSSM.ExtMSSM.flavor_to_TeX:~invalid~neutrino"
| U _ → invalid_arg

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      "Modellib_PSSSM.ExtMSSM.flavor_to_TeX:invalid_up_type_quark"
| D - → invalid_arg
      "Modellib_PSSSM.ExtMSSM.flavor_to_TeX:invalid_down_type_quark"
| Gl → "g" | Gluino → "\\widetilde{g}"
| Ga → "\\gamma" | Z → "Z" | Wp → "W^+" | Wm → "W^-
| SHiggs S1 → "S_1" | SHiggs S2 → "S_2" | SHiggs S3 → "S_3"
| SHiggs S4 → "S_4" | SHiggs S5 → "S_5" | SHiggs S6 → "S_6"
| SHiggs S7 → "S_7" | SHiggs S8 → "S_8" | SHiggs S9 → "S_9"
| PHiggs P1 → "P_1" | PHiggs P2 → "P_2" | PHiggs P3 → "P_3"
| PHiggs P4 → "P_4" | PHiggs P5 → "P_5" | PHiggs P6 → "P_6"
| PHiggs P7 → "P_7"
| CHiggs HC1 → "H^+" | CHiggs HC1c → "H^-"
| CHiggs HC2 → "X_{H,1}^+" | CHiggs HC2c → "X_{H,1}^-"
| CHiggs HC3 → "X_{H,2}^+" | CHiggs HC3c → "X_{H,2}^-"
| CHiggs HC4 → "X_{H,3}^+" | CHiggs HC4c → "X_{H,3}^-"
| CHiggs HC5 → "X_{H,4}^+" | CHiggs HC5c → "X_{H,4}^-"
| Slepton (M1,1) → "\\widetilde{e}_1^-"
| Slepton (M1,-1) → "\\widetilde{e}_1^+"
| Slepton (M1,2) → "\\widetilde{\\mu}_1^-"
| Slepton (M1,-2) → "\\widetilde{\\mu}_1^+"
| Slepton (M1,3) → "\\widetilde{\\tau}_1^-"
| Slepton (M1,-3) → "\\widetilde{\\tau}_1^+"
| Slepton (M2,1) → "\\widetilde{e}_2^-"
| Slepton (M2,-1) → "\\widetilde{e}_2^+"
| Slepton (M2,2) → "\\widetilde{\\mu}_2^-"
| Slepton (M2,-2) → "\\widetilde{\\mu}_2^+"
| Slepton (M2,3) → "\\widetilde{\\tau}_2^-"
| Slepton (M2,-3) → "\\widetilde{\\tau}_2^+"
| Sneutrino 1 → "\\widetilde{\\nu}_e"
| Sneutrino (-1) → "\\widetilde{\\nu}_e^*"
| Sneutrino 2 → "\\widetilde{\\nu}_\\mu"
| Sneutrino (-2) → "\\widetilde{\\nu}_\\mu^*"
| Sneutrino 3 → "\\widetilde{\\nu}_\\tau"
| Sneutrino (-3) → "\\widetilde{\\nu}_\\tau^*"
| Sup (M1,1) → "\\widetilde{u}_1"
| Sup (M1,-1) → "\\widetilde{u}_1^*"
| Sup (M1,2) → "\\widetilde{c}_1"
| Sup (M1,-2) → "\\widetilde{c}_1^*"
| Sup (M1,3) → "\\widetilde{t}_1"
| Sup (M1,-3) → "\\widetilde{t}_1^*"
| Sup (M2,1) → "\\widetilde{u}_2"
| Sup (M2,-1) → "\\widetilde{u}_2^*"
| Sup (M2,2) → "\\widetilde{c}_2"
| Sup (M2,-2) → "\\widetilde{c}_2^*"
| Sup (M2,3) → "\\widetilde{t}_2"
| Sup (M2,-3) → "\\widetilde{t}_2^*"
| Sdown (M1,1) → "\\widetilde{d}_1"
| Sdown (M1,-1) → "\\widetilde{d}_1^*"
| Sdown (M1,2) → "\\widetilde{s}_1"
| Sdown (M1,-2) → "\\widetilde{s}_1^*"

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| Sdown (M1,3) → "\\widetilde{b}_1"
| Sdown (M1,-3) → "\\widetilde{b}_1^*"
| Sdown (M2,1) → "\\widetilde{d}_2"
| Sdown (M2,-1) → "\\widetilde{d}_2^*"
| Sdown (M2,2) → "\\widetilde{s}_2"
| Sdown (M2,-2) → "\\widetilde{s}_2^*"
| Sdown (M2,3) → "\\widetilde{b}_2"
| Sdown (M2,-3) → "\\widetilde{b}_2^*"
| Neutralino N1 → "\\widetilde{\\chi}^0_1"
| Neutralino N2 → "\\widetilde{\\chi}^0_2"
| Neutralino N3 → "\\widetilde{\\chi}^0_3"
| Neutralino N4 → "\\widetilde{\\chi}^0_4"
| Neutralino N5 → "\\widetilde{\\chi}^0_5"
| Neutralino N6 → "\\widetilde{\\chi}^0_6"
| Neutralino N7 → "\\widetilde{\\chi}^0_7"
| Neutralino N8 → "\\widetilde{\\chi}^0_8"
| Neutralino N9 → "\\widetilde{\\chi}^0_9"
| Neutralino N10 → "\\widetilde{\\chi}^0_{10}"
| Neutralino N11 → "\\widetilde{\\chi}^0_{11}"
| Slepton _ → invalid_arg
| "Modellib_PSSSM.ExtMSSM.flavor_to_TeX:␣invalid␣slepton"
| Sneutrino _ → invalid_arg
| "Modellib_PSSSM.ExtMSSM.flavor_to_TeX:␣invalid␣sneutrino"
| Sup _ → invalid_arg
| "Modellib_PSSSM.ExtMSSM.flavor_to_TeX:␣invalid␣up␣type␣squark"
| Sdown _ → invalid_arg
| "Modellib_PSSSM.ExtMSSM.flavor_to_TeX:␣invalid␣down␣type␣squark"
| Chargino C1 → "\\widetilde{\\chi}^+_1"
| Chargino C1c → "\\widetilde{\\chi}^+_{-1}"
| Chargino C2 → "\\widetilde{\\chi}^+_2"
| Chargino C2c → "\\widetilde{\\chi}^+_{-2}"
| Chargino C3 → "\\widetilde{\\chi}^+_3"
| Chargino C3c → "\\widetilde{\\chi}^+_{-3}"
| Chargino C4 → "\\widetilde{\\chi}^+_4"
| Chargino C4c → "\\widetilde{\\chi}^+_{-4}"
| LQ (M1,1) → "D_{1,,1}" | LQ (M1,-1) → "D_{1,,1}^*"
| LQ (M2,1) → "D_{1,,2}" | LQ (M2,-1) → "D_{1,,2}^*"
| LQ (M1,2) → "D_{2,,1}" | LQ (M1,-2) → "D_{2,,1}^*"
| LQ (M2,2) → "D_{2,,2}" | LQ (M2,-2) → "D_{2,,2}^*"
| LQ (M1,3) → "D_{3,,1}" | LQ (M1,-3) → "D_{3,,1}^*"
| LQ (M2,3) → "D_{3,,2}" | LQ (M2,-3) → "D_{3,,2}^*"
| LQino 1 → "\\widetilde{D}_1" | LQino (-1) → "\\bar\\widetilde{D}_1"
| LQino 2 → "\\widetilde{D}_2" | LQino (-2) → "\\bar\\widetilde{D}_2"
| LQino 3 → "\\widetilde{D}_3" | LQino (-3) → "\\bar\\widetilde{D}_3"
| LQ _ → invalid_arg
| "Modellib_PSSSM.ExtMSSM.flavor_to_TeX:␣invalid␣leptoquark␣type"
| LQino _ → invalid_arg
| "Modellib_PSSSM.ExtMSSM.flavor_to_TeX:␣invalid␣leptoquarkino␣type"

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let *flavor\_symbol* = function

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| L g when g > 0 → "l" ^ string_of_int g
| L g → "l" ^ string_of_int (abs g) ^ "b"
| N g when g > 0 → "n" ^ string_of_int g
| N g → "n" ^ string_of_int (abs g) ^ "b"
| U g when g > 0 → "u" ^ string_of_int g
| U g → "u" ^ string_of_int (abs g) ^ "b"
| D g when g > 0 → "d" ^ string_of_int g
| D g → "d" ^ string_of_int (abs g) ^ "b"
| Gl → "gl"
| Ga → "a" | Z → "z"
| Wp → "wp" | Wm → "wm"
| Slepton (M1, g) when g > 0 → "sl1" ^ string_of_int g
| Slepton (M1, g) → "sl1c" ^ string_of_int (abs g)
| Slepton (M2, g) when g > 0 → "sl2" ^ string_of_int g
| Slepton (M2, g) → "sl2c" ^ string_of_int (abs g)
| Sneutrino g when g > 0 → "sn" ^ string_of_int g
| Sneutrino g → "snc" ^ string_of_int (abs g)
| Sup (M1, g) when g > 0 → "su1" ^ string_of_int g
| Sup (M1, g) → "su1c" ^ string_of_int (abs g)
| Sup (M2, g) when g > 0 → "su2" ^ string_of_int g
| Sup (M2, g) → "su2c" ^ string_of_int (abs g)
| Sdown (M1, g) when g > 0 → "sd1" ^ string_of_int g
| Sdown (M1, g) → "sd1c" ^ string_of_int (abs g)
| Sdown (M2, g) when g > 0 → "sd2" ^ string_of_int g
| Sdown (M2, g) → "sd2c" ^ string_of_int (abs g)
| Neutralino n → "neu" ^ (string_of_neu n)
| Chargino c when (int_of_char c) > 0 → "cp" ^ string_of_char c
| Chargino c → "cm" ^ string_of_int (abs (int_of_char c))
| Gluino → "sgl"
| SHiggs s → "h0" ^ (string_of_shiggs s)
| PHiggs p → "A0" ^ (string_of_phiggs p)
| CHiggs HC1 → "hp" | CHiggs HC1c → "hm"
| CHiggs _ → invalid_arg "charged_Higgs_not_yet_implemented"
| LQ (M1, g) when g > 0 → "lq" ^ string_of_int g ^ "1"
| LQ (M1, g) → "lq" ^ string_of_int (abs g) ^ "1c"
| LQ (M2, g) when g > 0 → "lq" ^ string_of_int g ^ "2"
| LQ (M2, g) → "lq" ^ string_of_int (abs g) ^ "2c"
| LQino g when g > 0 → "lqino" ^ string_of_int g
| LQino g → "lqino" ^ string_of_int (abs g) ^ "b"

let pdg = function
| L g when g > 0 → 9 + 2 × g
| L g → - 9 + 2 × g
| N g when g > 0 → 10 + 2 × g
| N g → - 10 + 2 × g
| U g when g > 0 → 2 × g
| U g → 2 × g
| D g when g > 0 → - 1 + 2 × g
| D g → 1 + 2 × g
| Gl → 21

```

```

|  $Ga \rightarrow 22$  |  $Z \rightarrow 23$ 
|  $Wp \rightarrow 24$  |  $Wm \rightarrow (-24)$ 
|  $SHiggs\ S1 \rightarrow 25$  |  $SHiggs\ S2 \rightarrow 35$  |  $PHiggs\ P1 \rightarrow 36$ 
(* JR: Only the first charged Higgs. *)
|  $CHiggs\ HC1 \rightarrow 37$  |  $CHiggs\ HC1c \rightarrow (-37)$ 
|  $CHiggs\ - \rightarrow invalid\_arg\ "charged\_Higgs\_not\_yet\_implemented"$ 
|  $Slepton\ (M1, g) \text{ when } g > 0 \rightarrow 1000009 + 2 \times g$ 
|  $Slepton\ (M1, g) \rightarrow -1000009 + 2 \times g$ 
|  $Slepton\ (M2, g) \text{ when } g > 0 \rightarrow 2000009 + 2 \times g$ 
|  $Slepton\ (M2, g) \rightarrow -2000009 + 2 \times g$ 
|  $Sneutrino\ g \text{ when } g > 0 \rightarrow 1000010 + 2 \times g$ 
|  $Sneutrino\ g \rightarrow -1000010 + 2 \times g$ 
|  $Sup\ (M1, g) \text{ when } g > 0 \rightarrow 1000000 + 2 \times g$ 
|  $Sup\ (M1, g) \rightarrow -1000000 + 2 \times g$ 
|  $Sup\ (M2, g) \text{ when } g > 0 \rightarrow 2000000 + 2 \times g$ 
|  $Sup\ (M2, g) \rightarrow -2000000 + 2 \times g$ 
|  $Sdown\ (M1, g) \text{ when } g > 0 \rightarrow 999999 + 2 \times g$ 
|  $Sdown\ (M1, g) \rightarrow -999999 + 2 \times g$ 
|  $Sdown\ (M2, g) \text{ when } g > 0 \rightarrow 1999999 + 2 \times g$ 
|  $Sdown\ (M2, g) \rightarrow -1999999 + 2 \times g$ 
|  $Gluino \rightarrow 1000021$ 
(* JR: only the first two charginos. *)
|  $Chargino\ C1 \rightarrow 1000024$  |  $Chargino\ C1c \rightarrow (-1000024)$ 
|  $Chargino\ C2 \rightarrow 1000037$  |  $Chargino\ C2c \rightarrow (-1000037)$ 
|  $Chargino\ C3 \rightarrow 1000039$  |  $Chargino\ C3c \rightarrow (-1000039)$ 
|  $Chargino\ C4 \rightarrow 1000041$  |  $Chargino\ C4c \rightarrow (-1000041)$ 
|  $Neutralino\ N1 \rightarrow 1000022$  |  $Neutralino\ N2 \rightarrow 1000023$ 
|  $Neutralino\ N3 \rightarrow 1000025$  |  $Neutralino\ N4 \rightarrow 1000035$ 
(* According to SLHA2 (not anymore !?)*
|  $Neutralino\ N5 \rightarrow 1000045$  |  $Neutralino\ N6 \rightarrow 1000046$ 
|  $Neutralino\ N7 \rightarrow 1000047$  |  $Neutralino\ N8 \rightarrow 1000048$ 
|  $Neutralino\ N9 \rightarrow 1000049$  |  $Neutralino\ N10 \rightarrow 1000050$ 
|  $Neutralino\ N11 \rightarrow 1000051$ 
|  $PHiggs\ P2 \rightarrow 46$  |  $PHiggs\ P3 \rightarrow 47$  |  $PHiggs\ P4 \rightarrow 48$ 
|  $PHiggs\ P5 \rightarrow 49$  |  $PHiggs\ P6 \rightarrow 50$  |  $PHiggs\ P7 \rightarrow 51$ 
|  $SHiggs\ S3 \rightarrow 45$  |  $SHiggs\ S4 \rightarrow 52$  |  $SHiggs\ S5 \rightarrow 53$ 
|  $SHiggs\ S6 \rightarrow 54$  |  $SHiggs\ S7 \rightarrow 55$  |  $SHiggs\ S8 \rightarrow 56$ 
|  $SHiggs\ S9 \rightarrow 57$ 
|  $LQ\ (M1, g) \text{ when } g > 0 \rightarrow 1000059 + g$ 
|  $LQ\ (M1, g) \rightarrow -1000059 + g$ 
|  $LQ\ (M2, g) \text{ when } g > 0 \rightarrow 2000059 + g$ 
|  $LQ\ (M2, g) \rightarrow -2000059 + g$ 
|  $LQino\ g \text{ when } g > 0 \rightarrow 59 + g$ 
|  $LQino\ g \rightarrow -59 + g$ 

```

We must take care of the pdg numbers for the two different kinds of sfermions in the MSSM. The particle data group in its Monte Carlo particle numbering scheme takes only into account mixtures of the third generation squarks and the stau. For the other sfermions we will use the number of the lefthanded field for the lighter mixed state and the one for the righthanded for the heavier. Below

are the official pdg numbers from the Particle Data Group. In order not to produce arrays with some million entries in the Fortran code for the masses and the widths we introduce our private pdg numbering scheme which only extends not too far beyond 42. Our private scheme then has the following pdf numbers (for the sparticles the subscripts  $L/R$  and  $1/2$  are taken synonymously):



$d$	down-quark	1
$u$	up-quark	2
$s$	strange-quark	3
$c$	charm-quark	4
$b$	bottom-quark	5
$t$	top-quark	6
$e^-$	electron	11
$\nu_e$	electron-neutrino	12
$\mu^-$	muon	13
$\nu_\mu$	muon-neutrino	14
$\tau^-$	tau	15
$\nu_\tau$	tau-neutrino	16
$g$	gluon	(9) 21
$\gamma$	photon	22
$Z^0$	Z-boson	23
$W^+$	W-boson	24
$h^0$	light Higgs boson	25
$H^0$	heavy Higgs boson	35
$A^0$	pseudoscalar Higgs	36
$H^\pm$	charged Higgs	37
$\tilde{d}_L$	down-squark 1	41
$\tilde{u}_L$	up-squark 1	42
$\tilde{s}_L$	strange-squark 1	43
$\tilde{c}_L$	charm-squark 1	44
$\tilde{b}_L$	bottom-squark 1	45
$\tilde{t}_L$	top-squark 1	46
$\tilde{d}_R$	down-squark 2	47
$\tilde{u}_R$	up-squark 2	48
$\tilde{s}_R$	strange-squark 2	49
$\tilde{c}_R$	charm-squark 2	50
$\tilde{b}_R$	bottom-squark 2	51
$\tilde{t}_R$	top-squark 2	52
$\tilde{e}_L$	selectron 1	53
$\tilde{\nu}_{e,L}$	electron-sneutrino	54
$\tilde{\mu}_L$	smuon 1	55
$\tilde{\nu}_{\mu,L}$	muon-sneutrino	56
$\tilde{\tau}_L$	stau 1	57
$\tilde{\nu}_{\tau,L}$	tau-sneutrino	58
$\tilde{e}_R$	selectron 2	59
$\tilde{\mu}_R$	smuon 2	61
$\tilde{\tau}_R$	stau 2	63
$\tilde{g}$	gluino 558	64
$\tilde{\chi}_1^0$	neutralino 1	65
$\tilde{\chi}_2^0$	neutralino 2	66
$\tilde{\chi}_3^0$	neutralino 3	67
$\tilde{\chi}_4^0$	neutralino 4	68
$\tilde{\chi}_5^0$	neutralino 5	69
$\tilde{\chi}_1^\pm$	chargino 1	70

```

let pdg_mw = function
| L g when g > 0 → 9 + 2 × g
| L g → - 9 + 2 × g
| N g when g > 0 → 10 + 2 × g
| N g → - 10 + 2 × g
| U g when g > 0 → 2 × g
| U g → 2 × g
| D g when g > 0 → - 1 + 2 × g
| D g → 1 + 2 × g
| Gl → 21
| Ga → 22 | Z → 23
| Wp → 24 | Wm → (-24)
| SHiggs S1 → 25 | SHiggs S2 → 35 | PHiggs P1 → 36
(* JR: Only the first charged Higgs. *)
| CHiggs HC1 → 37 | CHiggs HC1c → (-37)
| CHiggs _ → invalid_arg "charged_Higgs_not_yet_implemented"
| Sup (M1, g) when g > 0 → 40 + 2 × g
| Sup (M1, g) → - 40 + 2 × g
| Sup (M2, g) when g > 0 → 46 + 2 × g
| Sup (M2, g) → - 46 + 2 × g
| Sdown (M1, g) when g > 0 → 39 + 2 × g
| Sdown (M1, g) → - 39 + 2 × g
| Sdown (M2, g) when g > 0 → 45 + 2 × g
| Sdown (M2, g) → - 45 + 2 × g
| Slepton (M1, g) when g > 0 → 51 + 2 × g
| Slepton (M1, g) → - 51 + 2 × g
| Slepton (M2, g) when g > 0 → 57 + 2 × g
| Slepton (M2, g) → - 57 + 2 × g
| Sneutrino g when g > 0 → 52 + 2 × g
| Sneutrino g → - 52 + 2 × g
| Gluino → 64
(* JR: Only the first two charginos. *)
| Chargino C1 → 70 | Chargino C1c → (-70)
| Chargino C2 → 71 | Chargino C2c → (-71)
| Chargino C3 → 106 | Chargino C3c → (-106)
| Chargino C4 → 107 | Chargino C4c → (-107)
| Neutralino N1 → 65 | Neutralino N2 → 66
| Neutralino N3 → 67 | Neutralino N4 → 68
| Neutralino N5 → 69 | Neutralino N6 → 100
| Neutralino N7 → 101 | Neutralino N8 → 102
| Neutralino N9 → 103 | Neutralino N10 → 104
| Neutralino N11 → 105
| PHiggs P2 → 72 | PHiggs P3 → 89 | PHiggs P4 → 90
| PHiggs P5 → 91 | PHiggs P6 → 92 | PHiggs P7 → 93
| SHiggs S3 → 73 | SHiggs S4 → 94 | SHiggs S5 → 95
| SHiggs S6 → 96 | SHiggs S7 → 97 | SHiggs S8 → 98
| SHiggs S9 → 99
| LQ (M1, g) when g > 0 → 78 + 2 × g
| LQ (M1, g) → - 78 + 2 × g
| LQ (M2, g) when g > 0 → 79 + 2 × g

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|  $LQ(M2, g) \rightarrow -79 + 2 \times g$ 
|  $LQino\ g\ \text{when } g > 0 \rightarrow 85 + g$ 
|  $LQino\ g \rightarrow -85 + g$ 

let mass_symbol f =
  "mass(" ^ string_of_int (abs (pdg-mw f)) ^ ")"

let width_symbol f =
  "width(" ^ string_of_int (abs (pdg-mw f)) ^ ")"

let conj_symbol = function
| false, str → str
| true, str → str ^ "_c"

let constant_symbol = function
| E → "e" | G → "g" | G_Z → "gz"
| Q_lepton → "qlep" | Q_up → "qup" | Q_down → "qdwn"
| Q_charg → "qchar"
| G_NC_lepton → "gnclep" | G_NC_neutrino → "gncneu"
| G_NC_up → "gncup" | G_NC_down → "gncdwn"
| G_CC → "gcc"
| G_CCQ (vc, g1, g2) → conj_symbol (vc, "g-ccq") ^ "(" ^
  string_of_int g1 ^ ", " ^ string_of_int g2 ^ ")"
| I_Q_W → "iqw" | I_G_ZWW → "igzww"
| G_WWWW → "gw4" | G_ZZWW → "gzzww"
| G_PZWW → "gpzww" | G_PPWW → "gppww"
| G_GH4_ZZPP (p1, p2) → "g-ZZA0A0(" ^ string_of_phiggs p1 ^ ", " ^
  string_of_phiggs p2 ^ ")"
| G_GH4_ZZSS (s1, s2) → "g-ZZh0h0(" ^ string_of_shiggs s1 ^ ", " ^
  string_of_shiggs s2 ^ ")"
| G_GH4_ZZCC → "g-zzhphm"
| G_GH4_GaGaCC → "g-AAhphm"
| G_GH4_ZGaCC → "g-zAhphm"
| G_GH4_WWCC → "g-wwhphm"
| G_GH4_WWPP (p1, p2) → "g-WWA0A0(" ^ string_of_phiggs p1 ^ ", " ^
  string_of_phiggs p2 ^ ")"
| G_GH4_WWSS (s1, s2) → "g-WWh0h0(" ^ string_of_shiggs s1 ^ ", " ^
  string_of_shiggs s2 ^ ")"
| G_GH4_ZWSC s → "g-ZWhph0(" ^ string_of_shiggs s ^ ")"
| G_GH4_GaWSC s → "g-AWhph0(" ^ string_of_shiggs s ^ ")"
| G_GH4_ZWPC p → "g-ZWhpA0(" ^ string_of_phiggs p ^ ")"
| G_GH4_GaWPC p → "g-AWhpA0(" ^ string_of_phiggs p ^ ")"
| G_CICIS (n1, n2, s) → "g-neuneuh0(" ^ string_of_neu n1 ^ ", " ^
  string_of_neu n2 ^ ", " ^ string_of_shiggs s ^ ")"
| G_CICIP (n1, n2, p) → "g-neuneuA0(" ^ string_of_neu n1 ^ ", " ^
  string_of_neu n2 ^ ", " ^ string_of_phiggs p ^ ")"
| G_H3_SCC s → "g-h0hphm(" ^ string_of_shiggs s ^ ")"
| G_H3_SPP (s, p1, p2) → "g-h0A0A0(" ^ string_of_shiggs s ^ ", " ^
  string_of_phiggs p1 ^ ", " ^ string_of_phiggs p2 ^ ")"
| G_H3_SSS (s1, s2, s3) → "g-h0h0h0(" ^ string_of_shiggs s1 ^ ", " ^
  string_of_shiggs s2 ^ ", " ^ string_of_shiggs s3 ^ ")"
| G_CSC (c1, c2, s) → "g-chchh0(" ^ string_of_char c1 ^ ", " ^

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    string_of_char c2 ^ "," ^ string_of_shiggs s ^ ")"
| G_CPC (c1, c2, p) → "g_chchA0(" ^ string_of_char c1 ^ "," ^
    string_of_char c2 ^ "," ^ string_of_phiggs p ^ ")"
| G_YUK_FFS (f1, f2, s) → "g-yuk_h0-" ^ string_of_fermion_type f1 ^
    string_of_fermion_type f2 ^ "(" ^ string_of_shiggs s ^ "," ^
    string_of_fermion_gen f1 ^ ")"
| G_YUK_FFP (f1, f2, p) → "g-yuk_A0-" ^ string_of_fermion_type f1 ^
    string_of_fermion_type f2 ^ "(" ^ string_of_phiggs p ^ "," ^
    string_of_fermion_gen f1 ^ ")"
| G_YUK_LCN g → "g-yuk_hp_ln(" ^ string_of_int g ^ ")"
| G_NWC (n, c) → "g_nwc(" ^ string_of_char c ^ "," ^ string_of_neu n ^ ")"
| G_CWN (c, n) → "g_cwn(" ^ string_of_char c ^ "," ^ string_of_neu n ^ ")"
| G_SLSNW (vc, g, m) → conj_symbol (vc, "g_wsln") ^ "(" ^ string_of_int g
    ^ "," ^ string_of_sfm m ^ ")"
| G_NZN (n1, n2) → "g_zneuneu(" ^ string_of_neu n1 ^ "," ^
    string_of_neu n2 ^ ")"
| G_CZC (c1, c2) → "g_zchch(" ^ string_of_char c1 ^ "," ^
    string_of_char c2 ^ ")"
| Gs → "gs"
| G_YUK_UCD (n, m) → "g-yuk_hp_ud(" ^ string_of_int n ^ "," ^
    string_of_int m ^ ")"
| G_YUK_DCU (n, m) → "g-yuk_hm_du(" ^ string_of_int n ^ "," ^
    string_of_int m ^ ")"
| G_YUK_N (vc, f, n, sf, m) → conj_symbol (vc, "g-yuk_neu-" ^
    string_of_fermion_type f ^ string_of_sff sf) ^ "(" ^
    string_of_fermion_gen f ^ "," ^ string_of_neu n ^ "," ^
    string_of_sfm m ^ ")"
| G_YUK_G (vc, f, sf, m) → conj_symbol (vc, "g-yuk_gluino-" ^
    string_of_fermion_type f ^ string_of_sff sf) ^ "(" ^
    string_of_fermion_gen f ^ "," ^ string_of_sfm m ^ ")"
| G_YUK_C (vc, f, c, sf, m) → conj_symbol (vc, "g-yuk_char-" ^
    string_of_fermion_type f ^ string_of_sff sf) ^ "(" ^
    string_of_fermion_gen f ^ "," ^ string_of_char c ^ "," ^
    string_of_sfm m ^ ")"
| G_YUK_Q (vc, g1, f, c, sf, m) → conj_symbol (vc, "g-yuk_char-" ^
    string_of_fermion_type f ^ string_of_sff sf) ^ "(" ^ string_of_int g1 ^
    "," ^ string_of_fermion_gen f ^ "," ^ string_of_char c ^ "," ^
    string_of_sfm m ^ ")"
| G_WPSUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "g_wA_susd") ^ "(" ^
    string_of_int g1 ^ "," ^ string_of_int g2 ^ "," ^ string_of_sfm m1 ^
    "," ^ string_of_sfm m2 ^ ")"
| G_WZSUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "g_wz_susd") ^ "(" ^
    string_of_int g1 ^ "," ^ string_of_int g2 ^ "," ^ string_of_sfm m1
    ^ "," ^ string_of_sfm m2 ^ ")"

```

(\* 3vertex: Higgs-Gauge a la Franke-Fraas \*)

Nomenclature consistent with *flavor\_of\_string*

```

| G_GH_ZSP (s, p) → "g_zh0a0(" ^ string_of_shiggs s ^ "," ^
    string_of_phiggs p ^ ")"
| G_GH_WSC s → "g_Whph0(" ^ string_of_shiggs s ^ ")"

```

```

| G_GH_WPC p → "g_WhpA0(" ^ string_of_phiggs p ^ ")"
| G_GH_ZZS s → "g_ZZh0(" ^ string_of_shiggs s ^ ")"
| G_GH_WWS s → "g_WWh0(" ^ string_of_shiggs s ^ ")"
| G_GH_ZCC → "g_Zhmhp"
| G_GH_GaCC → "g_Ahmhp"
| G_ZSF (f, g, m1, m2) → "g-z" ^ string_of_sff f ^ string_of_sff f ^ "(" ^
    string_of_int g ^ ", " ^ string_of_sfm m1 ^ ", " ^ string_of_sfm m2 ^ ")"
| G_HSNSL (vc, g, m) → conj_symbol (vc, "g_hp_sl" ^ string_of_sfm m ^ "sn1")
    ^ "(" ^ string_of_int g ^ ")"
| G_GlGLSQSQ → "g-gg-sqsq"
| G_PPSFSF f → "g-AA-" ^ string_of_sff f ^ string_of_sff f
| G_ZZSFSF (f, g, m1, m2) → "g-zz-" ^ string_of_sff f ^ string_of_sff f ^ "(" ^
    string_of_int g ^ ", " ^ string_of_sfm m1 ^ ", " ^ string_of_sfm m2 ^ ")"
| G_ZPSFSF (f, g, m1, m2) → "g-zA-" ^ string_of_sff f ^ string_of_sff f ^ "(" ^
    string_of_int g ^ ", " ^ string_of_sfm m1 ^ ", " ^ string_of_sfm m2 ^ ")"
| G_GlPSQSQ → "g-gA-sqsq"
| G_GLZSFSF (f, g, m1, m2) → "g-gz-" ^ string_of_sff f ^ string_of_sff f ^
    "(" ^ string_of_int g ^ ", " ^ string_of_sfm m1 ^ ", " ^ string_of_sfm
    m2 ^ ")"
| G_GlWSUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "g-gw-susd") ^ "(" ^
    string_of_int g1 ^ ", " ^ string_of_int g2 ^ ", " ^ string_of_sfm m1 ^ ", "
    ^ string_of_sfm m2 ^ ")"
| G_strong → "gs" | G_SS → "gs**2"
| I_G_S → "igs"
| G_NHC (vc, n, c) → conj_symbol (vc, "g_neuhmchar") ^ "(" ^
    string_of_neu n ^ ", " ^ string_of_char c ^ ")"
| G_WWSFSF (f, g, m1, m2) → "g-ww-" ^ string_of_sff f ^ string_of_sff f ^
    "(" ^ string_of_int g ^ ", " ^ string_of_sfm m1 ^ ", " ^ string_of_sfm m2
    ^ ")"
| G_WPSLSN (vc, g, m) → conj_symbol (vc, "g-wA-slslsn") ^ "(" ^ string_of_int g
    ^ ", " ^ string_of_sfm m ^ ")"
| G_WZLSN (vc, g, m) → conj_symbol (vc, "g-wz-slslsn") ^ "(" ^ string_of_int
    g ^ ", " ^ string_of_sfm m ^ ")"
| G_SFSFS (s, f, g, m1, m2) → "g-h0-" ^ string_of_sff f ^ string_of_sfm m1
    ^ string_of_sff f ^ string_of_sfm m2 ^ "(" ^ string_of_shiggs s ^ ", " ^
    string_of_int g ^ ")"
| G_SFSFP (p, f, g, m1, m2) → "g-A0-" ^ string_of_sff f ^ string_of_sfm m1
    ^ string_of_sff f ^ string_of_sfm m2 ^ "(" ^ string_of_phiggs p ^ ", " ^
    string_of_int g ^ ")"
| G_HSUSD (vc, m1, m2, g1, g2) → conj_symbol (vc, "g_hp-su" ^ string_of_sfm m1
    ^ "sd" ^ string_of_sfm m2) ^ "(" ^ string_of_int g1 ^ ", "
    ^ string_of_int g2 ^ ")"
| G_WSQ (vc, g1, g2, m1, m2) → conj_symbol (vc, "g-wsusd") ^ "(" ^
    string_of_int g1 ^ ", " ^ string_of_int g2 ^ ", " ^ string_of_sfm m1 ^
    ", " ^ string_of_sfm m2 ^ ")"
| G_YUK_LQ_S (g1, s, g3) → "g-yuk_lq-s(" ^ string_of_int g1 ^ ", " ^
    string_of_shiggs s ^ ", " ^ string_of_int g3 ^ ")"
| G_YUK_LQ_P (g1, p, g3) → "g-yuk_lq-p(" ^ string_of_int g1 ^ ", " ^
    string_of_phiggs p ^ ", " ^ string_of_int g3 ^ ")"
| G_LQ_NEU (m, g1, g2, n) → "g_lq-neu(" ^ string_of_sfm m ^ ", " ^

```

```

      string_of_int g1 ^ "," ^ string_of_int g2 ^ "," ^ string_of_neu n ^ ")"
| G_LQ_GG (m, g1, g2) → "g_lq_gg(" ^ string_of_sfm m ^ "," ^
      string_of_int g1 ^ "," ^ string_of_int g2 ^ ")"
| G_LQ_EC_UC (vc, m, g1, g2, g3) → conj_symbol(vc, "g_lq_ec_uc") ^ "(" ^
      string_of_sfm m ^ "," ^ string_of_int g1 ^ "," ^ string_of_int g2 ^ "," ^
      ^ string_of_int g3 ^ ")"
| G_LQ_SSU (m1, m2, m3, g1, g2, g3) → "g_lq_sst(" ^ string_of_sfm m1 ^ "," ^
      string_of_sfm m2 ^ "," ^ string_of_sfm m3 ^ "," ^ string_of_int g1 ^ "," ^
      string_of_int g2 ^ "," ^ string_of_int g3 ^ ")"
| G_LQ_SSD (m1, m2, g1, g2, g3) → "g_lq_ssta(" ^ string_of_sfm m1 ^ "," ^
      string_of_sfm m2 ^ "," ^ string_of_int g1 ^ "," ^ string_of_int g2 ^
      ^ string_of_int g3 ^ ")"
| G_LQ_S (m1, m2, g1, s, g2) → "g_lq_s(" ^ string_of_sfm m1 ^ "," ^ string_of_sfm m2 ^ "," ^
      ^ string_of_int g1 ^ "," ^ string_of_shiggs s ^ "," ^ string_of_int g2 ^ ")"
| G_LQ_P (m1, m2, g1, p, g2) → "g_lq_s(" ^ string_of_sfm m1 ^ "," ^ string_of_sfm m2 ^ "," ^
      ^ string_of_int g1 ^ "," ^ string_of_phiggs p ^ "," ^ string_of_int g2 ^ ")"
| G_ZLQ (g, m1, m2) → "g_zlqlq(" ^ string_of_int g ^ "," ^
      string_of_sfm m1 ^ "," ^ string_of_sfm m2 ^ ")"
| G_ZZLQLQ → "g-zz_lqlq"
| G_ZPLQLQ → "g-zA_lqlq"
| G_PPLQLQ → "g-AA_lqlq"
| G_ZGLQLQ → "g-zg_lqlq"
| G_PGILQLQ → "g-Ag_lqlq"
| G_GILQLQ → "g-gg_lqlq"
| G_NLQC → "g-nlqc"

```

end

---

## —14—

### COMPHEP MODELS

#### 14.1 Interface of *Comphep\_syntax*

```
type raw =  
  | I | Integer of int | Symbol of string  
  | Application of string × raw  
  | Dotproduct of raw × raw  
  | Product of (raw × int) list  
  | Sum of (raw × int) list  
  
val symbol : string → raw  
val integer : int → raw  
val imag : raw  
  
val apply : string → raw → raw  
val dot : raw → raw → raw  
val multiply : raw → raw → raw  
val divide : raw → raw → raw  
val power : raw → int → raw  
val add : raw → raw → raw  
val subtract : raw → raw → raw  
val neg : raw → raw
```

#### 14.2 Implementation of *Comphep\_syntax*

```
type raw =  
  | I | Integer of int | Symbol of string  
  | Application of string × raw  
  | Dotproduct of raw × raw  
  | Product of (raw × int) list  
  | Sum of (raw × int) list  
  
let symbol name = Symbol name  
let integer n = Integer n  
let imag = I  
  
let apply f x = Application (f, x)  
let dot x y = Dotproduct (x, y)
```

```
let negate = List.map (fun (x, c) → (x, - c))
let scale n = List.map (fun (x, c) → (x, n × c))
```

```
let add1 (x, c) y =
  if c = 0 then
    y
  else
    try
      let c' = List.assoc x y + c in
      if c' = 0 then
        List.remove_assoc x y
      else
        (x, c') :: (List.remove_assoc x y)
    with
    | Not_found → (x, c) :: y
```

```
let addn = List.fold_right add1
```

```
let multiply x y =
  match x, y with
  | Product x', Product y' → Product (addn x' y')
  | Integer n, Product y' → Product (scale n y')
  | Product x', Integer n → Product (scale n x')
  | -, Product y' → Product (add1 (x, 1) y')
  | Product x', - → Product (add1 (y, 1) x')
  | - when x = y → Product ([ (x, 2) ])
  | - → Product ([ (x, 1); (y, 1) ])
```

```
let divide x y =
  match y with
  | Product y' → multiply x (Product (negate y'))
  | - when x = y → Product ([])
  | - → Product ([ (x, 1); (y, -1) ])
```

```
let power x n =
  match x with
  | Product x' → Product (scale n x')
  | x → Product ([ (x, n) ])
```

```
let add x y =
  match x, y with
  | Sum x', Sum y' → Sum (addn x' y')
  | -, Sum y' → Sum (add1 (x, 1) y')
  | Sum x', - → Sum (add1 (y, 1) x')
  | - when x = y → Sum ([ (x, 2) ])
  | - → Sum ([ (x, 1); (y, 1) ])
```

```
let subtract x y =
  match y with
  | Sum y' → add x (Sum (negate y'))
  | - when x = y → Sum ([])
  | - → Sum ([ (x, 1); (y, -1) ])
```

```
let neg = function
```



```

| Sum x → Sum (negate x)
| x → Sum [(x, -1)]

type vector =
| Momentum of int
| Index of int
| Index' of int

let vector_keyword = function
| "p1" → Some (Momentum 1)
| "p2" → Some (Momentum 2)
| "p3" → Some (Momentum 3)
| "p4" → Some (Momentum 4)
| "m1" → Some (Index 1)
| "m2" → Some (Index 2)
| "m3" → Some (Index 3)
| "m4" → Some (Index 4)
| "M1" → Some (Index' 1)
| "M2" → Some (Index' 2)
| "M3" → Some (Index' 3)
| "M4" → Some (Index' 4)
| _ → None

```

### 14.3 Lexer

```

{
open Comphep_parser
}

let digit = ['0'-'9']
let upper = ['A'-'Z']
let lower = ['a'-'z']
let alpha = upper | lower
let alphanum = alpha | digit

let symbol = alpha alphanum*
let integer = digit+

rule token = parse
  [' ' '\t'] { token lexbuf } (* skip blanks *)
| "(" { LPAREN }
| ")" { RPAREN }
| "i" { I }
| "." { DOT }
| "**" { POWER }
| "*" { MULT }
| "/" { DIV }
| "+" { PLUS }
| "-" { MINUS }
| symbol { SYMBOL (Lexing.lexeme lexbuf) }
| integer { INT (int_of_string (Lexing.lexeme lexbuf)) }

```

```
| - { failwith ("lexer fails @" ^ Lexing.lexeme lexbuf) }
| eof { END }
```

## 14.4 Parser

### Header

```
module S = Comphep_syntax
```

### Token declarations

```
%token < string > SYMBOL
%token < int > INT
%token I
%token LPAREN RPAREN
%token DOT MULT DIV POWER PLUS MINUS
%token END

%left PLUS MINUS
%left MULT DIV
%nonassoc UNARY
%nonassoc POWER
%nonassoc DOT

%start expr
%type < Comphep_syntax.raw > expr
```

### Grammar rules

```
expr ::=
  e END { $1 }

e ::=
  SYMBOL { S.symbol $1 }
| INT { S.integer $1 }
| I { S.imag }
| SYMBOL LPAREN e RPAREN { S.apply $1 $3 }
| LPAREN e RPAREN { $2 }
| e DOT e { S.dot $1 $3 }
| e MULT e { S.multiply $1 $3 }
| e DIV e { S.divide $1 $3 }
| e PLUS e { S.add $1 $3 }
| e MINUS e { S.subtract $1 $3 }
```

```
| PLUS e %prec UNARY { $2 }
| MINUS e %prec UNARY { S.neg $2 }
| e POWER INT { S.power $1 $3 }
```

## 14.5 Interface of *Comphep*

Wolfgang's idea: read *Comphep*'s model files:

```
module Model : Model.T
```

## 14.6 Implementation of *Comphep*

```
let rcs_file = RCS.parse "Comphep" ["Plagiarizing_CompHEP_models_..."]
  { RCS.revision = "$Revision: 6222$";
    RCS.date = "$Date: 2014-10-13 10:40:53 +0200 (Mon, 13 Oct 2014)$";
    RCS.author = "$Author: ohl$";
    RCS.source
      = "$URL: svn+ssh://jr-reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/s"
```

A friendlier *String.sub* that returns an empty string instead of raising an exception. Instead of the length, the second argument denotes the last position.

```
let substring buffer i1 i2 =
  let imax = String.length buffer - 1 in
  let i1 = max i1 0
  and i2 = min i2 imax in
  let len = i2 - i1 + 1 in
  if len > 0 then
    String.sub buffer i1 len
  else
    ""

let first_non_white buffer =
  let len = String.length buffer in
  let rec skip_white i =
    if i ≥ len then
      i
    else if buffer.[i] ≠ ' ' ∧ buffer.[i] ≠ '\t' then
      i
    else
      skip_white (succ i) in
  skip_white 0

let last_non_white buffer =
  let len = String.length buffer in
  let rec skip_white i =
    if i < 0 then
      i
    else if buffer.[i] ≠ ' ' ∧ buffer.[i] ≠ '\t' then
      i
```

```

    else
      skip_white (pred i) in
      skip_white (pred len)
let gobble_white buffer =
  substring buffer (first_non_white buffer) (last_non_white buffer)
let gobble_arrows buffer =
  let imax = String.length buffer - 1 in
  if imax ≥ 0 then
    gobble_white
      (substring buffer
        (if buffer.[0] = '>' then 1 else 0)
        (if buffer.[imax] = '<' then pred imax else imax))
  else
    ""
let fold_lines ic f init =
  let rec fold_lines' acc =
    let continue =
      try
        let acc' = f (input_line ic) acc in
        fun () → fold_lines' acc'
      with
        | End_of_file → fun () → acc in
    continue () in
  fold_lines' init
let column_tabs line =
  let len = String.length line in
  let rec tabs' acc i =
    if i ≥ len then
      List.rev acc
    else if line.[i] = '|' then
      tabs' (i :: acc) (succ i)
    else
      tabs' acc (succ i)
  in
  tabs' [] 0
let columns tabs line =
  let imax = String.length line - 1 in
  let rec columns' acc i = function
    | [] → List.rev_map gobble_white (substring line i imax :: acc)
    | tab :: rest →
      if tab < i then
        invalid_arg "columns: clash"
      else if (match rest with [] → false | _ → true)
        ∧ line.[tab] ≠ '|' then
        invalid_arg "columns: expecting '|'"
      else
        columns' (substring line i (pred tab) :: acc) (succ tab) rest
  in

```

```

    columns' [] 0 tabs
let input_table name =
  let ic = open_in name in
  let model = input_line ic in
  let table = input_line ic in
  let line = input_line ic in
  let tabs = column_tabs line in
  let titles = columns tabs line in
  let rows = fold_lines ic (fun line acc →
    if String.length line > 0 ∧ line.[0] = '=' then
      acc
    else
      columns tabs line :: acc) [] in
  close_in ic;
  (gobble_white model, gobble_white table, List.map gobble_arrows titles, rows)
let substitute_char (cold, cnew) s =
  for i = 0 to String.length s - 1 do
    if s.[i] = cold then
      s.[i] ← cnew
  done;
  s
let sanitize_symbol s =
  List.fold_right substitute_char [( '+', 'p' ); ( '-', 'm' )] (String.copy s)

```



Fodder for a future *Coupling* module ...

```

let rec fermion_of_lorentz = function
| Coupling.Spinor → 1
| Coupling.ConjSpinor → -1
| Coupling.Majorana → 1
| Coupling.Maj_Ghost → 1
| Coupling.Vectorspinor → 1
| Coupling.Vector | Coupling.Massive_Vector → 0
| Coupling.Scalar | Coupling.Tensor_1 | Coupling.Tensor_2 → 0
| Coupling.BRS f → fermion_of_lorentz f

let rec conjugate_lorentz = function
| Coupling.Spinor → Coupling.ConjSpinor
| Coupling.ConjSpinor → Coupling.Spinor
| Coupling.BRS f → Coupling.BRS (conjugate_lorentz f)
| f → f

```



Currently, this operates on the sanitized symbol names.

```

let pdg_heuristic name =
  match name with
  | "e1" → 11 | "E1" → -11 | "n1" → 12 | "N1" → -12
  | "e2" → 13 | "E2" → -13 | "n2" → 14 | "N2" → -14

```

```

| "e3" → 15 | "E3" → -15 | "n3" → 16 | "N3" → -16
| "u" → 2 | "U" → -2 | "d" → 1 | "D" → -1
| "c" → 4 | "C" → -4 | "s" → 3 | "S" → -3
| "t" → 6 | "T" → -6 | "b" → 5 | "B" → -5
| "G" → 21 | "A" → 22 | "Z" → 23
| "Wp" → 24 | "Wm" → -24 | "H" → 25
| - → invalid_arg ("pdg_heuristic_ failed: " ^ name)

module Model =
  struct

    type flavor = int
    type constant = string
    type gauge = unit

    module M = Modeltools.Mutable
      (struct type f = flavor type g = gauge type c = constant end)

    let flavors = M.flavors
    let external_flavors = M.external_flavors
    let lorentz = M.lorentz
    let color = M.color
    let propagator = M.propagator
    let width = M.width
    let goldstone = M.goldstone
    let conjugate = M.conjugate
    let fermion = M.fermion
    let vertices = M.vertices
    let fuse2 = M.fuse2
    let fuse3 = M.fuse3
    let fuse = M.fuse
    let max_degree = M.max_degree
    let parameters = M.parameters
    let flavor_of_string = M.flavor_of_string
    let flavor_to_string = M.flavor_to_string
    let flavor_to_TeX = M.flavor_to_TeX
    let flavor_symbol = M.flavor_symbol
    let gauge_symbol = M.gauge_symbol
    let pdg = M.pdg
    let mass_symbol = M.mass_symbol
    let width_symbol = M.width_symbol
    let constant_symbol = M.constant_symbol
    module Ch = M.Ch
    let charges = M.charges

    let rcs = rcs_file

    type symbol =
      | Selfconjugate of string
      | Conjugates of string × string

    type particle =
      { p_name : string;
        p_symbol : symbol;

```

```

    p_spin : Coupling.lorentz;
    p_mass  : Comphep-syntax.raw;
    p_width : Comphep-syntax.raw;
    p_color : Color.t;
    p_aux   : string option }

let count_flavors particles =
  List.fold_left (fun n p → n +
    match p.p_symbol with
    | Selfconjugate _ → 1
    | Conjugates _   → 2) 0 particles

type particle_flavor =
  { f_name : string;
    f_conjugate : int;
    f_symbol : string;
    f_pdg : int;
    f_spin : Coupling.lorentz;
    f_propagator : gauge Coupling.propagator;
    f_fermion : int;
    f_mass : string;
    f_width : string;
    f_color : Color.t;
    f_aux : string option }

let real_variable = function
  | Comphep-syntax.Integer 0 → "zero"
  | Comphep-syntax.Symbol s → s
  | _ → invalid_arg "real_variable"

let dummy_flavor =
  { f_name = "";
    f_conjugate = -1;
    f_symbol = "";
    f_pdg = 0;
    f_spin = Coupling.Scalar;
    f_propagator = Coupling.Prop_Scalar;
    f_fermion = 0;
    f_mass = real_variable (Comphep-syntax.integer 0);
    f_width = real_variable (Comphep-syntax.integer 0);
    f_color = Color.Singlet;
    f_aux = None }

let propagator_of_lorentz = function
  | Coupling.Scalar → Coupling.Prop_Scalar
  | Coupling.Spinor → Coupling.Prop_Spinor
  | Coupling.ConjSpinor → Coupling.Prop_ConjSpinor
  | Coupling.Majorana → Coupling.Prop_Majorana
  | Coupling.Maj_Ghost → invalid_arg
    "propagator_of_lorentz: SUSY ghosts do not propagate"
  | Coupling.Vector → Coupling.Prop_Feynman
  | Coupling.Massive_Vector → Coupling.Prop_Unitarity
  | Coupling.Vectorspinor →

```

```

      invalid_arg "propagator_of_lorentz:␣Vectorspinor"
    | Coupling.Tensor_1 → invalid_arg "propagator_of_lorentz:␣Tensor_1"
    | Coupling.Tensor_2 → invalid_arg "propagator_of_lorentz:␣Tensor_2"
    | Coupling.BRS _ → invalid_arg "propagator_of_lorentz:␣no␣BRST"

let flavor_of_particle symbol conjg particle =
  let spin = particle.p_spin in
  { f_name = particle.p_name;
    f_conjugate = conjg;
    f_symbol = symbol;
    f_pdg = pdg_heuristic symbol;
    f_spin = spin;
    f_propagator = propagator_of_lorentz spin;
    f_fermion = fermion_of_lorentz spin;
    f_mass = real_variable particle.p_mass;
    f_width = real_variable particle.p_width;
    f_color = particle.p_color;
    f_aux = particle.p_aux }

let flavor_of_antiparticle symbol conjg particle =
  let spin = conjugate_lorentz particle.p_spin in
  { f_name = "anti-" ^ particle.p_name;
    f_conjugate = conjg;
    f_symbol = symbol;
    f_pdg = pdg_heuristic symbol;
    f_spin = spin;
    f_propagator = propagator_of_lorentz spin;
    f_fermion = fermion_of_lorentz spin;
    f_mass = real_variable particle.p_mass;
    f_width = real_variable particle.p_width;
    f_color = Color.conjugate particle.p_color;
    f_aux = particle.p_aux }

let parse_expr text =
  try
    Comphep_parser.expr Comphep_lexer.token (Lexing.from_string text)
  with
    | Parsing.Parse_error → invalid_arg ("parse␣error:␣" ^ text)

let parse_function_row = function
  | name :: fct :: comment :: _ → (name, parse_expr fct, comment)
  | _ → invalid_arg "parse_function_row"

let parse_lagrangian_row = function
  | p1 :: p2 :: p3 :: p4 :: c :: t :: _ →
    ((p1, p2, p3, p4), parse_expr c, parse_expr t)
  | _ → invalid_arg "parse_lagrangian_row"

let parse_symbol s1 s2 =
  if s1 = s2 then
    Selfconjugate (sanitize_symbol s1)
  else
    Conjugates (sanitize_symbol s1, sanitize_symbol s2)

```



```

let parse_spin spin =
  match int_of_string spin with
  | 0 → Coupling.Scalar
  | 1 → Coupling.Spinor
  | 2 → Coupling.Vector
  | _ → invalid_arg ("parse_spin:␣spin␣=" ^ spin)

let parse_color color =
  match int_of_string color with
  | 1 → Color.Singlet
  | 3 → Color.SUN 3
  | 8 → Color.AdjSUN 3
  | _ → invalid_arg ("parse_color:␣color␣=" ^ color)

let parse_particle_row = function
| name :: symbol :: symbol_cc :: spin :: mass :: width :: color ::
aux :: _ →
  { p_name = name;
    p_symbol = parse_symbol symbol symbol_cc;
    p_spin = parse_spin spin;
    p_mass = parse_expr mass;
    p_width = parse_expr width;
    p_color = parse_color color;
    p_aux = match aux with "" → None | _ → Some aux }
| _ → invalid_arg "parse_particle_row"

let parse_variable_row = function
| name :: value :: comment :: _ →
  (name, float_of_string value, comment)
| _ → invalid_arg "parse_variable_row"

let parse_table parse_row name =
  let model, table, titles, rows = input_table name in
  (model, table, titles, List.rev_map parse_row rows)

let input_functions = parse_table parse_function_row
let input_lagrangian = parse_table parse_lagrangian_row
let input_particles = parse_table parse_particle_row
let input_variables = parse_table parse_variable_row

let input_model dir idx =
  let idx = string_of_int idx in
  (input_particles (dir ^ "/prtcls" ^ idx ^ ".mdl"),
   input_variables (dir ^ "/vars" ^ idx ^ ".mdl"),
   input_functions (dir ^ "/func" ^ idx ^ ".mdl"),
   input_lagrangian (dir ^ "/lgrng" ^ idx ^ ".mdl"))

let flavors_of_particles particles =
  let flavors = Array.make (count_flavors particles) dummy_flavor in
  ignore (List.fold_left (fun n p →
    match p.p_symbol with
    | Selfconjugate f →
      flavors.(n) ← flavor_of_particle f n p;
      n + 1

```

```

      | Conjugates (f1, f2) →
        flavors.(n) ← flavor_of_particle f1 (n + 1) p;
        flavors.(n + 1) ← flavor_of_antiparticle f2 n p;
        n + 2) 0 particles);
    flavors
module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)

let translate_tensor3 _ = Coupling.Scalar_Scalar_Scalar 1
let translate_tensor4 _ = Coupling.Scalar4 1
let translate_constant _ = ""

let init_flavors_variables_functions_vertices =
  let fmax = Array.length flavors - 1 in
  let flist = ThoList.range 0 fmax in
  let clamp_flavor msg f =
    if f ≥ 0 ∨ f ≤ fmax then
      f
    else
      invalid_arg (msg ^ ":␣invalid␣flavor:␣" ^ string_of_int f) in
  let flavor_hash = Hashtbl.create 37 in
  let flavor_of_string s =
    try
      Hashtbl.find flavor_hash s
    with
      | Not_found → invalid_arg ("flavor_of_string:␣" ^ s) in
  for f = 0 to fmax do
    Hashtbl.add flavor_hash flavors.(f).f_symbol f
  done;
  let vertices3, vertices4 =
    List.fold_left (fun (v3, v4) ((p1, p2, p3, p4), c, t) →
      if p4 = "" then
        (((flavor_of_string p1, flavor_of_string p2, flavor_of_string p3),
          translate_tensor3 t, translate_constant c) :: v3, v4)
      else
        (v3, ((flavor_of_string p1, flavor_of_string p2,
          flavor_of_string p3, flavor_of_string p4),
          translate_tensor4 t, translate_constant c) :: v4))
      ([], []) vertices in
  let max_degree = match vertices4 with [] → 3 | _ → 4 in
  let all_vertices () = (vertices3, vertices4, []) in
  let table = F.of_vertices (all_vertices ()) in
  let input_parameters =
    (real_variable (Comphep_syntax.integer 0), 0.0) ::
    (List.map (fun (n, v, _) → (n, v)) variables) in
  let derived_parameters =
    List.map (fun (n, f, _) → (Coupling.Real n, Coupling.Const 0))

```

```

    functions in
M.setup
~color : (fun f → flavors.(clamp_flavor "color" f).f_color)
~pdg : (fun f → flavors.(clamp_flavor "pdg" f).f_pdg)
~lorentz : (fun f → flavors.(clamp_flavor "spin" f).f_spin)
~propagator : (fun f →
    flavors.(clamp_flavor "propagator" f).f_propagator)
~width : (fun f → Coupling.Constant)
~goldstone : (fun f → None)
~conjugate : (fun f → flavors.(clamp_flavor "conjugate" f).f_conjugate)
~fermion : (fun f → flavors.(clamp_flavor "fermion" f).f_fermion)
~max_degree
~vertices : all_vertices
~fuse : (F.fuse2 table, F.fuse3 table, F.fuse table)
~flavors : ([("All_␣Flavors", flist)])
~parameters : (fun () →
    { Coupling.input = input_parameters;
      Coupling.derived = derived_parameters;
      Coupling.derived_arrays = [] })
~flavor_of_string
~flavor_to_string : (fun f →
    flavors.(clamp_flavor "flavor_to_string" f).f_name)
~flavor_to_TeX : (fun f →
    flavors.(clamp_flavor "flavor_to_TeX" f).f_name)
~flavor_symbol : (fun f →
    flavors.(clamp_flavor "flavor_symbol" f).f_symbol)
~gauge_symbol : (fun () → "")
~mass_symbol : (fun f →
    flavors.(clamp_flavor "mass_symbol" f).f_mass)
~width_symbol : (fun f →
    flavors.(clamp_flavor "width_symbol" f).f_width)
~constant_symbol : (fun c → failwith "constant_symbol")

let particles_file = ref "prtc1s1.mdl"
let variables_file = ref "vars1.mdl"
let functions_file = ref "func1.mdl"
let lagrangian_file = ref "lgrng1.mdl"

let load () =
    let (_, -, -, p), v, f, l =
        (input_particles !particles_file, input_variables !variables_file,
         input_functions !functions_file, input_lagrangian !lagrangian_file) in
    init (flavors_of_particles p) [] [] []

let options = Options.create
    [ ("p", Arg.String (fun name → particles_file := name),
      "CompHEP_␣particles_␣file_␣(default:␣" ^ !particles_file ^ ")");
      ("v", Arg.String (fun name → variables_file := name),
      "CompHEP_␣variables_␣file_␣(default:␣" ^ !variables_file ^ ")");
      ("f", Arg.String (fun name → functions_file := name),
      "CompHEP_␣functions_␣file_␣(default:␣" ^ !functions_file ^ ")");
      ("l", Arg.String (fun name → lagrangian_file := name),

```

```
"CompHEP_lagrangian_file_(default:_"!lagrangian_file ^ ")");
("exec", Arg.Unit load,
 "load_the_model_files_(required_before_any_particle)");
("help", Arg.Unit (fun () →
  print_endline
    ("[" ^ String.concat "|"
      (List.map M.flavor_to_string (M.flavors ())) ^ "]"
    ),
  "print_information_on_the_model"])
end
```

---

# —15—

## HARDCODED TARGETS

### 15.1 *Interface of Targets*

```
module Dummy : Target.Maker
```

#### 15.1.1 *Supported Targets*

```
module Fortran : Target.Maker  
module Fortran_Majorana : Target.Maker  
module VM : Target.Maker
```

#### 15.1.2 *Potential Targets*

```
module Fortran77 : Target.Maker  
module C : Target.Maker  
module Cpp : Target.Maker  
module Java : Target.Maker  
module Ocaml : Target.Maker  
module LaTeX : Target.Maker
```

### 15.2 *Implementation of Targets*

```
let rsc_file = RCS.parse "Targets" ["Code_Generation"]  
  { RCS.revision = "$Revision: 6295$";  
    RCS.date = "$Date: 2014-11-21 19:58:53 +0100 (Fri, 21 Nov 2014)$";  
    RCS.author = "$Author: bchokoufe$";  
    RCS.source  
      = "$URL: svn+ssh://jr_reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/s";  
  }  
module Dummy (F : Fusion.Maker) (P : Momentum.T) (M : Model.T) =  
  struct  
    let rsc_list = []  
    type amplitudes = Fusion.Multi(F)(P)(M).amplitudes  
    type diagnostic = All | Arguments | Momenta | Gauge  
    let options = Options.empty
```

```

let amplitudes_to_channel _ _ _ = failwith "Targets.Dummy"
let parameters_to_channel _ = failwith "Targets.Dummy"
end

```

### 15.2.1 O'Mega Virtual Machine with Fortran 90/95

#### Preliminaries

```

module VM (Fusion_Maker : Fusion.Maker) (P : Momentum.T) (M : Model.T) =
struct
  let rcs_list =
    [RCS.rename rcs_file "Targets.VM"
     ["Virtual_Machine_able_to_compute_amplitudes_from_byte_code"]]

  open Coupling
  open Format

  module CM = Colorize.It(M)
  module F = Fusion_Maker(P)(M)
  module CF = Fusion.Multi(Fusion_Maker)(P)(M)
  module CFlow = Color.Flow
  type amplitudes = CF.amplitudes

```

Options.

```

type diagnostic = All | Arguments | Momenta | Gauge

let wrapper_module = ref "ovm_wrapper"
let parameter_module_external = ref "some_external_module_with_model_info"
let bytecode_file = ref "bytecode.hbc"
let md5sum = ref None
let openmp = ref false
let kind = ref "default"
let whizard = ref false

let options = Options.create
[ "wrapper_module", Arg.String (fun s → wrapper_module := s),
  "name_of_wrapper_module";
  "bytecode_file", Arg.String (fun s → bytecode_file := s),
  "bytecode_file_to_be_used_in_wrapper";
  "parameter_module_external", Arg.String (fun s →
    parameter_module_external := s),
  "external_parameter_module_to_be_used_in_wrapper";
  "md5sum", Arg.String (fun s → md5sum := Some s),
  "transfer_MD5_checksum_in_wrapper";
  "whizard", Arg.Set whizard, "include_WHIZARD_interface_in_wrapper";
  "openmp", Arg.Set openmp,
  "activate_parallel_computation_of_amplitude_with_OpenMP"]

```

This is part of OCaml 4.01.

```

let (| >) fn x = x fn

```

```
let (@@) fn x = fn x
```

Integers encode the opcodes (operation codes).

```
let ovm_ADD_MOMENTA = 1
let ovm_CALC_BRAKET = 2

let ovm_LOAD_SCALAR = 10
let ovm_LOAD_SPINOR_INC = 11
let ovm_LOAD_SPINOR_OUT = 12
let ovm_LOAD_CONJSPINOR_INC = 13
let ovm_LOAD_CONJSPINOR_OUT = 14
let ovm_LOAD_MAJORANA_INC = 15
let ovm_LOAD_MAJORANA_OUT = 16
let ovm_LOAD_VECTOR_INC = 17
let ovm_LOAD_VECTOR_OUT = 18
let ovm_LOAD_VECTORSPINOR_INC = 19
let ovm_LOAD_VECTORSPINOR_OUT = 20
let ovm_LOAD_TENSOR2_INC = 21
let ovm_LOAD_TENSOR2_OUT = 22
let ovm_LOAD_BRS_SCALAR = 30
let ovm_LOAD_BRS_SPINOR_INC = 31
let ovm_LOAD_BRS_SPINOR_OUT = 32
let ovm_LOAD_BRS_CONJSPINOR_INC = 33
let ovm_LOAD_BRS_CONJSPINOR_OUT = 34
let ovm_LOAD_BRS_VECTOR_INC = 37
let ovm_LOAD_BRS_VECTOR_OUT = 38
let ovm_LOAD_MAJORANA_GHOST_INC = 23
let ovm_LOAD_MAJORANA_GHOST_OUT = 24
let ovm_LOAD_BRS_MAJORANA_INC = 35
let ovm_LOAD_BRS_MAJORANA_OUT = 36

let ovm_PROPAGATE_SCALAR = 51
let ovm_PROPAGATE_COL_SCALAR = 52
let ovm_PROPAGATE_GHOST = 53
let ovm_PROPAGATE_SPINOR = 54
let ovm_PROPAGATE_CONJSPINOR = 55
let ovm_PROPAGATE_MAJORANA = 56
let ovm_PROPAGATE_COL_MAJORANA = 57
let ovm_PROPAGATE_UNITARITY = 58
let ovm_PROPAGATE_COL_UNITARITY = 59
let ovm_PROPAGATE_FEYNMAN = 60
let ovm_PROPAGATE_COL_FEYNMAN = 61
let ovm_PROPAGATE_VECTORSPINOR = 62
let ovm_PROPAGATE_TENSOR2 = 63
```



*ovm\_PROPAGATE\_NONE* has to be split up to different types to work in conjunction with color MC ...

```
let ovm_PROPAGATE_NONE = 64
let ovm_FUSE_V_FF = -1
```

```

let ovm_FUSE_F_VF = - 2
let ovm_FUSE_F_FV = - 3
let ovm_FUSE_VA_FF = - 4
let ovm_FUSE_F_VAF = - 5
let ovm_FUSE_F_FVA = - 6
let ovm_FUSE_VA2_FF = - 7
let ovm_FUSE_F_VA2F = - 8
let ovm_FUSE_F_FVA2 = - 9
let ovm_FUSE_A_FF = - 10
let ovm_FUSE_F_AF = - 11
let ovm_FUSE_F_FA = - 12
let ovm_FUSE_VL_FF = - 13
let ovm_FUSE_F_VLF = - 14
let ovm_FUSE_F_FVL = - 15
let ovm_FUSE_VR_FF = - 16
let ovm_FUSE_F_VRF = - 17
let ovm_FUSE_F_FVR = - 18
let ovm_FUSE_VLR_FF = - 19
let ovm_FUSE_F_VLRF = - 20
let ovm_FUSE_F_FVLR = - 21
let ovm_FUSE_SP_FF = - 22
let ovm_FUSE_F_SPF = - 23
let ovm_FUSE_F_FSP = - 24
let ovm_FUSE_S_FF = - 25
let ovm_FUSE_F_SF = - 26
let ovm_FUSE_F_FS = - 27
let ovm_FUSE_P_FF = - 28
let ovm_FUSE_F_PF = - 29
let ovm_FUSE_F_FP = - 30
let ovm_FUSE_SL_FF = - 31
let ovm_FUSE_F_SLF = - 32
let ovm_FUSE_F_FSL = - 33
let ovm_FUSE_SR_FF = - 34
let ovm_FUSE_F_SRF = - 35
let ovm_FUSE_F_FSR = - 36
let ovm_FUSE_SLR_FF = - 37
let ovm_FUSE_F_SLRF = - 38
let ovm_FUSE_F_FSLR = - 39

let ovm_FUSE_G_GG = - 40
let ovm_FUSE_V_SS = - 41
let ovm_FUSE_S_VV = - 42
let ovm_FUSE_S_VS = - 43
let ovm_FUSE_V_SV = - 44
let ovm_FUSE_S_SS = - 45
let ovm_FUSE_S_SVV = - 46
let ovm_FUSE_V_SSV = - 47
let ovm_FUSE_S_SSS = - 48
let ovm_FUSE_V_VVV = - 49

let ovm_FUSE_S_G2 = - 50

```



```

let ovm_FUSE_G_SG = - 51
let ovm_FUSE_G_GS = - 52
let ovm_FUSE_S_G2_SKEW = - 53
let ovm_FUSE_G_SG_SKEW = - 54
let ovm_FUSE_G_GS_SKEW = - 55

let inst_length = 8

```

Some helper functions.

```

let printi ~lhs : l ~rhs1 : r1 ?coupl : (cp = 0) ?coeff : (co = 0)
      ?rhs2 : (r2 = 0) ?rhs3 : (r3 = 0) ?rhs4 : (r4 = 0) code =
  printf "@\n%d_%d_%d_%d_%d_%d_%d_%d" code cp co l r1 r2 r3 r4

let nl () = printf "@\n"

let print_int_lst lst = nl (); lst |> List.iter (printf "%d_")

let print_str_lst lst = nl (); lst |> List.iter (printf "%s_")

let break () = printi ~lhs : 0 ~rhs1 : 0 0

```

Copied from below. Needed for header.



Could be fused with *lorentz\_ordering*.

```

type declarations =
{ scalars : F.wf list;
  spinors : F.wf list;
  conjspinors : F.wf list;
  realspinors : F.wf list;
  ghostspinors : F.wf list;
  vectorspinors : F.wf list;
  vectors : F.wf list;
  ward_vectors : F.wf list;
  massive_vectors : F.wf list;
  tensors_1 : F.wf list;
  tensors_2 : F.wf list;
  brs_scalars : F.wf list;
  brs_spinors : F.wf list;
  brs_conjspinors : F.wf list;
  brs_realspinors : F.wf list;
  brs_vectorspinors : F.wf list;
  brs_vectors : F.wf list;
  brs_massive_vectors : F.wf list }

let rec classify_wfs' acc = function
| [] → acc
| wf :: rest →
  classify_wfs'
    (match CM.lorentz (F.flavor wf) with
    | Scalar → {acc with scalars = wf :: acc.scalars}
    | Spinor → {acc with spinors = wf :: acc.spinors}
    | ConjSpinor → {acc with conjspinors = wf :: acc.conjspinors}
    | Majorana → {acc with realspinors = wf :: acc.realspinors})

```

---

```

| Maj_Ghost → {acc with ghostspinors = wf :: acc.ghostspinors}
| Vectorspinor →
  {acc with vectorspinors = wf :: acc.vectorspinors}
| Vector → {acc with vectors = wf :: acc.vectors}
| Massive_Vector →
  {acc with massive_vectors = wf :: acc.massive_vectors}
| Tensor_1 → {acc with tensors_1 = wf :: acc.tensors_1}
| Tensor_2 → {acc with tensors_2 = wf :: acc.tensors_2}
| BRS_Scalar → {acc with brs_scalars = wf :: acc.brs_scalars}
| BRS_Spinor → {acc with brs_spinors = wf :: acc.brs_spinors}
| BRS_ConjSpinor → {acc with brs_conjspinors =
  wf :: acc.brs_conjspinors}
| BRS_Majorana → {acc with brs_realspinors =
  wf :: acc.brs_realspinors}
| BRS_Vectorspinor → {acc with brs_vectorspinors =
  wf :: acc.brs_vectorspinors}
| BRS_Vector → {acc with brs_vectors = wf :: acc.brs_vectors}
| BRS_Massive_Vector → {acc with brs_massive_vectors =
  wf :: acc.brs_massive_vectors}
| BRS _ → invalid_arg "Targets.classify_wfs': not needed here")
rest

let classify_wfs wfs = classify_wfs'
{ scalars = [];
  spinors = [];
  conjspinors = [];
  realspinors = [];
  ghostspinors = [];
  vectorspinors = [];
  vectors = [];
  ward_vectors = [];
  massive_vectors = [];
  tensors_1 = [];
  tensors_2 = [];
  brs_scalars = [];
  brs_spinors = [];
  brs_conjspinors = [];
  brs_realspinors = [];
  brs_vectorspinors = [];
  brs_vectors = [];
  brs_massive_vectors = [] } wfs

```

### Sets and maps

The OVM identifies all objects via integers. Therefore, we need maps which assign the abstract object a unique ID.

I want *int lists* with less elements to come first. Used in conjunction with the int list representation of momenta, this will set the outer particles at first position and allows the OVM to set them without further instructions.



Using the Momentum module might give better performance than integer lists?

```
let rec int_lst_compare (e1 : int list) (e2 : int list) =
  match e1, e2 with
  | [], [] → 0
  | -, [] → +1
  | [], - → -1
  | [-; -], [-] → +1
  | [-], [-; -] → -1
  | hd1 :: tl1, hd2 :: tl2 →
    let c = compare hd1 hd2 in
    if (c ≠ 0 ∧ List.length tl1 = List.length tl2) then
      c
    else
      int_lst_compare tl1 tl2
```

We need a canonical ordering for the different types of wfs. Copied, and slightly modified to order *wfs*, from `fusion.ml`.

```
let lorentz_ordering wf =
  match CM.lorentz (F.flavor wf) with
  | Scalar → 0
  | Spinor → 1
  | ConjSpinor → 2
  | Majorana → 3
  | Vector → 4
  | Massive_Vector → 5
  | Tensor_2 → 6
  | Tensor_1 → 7
  | Vectorspinor → 8
  | BRS Scalar → 9
  | BRS Spinor → 10
  | BRS ConjSpinor → 11
  | BRS Majorana → 12
  | BRS Vector → 13
  | BRS Massive_Vector → 14
  | BRS Tensor_2 → 15
  | BRS Tensor_1 → 16
  | BRS Vectorspinor → 17
  | Maj_Ghost → invalid_arg "lorentz_ordering: not implemented"
  | BRS _ → invalid_arg "lorentz_ordering: not needed"

let wf_compare (wf1, mult1) (wf2, mult2) =
  let c1 = compare (lorentz_ordering wf1) (lorentz_ordering wf2) in
  if c1 ≠ 0 then
    c1
  else
    let c2 = compare wf1 wf2 in
    if c2 ≠ 0 then
      c2
```

```

    else
      compare mult1 mult2
let amp_compare amp1 amp2 =
  let cflow a = CM.flow (F.incoming a) (F.outgoing a) in
  let c1 = compare (cflow amp1) (cflow amp2) in
  if c1 ≠ 0 then
    c1
  else
    let process_sans_color a =
      (List.map CM.flavor_sans_color (F.incoming a),
       List.map CM.flavor_sans_color (F.outgoing a)) in
    compare (process_sans_color amp1) (process_sans_color amp2)
let level_compare (f1, amp1) (f2, amp2) =
  let p1 = F.momentum_list (F.lhs f1)
  and p2 = F.momentum_list (F.lhs f2) in
  let c1 = int_lst_compare p1 p2 in
  if c1 ≠ 0 then
    c1
  else
    let c2 = compare f1 f2 in
    if c2 ≠ 0 then
      c2
    else
      amp_compare amp1 amp2
module ISet = Set.Make (struct type t = int list
                          let compare = int_lst_compare end)
module WFSets = Set.Make (struct type t = CF.wf × int
                              let compare = wf_compare end)
module CSet = Set.Make (struct type t = CM.constant
                          let compare = compare end)
module FSet = Set.Make (struct type t = F.fusion × F.amplitude
                          let compare = level_compare end)

```



It might be preferable to use a *PMap* which maps mom to int, instead of this way. More standard functions like *mem* could be used. Also, *get\_ID* would be faster,  $\mathcal{O}(\log N)$  instead of  $\mathcal{O}(N)$ , and simpler. For 8 gluons:  $N=127$  momenta. Minor performance issue.

```

module IMap = Map.Make (struct type t = int let compare = compare end)

```

For *wfs* it is crucial for the performance to use a different type of *Maps*.

```

module WFSMap = Map.Make (struct type t = CF.wf × int
                              let compare = wf_compare end)

type lookups = { pmap : int list IMap.t;
                 wfmap : int WFSMap.t;
                 cmap : CM.constant IMap.t × CM.constant IMap.t;

```

```

    amap : F.amplitude IMap.t;
    n_wfs : int list;
    amplitudes : CF.amplitudes;
    dict : F.amplitude → F.wf → int }

```

```

let largest_key imap =
  if (IMap.is_empty imap) then
    failwith "largest_key: IMap is empty!"
  else
    fst (IMap.max_binding imap)

```

OCaml's *compare* from *pervasives* cannot compare functional types, e.g. for type *amplitude*, if no specific equality function is given ("equal: functional value"). Therefore, we allow to specify the ordering.

```

let get_ID' comp map elt : int =
  let smallmap = IMap.filter (fun _ x → (comp x elt) = 0 ) map in
  if IMap.is_empty smallmap then
    raise Not_found
  else
    fst (IMap.min_binding smallmap)

```



Trying to curry *map* here leads to type errors of the polymorphic function *get\_ID*?

```

let get_ID map = match map with
| map → get_ID' compare map

let get_const_ID map x = match map with
| (map1, map2) → try get_ID' compare map1 x with
- → try get_ID' compare map2 x with
- → failwith "Impossible"

```

Creating an integer map of a list with an optional argument that indicates where the map should start counting.

```

let map_of_list ?start : (st = 1) lst =
  let g (ind, map) wf = (succ ind, IMap.add ind wf map) in
  lst |> List.fold_left g (st, IMap.empty) |> snd

let wf_map_of_list ?start : (st = 1) lst =
  let g (ind, map) wf = (succ ind, WFMap.add wf ind map) in
  lst |> List.fold_left g (st, WFMap.empty) |> snd

```

### Header



It would be nice to save the creation date as comment. However, the Unix module doesn't seem to be loaded on default.

```

let version_string x = RCS.name x ^ "-rev" ^ RCS.revision x

let print_description cmdline =
  rcs_list @ [M.rcs] |> List.map version_string

```

```

—> List.iter (printf "%s\n");

printf "@\nBytecode_file_generated_automatically_by_0'Mega_for_OVM";
printf "@\nDo_not_delete_any_lines.You_called_0'Mega_with";
printf "@\n%s" cmdline;
printf "@\n"

let num_classified_wfs wfs =
  let wfs' = classify_wfs wfs in
  List.map List.length
    [ wfs'.scalars @ wfs'.brs_scalars;
      wfs'.spinors @ wfs'.brs_spinors;
      wfs'.conjspinors @ wfs'.brs_conjspinors;
      wfs'.realspinors @ wfs'.brs_realspinors @ wfs'.ghostspinors;
      wfs'.vectors @ wfs'.massive_vectors @ wfs'.brs_vectors
        @ wfs'.brs_massive_vectors @ wfs'.ward_vectors;
      wfs'.tensors_2;
      wfs'.tensors_1;
      wfs'.vectorspinors ]

let description_classified_wfs =
  [ "N_scalars";
    "N_spinors";
    "N_conjspinors";
    "N_bispinors";
    "N_vectors";
    "N_tensors_2";
    "N_tensors_1";
    "N_vectorspinors" ]

let num_particles_in amp =
  match CF.flavors amp with
  | [] → 0
  | (fin, _) :: _ → List.length fin

let num_particles_out amp =
  match CF.flavors amp with
  | [] → 0
  | (_, fout) :: _ → List.length fout

let num_particles amp =
  match CF.flavors amp with
  | [] → 0
  | (fin, fout) :: _ → List.length fin + List.length fout

let num_color_indices_default = 2 (* Standard model and non-color-
exotica *)

let num_color_indices amp =
  try CFlow.rank (List.hd (CF.color_flows amp)) with
  _ → num_color_indices_default

let num_color_factors amp =
  let table = CF.color_factors amp in
  let n_cflow = Array.length table

```

```

and n_cfactors = ref 0 in
for c1 = 0 to pred n_cflow do
  for c2 = 0 to pred n_cflow do
    if c1 ≤ c2 then begin
      match table.(c1).(c2) with
      | [] → ()
      | - → incr n_cfactors
    end
  done
done;
!n_cfactors

let num_helicities amp = amp |> CF.helicities |> List.length
let num_flavors amp = amp |> CF.flavors |> List.length
let num_ks amp = amp |> CF.processes |> List.length
let num_color_flows amp = amp |> CF.color_flows |> List.length

Use fst since WFSet.t = F.wf × int.

let num_wfs wfset = wfset |> WFSet.elements |> List.map fst
                    →> num_classified_wfs

largest_key gives the number of momenta if applied to pmap.

let num_lst lookups wfset =
[ largest_key lookups.pmap;
  num_particles lookups.amplitudes;
  num_particles_in lookups.amplitudes;
  num_particles_out lookups.amplitudes;
  num_ks lookups.amplitudes;
  num_helicities lookups.amplitudes;
  num_color_flows lookups.amplitudes;
  num_color_indices lookups.amplitudes;
  num_flavors lookups.amplitudes;
  num_color_factors lookups.amplitudes ] @ num_wfs wfset

let description_lst =
[ "N_momenta";
  "N_particles";
  "N_prt_in";
  "N_prt_out";
  "N_amplitudes";
  "N_helicities";
  "N_col_flows";
  "N_col_indices";
  "N_flavors";
  "N_col_factors" ] @ description_classified_wfs

let print_header' numbers =
  let chopped_num_lst = ThoList.chopn inst_length numbers
  and chopped_desc_lst = ThoList.chopn inst_length description_lst
  and printer a b = print_str_lst a; print_int_lst b in

```

```

List.iter2 printer chopped_desc_lst chopped_num_lst

let print_header lookups wfset = print_header' (num_lst lookups wfset)

let print_zero_header () =
  let rec zero_list' j =
    if j < 1 then []
    else 0 :: zero_list' (j - 1) in
  let zero_list i = zero_list' (i + 1) in
  description_lst |> List.length |> zero_list |> print_header'

```

### Tables

```

let print_spin_table' tuples =
  match tuples with
  | [] → ()
  | - → tuples |> List.iter (fun (tuple1, tuple2) →
    tuple1 @ tuple2 |> List.map (Printf.sprintf "%d_")
    → String.concat "" → printf "@\n%s" )

let print_spin_table amplitudes =
  printf "@\nSpin_states_table";
  print_spin_table' @@ CF.helicities amplitudes

let print_flavor_table tuples =
  match tuples with
  | [] → ()
  | - → List.iter (fun tuple → tuple
    → List.map (fun f → Printf.sprintf "%d_" @@ M.pdg f)
    → String.concat "" → printf "@\n%s"
    ) tuples

let print_flavor_tables amplitudes =
  printf "@\nFlavor_states_table";
  print_flavor_table @@ List.map (fun (fin, fout) → fin @ fout)
  @@ CF.flavors amplitudes

let print_color_flows_table' tuple =
  match CFlow.to_lists tuple with
  | [] → ()
  | cfs → printf "@\n%s" @@ String.concat "" @@ List.map
    (fun cf → cf |> List.map (Printf.sprintf "%d_")
    → String.concat ""
    ) cfs

let print_color_flows_table tuples =
  match tuples with
  | [] → ()
  | - → List.iter print_color_flows_table' tuples

let print_ghost_flags_table tuples =
  match tuples with
  | [] → ()

```



```

| _ →
  List.iter (fun tuple →
    match CFlow.ghost_flags tuple with
    | [] → ()
    | gfs → printf "@\n"; List.iter (fun gf → printf "%s_"
      (if gf then "1" else "0")) gfs
    ) tuples

let format_power
{ CFlow.num = num; CFlow.den = den; CFlow.power = pwr } =
match num, den, pwr with
| -, 0, _ → invalid_arg "targets.format_power:_zero_denominator"
| n, d, p → [n; d; p]

let format_powers = function
| [] → [0]
| powers → List.flatten (List.map format_power powers)

```

Straightforward iteration gives a great speedup compared to the fancier approach which only collects nonzero colorfactors.

```

let print_color_factor_table table =
  let n_cflow = Array.length table in
  if n_cflow > 0 then begin
    for c1 = 0 to pred n_cflow do
      for c2 = 0 to pred n_cflow do
        if c1 ≤ c2 then begin
          match table.(c1).(c2) with
          | [] → ()
          | cf → printf "@\n"; List.iter (printf "%9d")
            ([succ c1; succ c2] @ (format_powers cf));
        end
      done
    done
  end

let option_to_binary = function
| Some _ → "1"
| None → "0"

let print_flavor_color_table n_flv n_cflow table =
  if n_flv > 0 then begin
    for c = 0 to pred n_cflow do
      printf "@\n";
      for f = 0 to pred n_flv do
        printf "%s_" (option_to_binary table.(f).(c))
      done;
    done;
  end

let print_color_tables amplitudes =
  let cflows = CF.color_flows amplitudes
  and cfactors = CF.color_factors amplitudes in
  printf "@\nColor_flows_table:_[_(i,_)_(k,_)_]_>_(m,_)_...";

```

```

print_color_flows_table cflows;
printf "@\nColor_ghost_flags_table:";
print_ghost_flags_table cflows;
printf "@\nColor_factors_table: [i,j:num_den_power], %s"
    "i,j_are_indexed_color_flows";
print_color_factor_table cfactors;
printf "@\nFlavor_color_combination_is_allowed:";
print_flavor_color_table (num_flavors amplitudes) (List.length
    (CF.color_flows amplitudes)) (CF.process_table amplitudes)

```

### Momenta

Add the momenta of a WFSet to a Iset. For now, we are throwing away the information to which amplitude the momentum belongs. This could be optimized for random color flow computations.

```

let momenta_set wfset =
  let get_mom wf = wf |> fst |> F.momentum_list in
  let momenta = List.map get_mom (WFSet.elements wfset) in
  momenta |> List.fold_left (fun set x → set |> ISet.add x) ISet.empty

let chop_in_3 lst =
  let ceil_div i j = if (i mod j = 0) then i/j else i/j + 1 in
  ThoList.chopn (ceil_div (List.length lst) 3) lst

```

Assign momenta via instruction code. External momenta `[_]` are already set by the OVM. To avoid unnecessary look-ups of IDs we separate two cases. If we have more, we split up in two or three parts.

```

let add_mom p pmap =
  let print_mom lhs rhs1 rhs2 rhs3 = if (rhs1 ≠ 0) then
    printi ~lhs : lhs ~rhs1 : rhs1 ~rhs2 : rhs2 ~rhs3 : rhs3 ovm_ADD_MOMENTA in
  let get_p_ID = get_ID pmap in
  match p with
  | [] | [-] → print_mom 0 0 0 0
  | [rhs1; rhs2] → print_mom (get_p_ID [rhs1; rhs2]) rhs1 rhs2 0
  | [rhs1; rhs2; rhs3] → print_mom (get_p_ID [rhs1; rhs2; rhs3]) rhs1 rhs2 rhs3
  | more →
    let ids = List.map get_p_ID (chop_in_3 more) in
    if (List.length ids = 3) then
      print_mom (get_p_ID more) (List.nth ids 0) (List.nth ids 1)
        (List.nth ids 2)
    else
      print_mom (get_p_ID more) (List.nth ids 0) (List.nth ids 1) 0

```

Hand through the current level and print level separators if necessary.

```

let add_all_mom lookups pset =
  let add_all' level p =
    let level' = List.length p in
    if (level' > level ∧ level' > 3) then break ();
    add_mom p lookups.pmap; level'
  in

```

```
ignore (pset | > ISet.elements | > List.fold_left add_all' 1)
```

Expand a set of momenta to contain all needed momenta for the computation in the OVM. For this, we create a list of sets which contains the chopped momenta and unify them afterwards. If the set has become larger, we expand again.

```
let rec expand_pset p =
  let momlst = ISet.elements p in
  let pset_of lst = List.fold_left (fun s x → ISet.add x s) ISet.empty
    lst in
  let sets = List.map (fun x → pset_of (chop_in_3 x)) momlst in
  let bigset = List.fold_left ISet.union ISet.empty sets in
  let biggerset = ISet.union bigset p in
  if (List.length momlst < List.length (ISet.elements biggerset)) then
    expand_pset biggerset
  else
    biggerset
let mom_ID pmap wf = get_ID pmap (F.momentum_list wf)
```

### Wavefunctions and externals

*mult\_wf* is needed because the *wf* with same combination of flavor and momentum can have different dependencies and content.

```
let mult_wf dict amplitude wf =
  try
    wf, dict amplitude wf
  with
    | Not_found → wf, 0
```

Build the union of all *wfs* of all amplitudes and a map of the amplitudes.

```
let wfset_amps amplitudes =
  let amap = amplitudes | > CF.processes | > List.sort amp_compare
    → map_of_list
  and dict = CF.dictionary amplitudes in
  let wfset_amp amp =
    let f = mult_wf dict amp in
    let lst = List.map f ((F.externals amp) @ (F.variables amp)) in
    lst | > List.fold_left (fun s x → WFSet.add x s) WFSet.empty in
  let list_of_sets = amplitudes | > CF.processes | > List.map wfset_amp in
  List.fold_left WFSet.union WFSet.empty list_of_sets, amap
```

To obtain the Fortran index, we subtract the number of precedent wave functions.

```
let lorentz_ordering_reduced wf =
  match CM.lorentz (F.flavor wf) with
  | Scalar | BRS Scalar → 0
  | Spinor | BRS Spinor → 1
  | ConjSpinor | BRS ConjSpinor → 2
  | Majorana | BRS Majorana → 3
  | Vector | BRS Vector | Massive_Vector | BRS Massive_Vector → 4
```

```

| Tensor_2 | BRS Tensor_2 → 5
| Tensor_1 | BRS Tensor_1 → 6
| Vectorspinor | BRS Vectorspinor → 7
| Maj_Ghost → invalid_arg "lorentz-ordering: not implemented"
| BRS _ → invalid_arg "lorentz-ordering: not needed"

let wf_index wfmap num_lst (wf, i) =
  let wf_ID = WFMap.find (wf, i) wfmap
  and sum_lst = List.fold_left (fun x y → x + y) 0 lst in
  wf_ID - sum (ThoList.hdn (lorentz_ordering_reduced wf) num_lst)

let print_ext lookups amp_ID inc (wf, i) =
  let mom = (F.momentum_list wf) in
  let outer_index = if List.length mom = 1 then List.hd mom else
    failwith "targets.print_ext: called with non-external particle"
  and f = F.flavor wf in
  let pdg = CM.pdg f
  and wf_code =
    match CM.lorentz f with
    | Scalar → ovm_LOAD_SCALAR
    | BRS Scalar → ovm_LOAD_BRS_SCALAR
    | Spinor →
      if inc then ovm_LOAD_SPINOR_INC
      else ovm_LOAD_SPINOR_OUT
    | BRS Spinor →
      if inc then ovm_LOAD_BRS_SPINOR_INC
      else ovm_LOAD_BRS_SPINOR_OUT
    | ConjSpinor →
      if inc then ovm_LOAD_CONJSPINOR_INC
      else ovm_LOAD_CONJSPINOR_OUT
    | BRS ConjSpinor →
      if inc then ovm_LOAD_BRS_CONJSPINOR_INC
      else ovm_LOAD_BRS_CONJSPINOR_OUT
    | Vector | Massive_Vector →
      if inc then ovm_LOAD_VECTOR_INC
      else ovm_LOAD_VECTOR_OUT
    | BRS Vector | BRS Massive_Vector →
      if inc then ovm_LOAD_BRS_VECTOR_INC
      else ovm_LOAD_BRS_VECTOR_OUT
    | Tensor_2 →
      if inc then ovm_LOAD_TENSOR2_INC
      else ovm_LOAD_TENSOR2_OUT
    | Vectorspinor | BRS Vectorspinor →
      if inc then ovm_LOAD_VECTORSPINOR_INC
      else ovm_LOAD_VECTORSPINOR_OUT
    | Majorana →
      if inc then ovm_LOAD_MAJORANA_INC
      else ovm_LOAD_MAJORANA_OUT
    | BRS Majorana →
      if inc then ovm_LOAD_BRS_MAJORANA_INC
      else ovm_LOAD_BRS_MAJORANA_OUT

```

```

| Maj_Ghost →
  if inc then ovm_LOAD_MAJORANA_GHOST_INC
  else ovm_LOAD_MAJORANA_GHOST_OUT
| Tensor_1 →
  invalid_arg "targets.print_ext: Tensor_1 only internal"
| BRS _ →
  failwith "targets.print_ext: Not implemented"
and wf_ind = wf_index lookups.wfmap lookups.n_wfs (wf, i)
in
  printi wf_code ~lhs : wf_ind ~coupl : (abs(pdg)) ~rhs1 : outer_index ~rhs4 :
amp_ID

let print_ext_amp lookups amplitude =
  let incoming = (List.map (fun _ → true) (F.incoming amplitude) @
    List.map (fun _ → false) (F.outgoing amplitude))
  and amp_ID = get_ID' amp_compare lookups.amap amplitude in
  let wf_tpl wf = mult_wf lookups.dict amplitude wf in
  let print_ext_wf inc wf = wf |> wf_tpl |> print_ext lookups amp_ID inc in
  List.iter2 print_ext_wf incoming (F.externals amplitude)

let printexternals lookups seen_wfs amplitude =
  let externals =
    List.combine
      (F.externals amplitude)
      (List.map (fun _ → true) (F.incoming amplitude) @
        List.map (fun _ → false) (F.outgoing amplitude)) in
  List.fold_left (fun seen (wf, incoming) →
    let amp_ID = get_ID' amp_compare lookups.amap amplitude in
    let wf_tpl = mult_wf lookups.dict amplitude wf in
    if ¬ (WFSet.mem wf_tpl seen) then begin
      wf_tpl |> print_ext lookups amp_ID incoming
    end;
    WFSet.add wf_tpl seen) seen_wfs externals

```

*printexternals* and *print\_ext\_amp* do in principle the same thing but *printexternals* filters out duplicate external wave functions. Even with *printexternals* the same (numerically) external wave function will be loaded if it belongs to a different color flow, just as in the native Fortran code. For color MC, *print\_ext\_amp* has to be used (redundant instructions but only one flow is computed) and the filtering of duplicate fusions has to be disabled.

```

let print_ext_amps lookups =
  let print_external_amp s x = printexternals lookups s x in
  ignore (
    List.fold_left print_external_amp WFSet.empty
      (CF.processes lookups.amplitudes)
  )

```

(\*

*Currents*

\*)

Parallelization issues: All fusions have to be completed before the propagation takes place. Preferably each fusion and propagation is done by one thread. Solution: All fusions are subinstructions, i.e. if they are read by the main loop they are skipped. If a propagation occurs, all fusions have to be computed first. The additional control bit is the sign of the first int of an instruction.

```

let print_fermion_current code_a code_b code_c coeff lhs c wf1 wf2 fusion =
  let printc code r1 r2 = printi code ~lhs : lhs ~coupl : c ~coeff : coeff
    ~rhs1 : r1 ~rhs2 : r2 in
  match fusion with
  | F13 → printc code_a wf1 wf2
  | F31 → printc code_a wf2 wf1
  | F23 → printc code_b wf1 wf2
  | F32 → printc code_b wf2 wf1
  | F12 → printc code_c wf1 wf2
  | F21 → printc code_c wf2 wf1

let ferm_print_current = function
| coeff, Psibar, V, Psi → print_fermion_current
  ovm_FUSE_V_FF ovm_FUSE_F_VF ovm_FUSE_F_FV coeff
| coeff, Psibar, VA, Psi → print_fermion_current
  ovm_FUSE_VA_FF ovm_FUSE_F_VAF ovm_FUSE_F_FVA coeff
| coeff, Psibar, VA2, Psi → print_fermion_current
  ovm_FUSE_VA2_FF ovm_FUSE_F_VA2F ovm_FUSE_F_FVA2 coeff
| coeff, Psibar, A, Psi → print_fermion_current
  ovm_FUSE_A_FF ovm_FUSE_F_AF ovm_FUSE_F_FA coeff
| coeff, Psibar, VL, Psi → print_fermion_current
  ovm_FUSE_VL_FF ovm_FUSE_F_VLF ovm_FUSE_F_FVL coeff
| coeff, Psibar, VR, Psi → print_fermion_current
  ovm_FUSE_VR_FF ovm_FUSE_F_VRF ovm_FUSE_F_FVR coeff
| coeff, Psibar, VLR, Psi → print_fermion_current
  ovm_FUSE_VLR_FF ovm_FUSE_F_VLRF ovm_FUSE_F_FVLR coeff
| coeff, Psibar, SP, Psi → print_fermion_current
  ovm_FUSE_SP_FF ovm_FUSE_F_SPF ovm_FUSE_F_FSP coeff
| coeff, Psibar, S, Psi → print_fermion_current
  ovm_FUSE_S_FF ovm_FUSE_F_SF ovm_FUSE_F_FS coeff
| coeff, Psibar, P, Psi → print_fermion_current
  ovm_FUSE_P_FF ovm_FUSE_F_PF ovm_FUSE_F_FP coeff
| coeff, Psibar, SL, Psi → print_fermion_current
  ovm_FUSE_SL_FF ovm_FUSE_F_SLF ovm_FUSE_F_FSL coeff
| coeff, Psibar, SR, Psi → print_fermion_current
  ovm_FUSE_SR_FF ovm_FUSE_F_SRF ovm_FUSE_F_FSR coeff
| coeff, Psibar, SLR, Psi → print_fermion_current
  ovm_FUSE_SLR_FF ovm_FUSE_F_SLRF ovm_FUSE_F_FSLR coeff
| -, Psibar, -, Psi → invalid_arg
  "Targets.Fortran.VM:␣no␣superpotential␣here"
| -, Chibar, -, - | -, -, -, Chi → invalid_arg
  "Targets.Fortran.VM:␣Majorana␣spinors␣not␣handled"
| -, Gravbar, -, - | -, -, -, Grav → invalid_arg
  "Targets.Fortran.VM:␣Gravitinos␣not␣handled"

```

```

let children2 rhs =
  match F.children rhs with
  | [wf1; wf2] → (wf1, wf2)
  | _ → failwith "Targets.children2:␣can't␣happen"

let children3 rhs =
  match F.children rhs with
  | [wf1; wf2; wf3] → (wf1, wf2, wf3)
  | _ → invalid_arg "Targets.children3:␣can't␣happen"

let print_vector4 c lhs wf1 wf2 wf3 fusion (coeff, contraction) =
  let printc r1 r2 r3 = printi ovm_FUSE_V_VVV ~lhs : lhs ~coupl : c
    ~coeff : coeff ~rhs1 : r1 ~rhs2 : r2 ~rhs3 : r3 in
  match contraction, fusion with
  | C_12_34, (F341 | F431 | F342 | F432 | F123 | F213 | F124 | F214)
  | C_13_42, (F241 | F421 | F243 | F423 | F132 | F312 | F134 | F314)
  | C_14_23, (F231 | F321 | F234 | F324 | F142 | F412 | F143 |
F413) →
    printc wf1 wf2 wf3
  | C_12_34, (F134 | F143 | F234 | F243 | F312 | F321 | F412 | F421)
  | C_13_42, (F124 | F142 | F324 | F342 | F213 | F231 | F413 | F431)
  | C_14_23, (F123 | F132 | F423 | F432 | F214 | F241 | F314 |
F341) →
    printc wf2 wf3 wf1
  | C_12_34, (F314 | F413 | F324 | F423 | F132 | F231 | F142 | F241)
  | C_13_42, (F214 | F412 | F234 | F432 | F123 | F321 | F143 | F341)
  | C_14_23, (F213 | F312 | F243 | F342 | F124 | F421 | F134 |
F431) →
    printc wf1 wf3 wf2

let print_current lookups lhs amplitude rhs =
  let f = mult_wf lookups.dict amplitude in
  match F.coupling rhs with
  | V3 (vertex, fusion, constant) →
    let ch1, ch2 = children2 rhs in
    let wf1 = wf_index lookups.wfmap lookups.n_wfs (f ch1)
    and wf2 = wf_index lookups.wfmap lookups.n_wfs (f ch2)
    and p1 = mom_ID lookups.pmap ch1
    and p2 = mom_ID lookups.pmap ch2
    and const_ID = get_const_ID lookups.cmap constant in
    let c = if (F.sign rhs) < 0 then - const_ID else const_ID in
    begin match vertex with
    | FBF (coeff, fb, b, f) →
      begin match coeff, fb, b, f with
      | -, Psibar, VLRM, Psi | -, Psibar, SPM, Psi
      | -, Psibar, TVA, Psi | -, Psibar, TVAM, Psi
      | -, Psibar, TLR, Psi | -, Psibar, TLRM, Psi
      | -, Psibar, TRL, Psi | -, Psibar, TRLM, Psi → failwith
"print_current:␣V3:␣Momentum␣dependent␣fermion␣couplings␣not␣implemented"
      | -, -, -, - →
        ferm_print_current (coeff, fb, b, f) lhs c wf1 wf2 fusion

```

---

```

    end
  | PBP (_, -, -, -) →
    failwith "print_current:␣V3:␣PBP␣not␣implemented"
  | BBB (_, -, -, -) →
    failwith "print_current:␣V3:␣BBB␣not␣implemented"
  | GBG (_, -, -, -) →
    failwith "print_current:␣V3:␣GBG␣not␣implemented"
  | Gauge_Gauge_Gauge coeff →
    let printc r1 r2 r3 r4 = printi ovm_FUSE_G_GG
      ~lhs : lhs ~coupl : c ~coeff : coeff ~rhs1 : r1 ~rhs2 : r2 ~rhs3 :
r3
      ~rhs4 : r4 in
    begin match fusion with
    | (F23 | F31 | F12) → printc wf1 p1 wf2 p2
    | (F32 | F13 | F21) → printc wf2 p2 wf1 p1
    end
  | Aux_Gauge_Gauge _ →
    failwith "print_current:␣V3:␣not␣implemented"
  | Scalar_Vector_Vector coeff →
    let printc code r1 r2 = printi code
      ~lhs : lhs ~coupl : c ~coeff : coeff ~rhs1 : r1 ~rhs2 : r2 in
    begin match fusion with
    | (F23 | F32) → printc ovm_FUSE_S_VV wf1 wf2
    | (F12 | F13) → printc ovm_FUSE_V_SV wf1 wf2
    | (F21 | F31) → printc ovm_FUSE_V_SV wf2 wf1
    end
  | Scalar_Scalar_Scalar coeff →
    printi ovm_FUSE_S_SS ~lhs : lhs ~coupl : c ~coeff : coeff ~rhs1 :
wf1 ~rhs2 : wf2
  | Vector_Scalar_Scalar coeff →
    let printc code ?flip : (f = 1) r1 r2 r3 r4 = printi code
      ~lhs : lhs ~coupl : (c × f) ~coeff : coeff ~rhs1 : r1 ~rhs2 :
r2 ~rhs3 : r3
      ~rhs4 : r4 in
    begin match fusion with
    | F23 → printc ovm_FUSE_V_SS wf1 p1 wf2 p2
    | F32 → printc ovm_FUSE_V_SS wf2 p2 wf1 p1
    | F12 → printc ovm_FUSE_S_VS wf1 p1 wf2 p2
    | F21 → printc ovm_FUSE_S_VS wf2 p2 wf1 p1
    | F13 → printc ovm_FUSE_S_VS wf1 p1 wf2 p2 ~flip : (-1)
    | F31 → printc ovm_FUSE_S_VS wf2 p2 wf1 p1 ~flip : (-1)
    end
  | Aux_Vector_Vector _ →
    failwith "print_current:␣V3:␣not␣implemented"
  | Aux_Scalar_Scalar _ →
    failwith "print_current:␣V3:␣not␣implemented"

```



---

```

| Aux_Scalar_Vector _ →
  failwith "print_current: V3: not implemented"
| Graviton_Scalar_Scalar _ →
  failwith "print_current: V3: not implemented"
| Graviton_Vector_Vector _ →
  failwith "print_current: V3: not implemented"
| Graviton_Spinor_Spinor _ →
  failwith "print_current: V3: not implemented"
| Dim4_Vector_Vector_Vector_T _ →
  failwith "print_current: V3: not implemented"
| Dim4_Vector_Vector_Vector_L _ →
  failwith "print_current: V3: not implemented"
| Dim6_Gauge_Gauge_Gauge _ →
  failwith "print_current: V3: not implemented"
| Dim4_Vector_Vector_Vector_T5 _ →
  failwith "print_current: V3: not implemented"
| Dim4_Vector_Vector_Vector_L5 _ →
  failwith "print_current: V3: not implemented"
| Dim6_Gauge_Gauge_Gauge_5 _ →
  failwith "print_current: V3: not implemented"
| Aux_DScalar_DScalar _ →
  failwith "print_current: V3: not implemented"
| Aux_Vector_DScalar _ →
  failwith "print_current: V3: not implemented"
| Dim5_Scalar_Gauge2 coeff →
  let printc code r1 r2 r3 r4 = printi code
    ~lhs : lhs ~coupl : c ~coeff : coeff ~rhs1 : r1 ~rhs2 : r2 ~rhs3 :
    r3
    ~rhs4 : r4 in
  begin match fusion with
  | (F23 | F32) → printc ovm_FUSE_S_G2 wf1 p1 wf2 p2
  | (F12 | F13) → printc ovm_FUSE_G_SG wf1 p1 wf2 p2
  | (F21 | F31) → printc ovm_FUSE_G_GS wf2 p2 wf1 p1
  end
| Dim5_Scalar_Gauge2_Skew coeff →
  let printc code ?flip : (f = 1) r1 r2 r3 r4 = printi code
    ~lhs : lhs ~coupl : (c × f) ~coeff : coeff ~rhs1 : r1 ~rhs2 :
    r2 ~rhs3 : r3
    ~rhs4 : r4 in
  begin match fusion with
  | (F23 | F32) → printc ovm_FUSE_S_G2_SKEW wf1 p1 wf2 p2
  | (F12 | F13) → printc ovm_FUSE_G_SG_SKEW wf1 p1 wf2 p2
  | (F21 | F31) → printc ovm_FUSE_G_GS_SKEW wf2 p1 wf1 p2 ~flip :
    (-1)

```

```

end
| Dim5_Scalar_Vector_Vector_T _ →
  failwith "print_current: V3: not implemented"
| Dim5_Scalar_Vector_Vector_U _ →
  failwith "print_current: V3: not implemented"
| Dim6_Vector_Vector_Vector_T _ →
  failwith "print_current: V3: not implemented"
| Tensor_2_Vector_Vector _ →
  failwith "print_current: V3: not implemented"
| Dim5_Tensor_2_Vector_Vector_1 _ →
  failwith "print_current: V3: not implemented"
| Dim5_Tensor_2_Vector_Vector_2 _ →
  failwith "print_current: V3: not implemented"
| Dim7_Tensor_2_Vector_Vector_T _ →
  failwith "print_current: V3: not implemented"
| Dim5_Scalar_Vector_Vector_TU _ →
  failwith "print_current: V3: not implemented"
| Scalar_Vector_Vector_t _ →
  failwith "print_current: V3: not implemented"
| Tensor_2_Vector_Vector_1 _ →
  failwith "print_current: V3: not implemented"
| Tensor_2_Vector_Vector_t _ →
  failwith "print_current: V3: not implemented"
end

```

Flip the sign in  $c$  to account for the  $i^2$  relative to diagrams with only cubic couplings.

```

| V4 (vertex, fusion, constant) →
  let ch1, ch2, ch3 = children3 rhs in
  let wf1 = wf_index lookups.wfmap lookups.n_wfs (f ch1)
  and wf2 = wf_index lookups.wfmap lookups.n_wfs (f ch2)
  and wf3 = wf_index lookups.wfmap lookups.n_wfs (f ch3)
  and const_ID = get_const_ID lookups.cmap constant in
  let c =
    if (F.sign rhs) < 0 then const_ID else - const_ID in
  begin match vertex with
  | Scalar4 coeff →
    printi ovm_FUSE_S_SSS ~lhs : lhs ~coupl : c ~coeff : coeff ~rhs1 :
wf1
      ~rhs2 : wf2 ~rhs3 : wf3
  | Scalar2_Vector2 coeff →
    let printc code r1 r2 r3 = printi code
      ~lhs : lhs ~coupl : c ~coeff : coeff ~rhs1 : r1 ~rhs2 : r2 ~rhs3 :
r3 in

```

```

begin match fusion with
| F134 | F143 | F234 | F243 →
  printc ovm_FUSE_S_SVV wf1 wf2 wf3
| F314 | F413 | F324 | F423 →
  printc ovm_FUSE_S_SVV wf2 wf1 wf3
| F341 | F431 | F342 | F432 →
  printc ovm_FUSE_S_SVV wf3 wf1 wf2
| F312 | F321 | F412 | F421 →
  printc ovm_FUSE_V_SSV wf2 wf3 wf1
| F231 | F132 | F241 | F142 →
  printc ovm_FUSE_V_SSV wf1 wf3 wf2
| F123 | F213 | F124 | F214 →
  printc ovm_FUSE_V_SSV wf1 wf2 wf3
end

| Vector4 contractions →
  List.iter (print_vector4 c lhs wf1 wf2 wf3 fusion) contractions

| Vector4_K_Matrix_tho _
| Vector4_K_Matrix_jr _ →
  failwith "print_current: V4: K_Matrix not implemented"

| GBBG _ →
  failwith "print_current: V4: GBBG not implemented"

| DScalar4 _
| DScalar2_Vector2 _ →
  failwith "print_current: V4: DScalars not implemented"
end

| Vn (_, -, -) → invalid_arg "Targets.print_current: n-ary fusion."

```

### Fusions

```

let print_fusion lookups lhs_momID fusion amplitude =
  if F.on_shell amplitude (F.lhs fusion) then
    failwith "print_fusion: on-shell projectors not implemented!";
  if F.is_gauss amplitude (F.lhs fusion) then
    failwith "print_fusion: gauss amplitudes not implemented!";
  let lhs_wf = mult_wf lookups.dict amplitude (F.lhs fusion) in
  let lhs_wfID = wf_index lookups.wfmap lookups.n_wfs lhs_wf in
  let f = F.flavor (F.lhs fusion) in
  let pdg = CM.pdg f in
  let w =
    begin match CM.width f with
    | Vanishing | Fudged → 0
    | Constant → 1
    | Timelike → 2
    | Running → failwith "Targets.VM: running width not available"
    | Custom _ → failwith "Targets.VM: custom width not available"
    end
  in

```

```

let propagate code = printi code ~lhs : lhs_wfID ~rhs1 : lhs_momID
  ~coupl : (abs(pdg)) ~coeff : w ~rhs4 : (get_ID' amp_compare lookups.amap amplitude)
in
begin match CM.propagator f with
| Prop_Scalar →
  propagate ovm_PROPAGATE_SCALAR
| Prop_Col_Scalar →
  propagate ovm_PROPAGATE_COL_SCALAR
| Prop_Ghost →
  propagate ovm_PROPAGATE_GHOST
| Prop_Spinor →
  propagate ovm_PROPAGATE_SPINOR
| Prop_ConjSpinor →
  propagate ovm_PROPAGATE_CONJSPINOR
| Prop_Majorana →
  propagate ovm_PROPAGATE_MAJORANA
| Prop_Col_Majorana →
  propagate ovm_PROPAGATE_COL_MAJORANA
| Prop_Unitarity →
  propagate ovm_PROPAGATE_UNITARITY
| Prop_Col_Unitarity →
  propagate ovm_PROPAGATE_COL_UNITARITY
| Prop_Feynman →
  propagate ovm_PROPAGATE_FEYNMAN
| Prop_Col_Feynman →
  propagate ovm_PROPAGATE_COL_FEYNMAN
| Prop_Vectorspinor →
  propagate ovm_PROPAGATE_VECTORSPINOR
| Prop_Tensor_2 →
  propagate ovm_PROPAGATE_TENSOR2
| Aux_Col_Scalar | Aux_Col_Vector | Aux_Col_Tensor_1 →
  failwith "print_fusion:␣Aux_Col_*␣not␣implemented!"
| Aux_Vector | Aux_Tensor_1 | Aux_Scalar | Aux_Spinor |
Aux_ConjSpinor
| Aux_Majorana | Only_Insertion →
  propagate ovm_PROPAGATE_NONE
| Prop_Gauge _ →
  failwith "print_fusion:␣Prop_Gauge␣not␣implemented!"
| Prop_Rxi _ →
  failwith "print_fusion:␣Prop_Rxi␣not␣implemented!"
end;

```

Since the OVM knows that we want to propagate a wf, we can send the necessary fusions now.

```

List.iter (print_current lookups lhs_wfID amplitude) (F.rhs fusion)
let print_all_fusions lookups =
  let fusions = CF.fusions lookups.amplitudes in
  let fset = List.fold_left (fun s x → FSet.add x s) FSet.empty fusions in
  ignore (List.fold_left (fun level (f, amplitude) →
    let wf = F.lhs f in

```

```

let lhs_momID = mom_ID lookups.pmap wf in
let level' = List.length (F.momentum_list wf) in
if (level' > level ∧ level' > 2) then break ();
print_fusion lookups lhs_momID f amplitude;
level')
1 (FSet.elements fset) )

```

### Brakets

```

let print_braket lookups amplitude braket =
let bra = F.bra braket
and ket = F.ket braket in
let braID = wf_index lookups.wfmap lookups.n_wfs
(mult_wf lookups.dict amplitude bra) in
List.iter (print_current lookups braID amplitude) ket

```

$$iT = i^{\#\text{vertices}} i^{\#\text{propagators}} \dots = i^{n-2} i^{n-3} \dots = -i(-1)^n \dots \quad (15.1)$$

All brakets for one cflow amplitude should be calculated by one thread to avoid multiple access on the same memory (amplitude).

```

let print_brakets lookups (amplitude, i) =
let n = List.length (F.externals amplitude) in
let sign = if n mod 2 = 0 then -1 else 1
and sym = F.symmetry amplitude in
printi ovm_CALC_BRAKET ~lhs : i ~rhs1 : sym ~coupl : sign;
amplitude | > F.brakets | > List.iter (print_braket lookups amplitude)

```

Fortran arrays/OCaml lists start on 1/0. The amplitude list is sorted by *amp\_compare* according to their color flows. In this way the amp array is sorted in the same way as *table\_color\_factors*.

```

let print_all_brakets lookups =
let g i elt = print_brakets lookups (elt, i + 1) in
lookups.amplitudes | > CF.processes | > List.sort amp_compare
—> ThoList.iteri g 0

```

### Couplings

For now we only care to catch the arrays *gncneu*, *gnclep*, *gncup* and *gncdown* of the SM. This will need an overhaul when it is clear how we store the type information of coupling constants.

```

let strip_array_tag = function
| Real_Array x → x
| Complex_Array x → x

let array_constants_list =
let params = M.parameters()
and strip_to_constant (lhs, _) = strip_array_tag lhs in
List.map strip_to_constant params.derived_arrays

```

```

let is_array x = List.mem x array_constants_list
let constants_map =
  let first = fun (x, -, -) → x in
  let second = fun (_, y, -) → y in
  let third = fun (_, -, z) → z in
  let v3 = List.map third (first (M.vertices () ))
  and v4 = List.map third (second (M.vertices () )) in
  let set = List.fold_left (fun s x → CSet.add x s) CSet.empty (v3 @ v4) in
  let (arrays, singles) = CSet.partition is_array set in
  (singles |> CSet.elements |> map_of_list,
   arrays |> CSet.elements |> map_of_list)

```

*Output calls*

```

let amplitudes_to_channel (cmdline : string) (oc : out_channel)
  (diagnostics : (diagnostic × bool) list) (amplitudes : CF.amplitudes) =
  set_formatter_out_channel oc;
  if (num_particles amplitudes = 0) then begin
    print_description cmdline;
    print_zero_header (); nl ()
  end else begin
    let (wfset, amap) = wfset_amps amplitudes in
    let pset = expand_pset (momenta_set wfset)
    and n_wfs = num_wfs wfset in
    let wfmap = wf_map_of_list (WFSet.elements wfset)
    and pmap = map_of_list (ISet.elements pset)
    and cmap = constants_map in

    let lookups = {pmap = pmap; wfmap = wfmap; cmap = cmap; amap = amap;
      n_wfs = n_wfs; amplitudes = amplitudes;
      dict = CF.dictionary amplitudes} in

    print_description cmdline;
    print_header lookups wfset;
    print_spin_table amplitudes;
    print_flavor_tables amplitudes;
    print_color_tables amplitudes;
    printf "@\n%s" ("OVM_instructions_for_momenta_addition," ^
      "fusions_and_brackets_start_here:");

    break ();
    add_all_mom lookups pset;
    print_ext_amps lookups;
    break ();
    print_all_fusions lookups;
    break ();
    print_all_brackets lookups;
    break (); nl ();
    print_flush ()
  end
end

```

```

let parameters_to_fortran oc _ =
  set_formatter_out_channel oc;
let arrays_to_set = ¬ (IMap.is_empty (snd constants_map)) in
let set_coupl ty dim cmap = IMap.iter (fun key elt →
  printf "      %s(%s%d) = %s" ty dim key (M.constant_symbol elt);
  nl () ) cmap in
let declarations () =
  printf "    complex(%s), dimension(%d) :: ovm_coupl_cmplx"
    !kind (constants_map | > fst | > largest_key); nl ();
  if arrays_to_set then
    printf "    complex(%s), dimension(2,%d) :: ovm_coupl_cmplx2"
      !kind (constants_map | > snd | > largest_key); nl () in
let print_line str = printf "%s" str; nl() in
let print_md5sum = function
  | Some s →
    print_line "function_md5sum()";
    print_line "character(len=32) :: md5sum";
    print_line ("bytecode_file = " ^ !bytecode_file ^ "");
    print_line "call initialize_vm(vm, bytecode_file)";
    print_line "!! DON'T EVEN THINK of modifying the following line!";
    print_line ("md5sum = " ^ s ^ "");
    print_line "end_function_md5sum";
  | None → ()
in
let print_inquiry_function_omp () = begin
  print_line "pure_function_omp_supported() result(status)";
  print_line "logical :: status";
  print_line ("status = " ^ (if !omp then ".true." else ".false."));
  print_line "end_function_omp_supported";
  nl ()
end in
let print_interface whizard =
if whizard then begin
  print_line "subroutine_init(par)";
  print_line "real(kind=default), dimension(*), intent(in) :: par";
  print_line ("bytecode_file = " ^ !bytecode_file ^ "");
  print_line "call import_from_whizard(par)";
  print_line "call initialize_vm(vm, bytecode_file)";
  print_line "end_subroutine_init";
  nl ();
  print_line "subroutine_final()";
  print_line "call vm%final()";
  print_line "end_subroutine_final";
  nl ();
  print_line "subroutine_update_alpha_s(alpha_s)";
  print_line ("real(kind=" ^ !kind ^ "), intent(in) :: alpha_s");
  print_line "call model_update_alpha_s(alpha_s)";
  print_line "end_subroutine_update_alpha_s";
  nl ()
end

```

```

else begin
  print_line "subroutine_init()";
  print_line ("bytecode_file=' ' ^ !bytecode_file ^ ' ');
  print_line "call_init_parameters()";
  print_line "call_initialize_vm(vm, bytecode_file)";
  print_line "end_subroutine"
end in
let print_lookup_functions () = begin
  print_line "pure_function_number_particles_in() result(n)";
  print_line "integer::n";
  print_line "n=vm%number_particles_in()";
  print_line "end_function_number_particles_in";
  nl();
  print_line "pure_function_number_particles_out() result(n)";
  print_line "integer::n";
  print_line "n=vm%number_particles_out()";
  print_line "end_function_number_particles_out";
  nl();
  print_line "pure_function_number_spin_states() result(n)";
  print_line "integer::n";
  print_line "n=vm%number_spin_states()";
  print_line "end_function_number_spin_states";
  nl();
  print_line "pure_subroutine_spin_states(a)";
  print_line "integer, dimension(:, :), intent(out)::a";
  print_line "call_vm%spin_states(a)";
  print_line "end_subroutine_spin_states";
  nl();
  print_line "pure_function_number_flavor_states() result(n)";
  print_line "integer::n";
  print_line "n=vm%number_flavor_states()";
  print_line "end_function_number_flavor_states";
  nl();
  print_line "pure_subroutine_flavor_states(a)";
  print_line "integer, dimension(:, :), intent(out)::a";
  print_line "call_vm%flavor_states(a)";
  print_line "end_subroutine_flavor_states";
  nl();
  print_line "pure_function_number_color_indices() result(n)";
  print_line "integer::n";
  print_line "n=vm%number_color_indices()";
  print_line "end_function_number_color_indices";
  nl();
  print_line "pure_function_number_color_flows() result(n)";
  print_line "integer::n";
  print_line "n=vm%number_color_flows()";
  print_line "end_function_number_color_flows";
  nl();
  print_line "pure_subroutine_color_flows(a, g)";
  print_line "integer, dimension(:, :, :), intent(out)::a";

```



```

print_line "uuuuu logical, u dimension(:, :), u intent(out) u::ug";
print_line "uuuuu call vm%color_flows u(a, ug)";
print_line "uu end subroutine color_flows";
nl();
print_line "uu pure function number_color_factors u() u result u(n)";
print_line "uuuu integer u::un";
print_line "uuuuu n = vm%number_color_factors u()";
print_line "uu end function number_color_factors";
nl();
print_line "uu pure subroutine color_factors u(cf)";
print_line "uuuu use omega_color";
print_line "uuuu type(omega_color_factor), u dimension(:, :), u intent(out) u::ucf";
print_line "uuuu call vm%color_factors u(cf)";
print_line "uu end subroutine color_factors";
nl();
print_line "uu !pure unless OpenMP";
print_line "uu !pure function color_sum u(flv, uhel) u result u(amp2)";
print_line "uu function color_sum u(flv, uhel) u result u(amp2)";
print_line "uuuu use kinds";
print_line "uuuu integer, u intent(in) u::uflv, uhel";
print_line "uuuu real(kind=default) u::uamp2";
print_line "uuuu amp2 = vm%color_sum u(flv, uhel)";
print_line "uu end function color_sum";
nl();
print_line "uu subroutine new_event u(p)";
print_line "uuuu use kinds";
print_line "uuuu real(kind=default), u dimension(0:3, *), u intent(in) u::up";
print_line "uuuu call vm%new_event u(p)";
print_line "uu end subroutine new_event";
nl();
print_line "uu subroutine reset_helicity_selection u(threshold, ucutoff)";
print_line "uuuu use kinds";
print_line "uuuu real(kind=default), u intent(in) u::uthreshold";
print_line "uuuu integer, u intent(in) u::ucutoff";
print_line "uuuu call vm%reset_helicity_selection u(threshold, ucutoff)";
print_line "uu end subroutine reset_helicity_selection";
nl();
print_line "uu pure function is_allowed u(flv, uhel, ucol) u result u(yorn)";
print_line "uuuu logical u::uyorn";
print_line "uuuu integer, u intent(in) u::uflv, uhel, ucol";
print_line "uuuu yorn = vm%is_allowed u(flv, uhel, ucol)";
print_line "uu end function is_allowed";
nl();
print_line "uu pure function get_amplitude u(flv, uhel, ucol) u result u(amp_result)";
print_line "uuuu use kinds";
print_line "uuuu complex(kind=default) u::uamp_result";
print_line "uuuu integer, u intent(in) u::uflv, uhel, ucol";
print_line "uuuu amp_result = vm%get_amplitude u(flv, uhel, ucol)";
print_line "uu end function get_amplitude";
nl();

```

```

end in
let rcs_str s = String.sub s 0 (String.length s - 1) in
let rcs_tags = rcs_list @ [M.rcs] |> List.map version_string
               -> List.map rcs_str in

print_line ("module_" ^ !wrapper_module);
print_line ("use_" ^ !parameter_module_external);
print_line "use_iso_varying_string, string_t=>varying_string";
print_line "use_kinds";
print_line "use_omegavm95";
print_line "implicit_none";
print_line "private";
print_line "type(vm_t)::vm";
print_line "type(string_t)::bytecode_file";
print_line ("public::number_particles_in, number_particles_out," ^
  "number_spin_states,&");
print_line ("spin_states, number_flavor_states, flavor_states," ^
  "number_color_indices,&");
print_line ("number_color_flows, color_flows," ^
  "number_color_factors, color_factors,&");
print_line ("color_sum, new_event, reset_helicity_selection," ^
  "is_allowed, get_amplitude,&");
print_line ("init," ^
  (match !md5sum with Some _ -> "md5sum,"
   | None -> "") ^ "openmp-supported");
if !whizard then
  print_line ("public::final, update_alpha_s")
else
  print_line ("public::initialize_vm");
declarations ();
print_line "contains";

print_line "subroutine_setup_couplings()";
set_coupl "ovm_coupl_cmplx" "" (fst constants_map);
if arrays_to_set then
  set_coupl "ovm_coupl_cmplx2" ":", (snd constants_map);
print_line "end_subroutine_setup_couplings";
print_line "subroutine_initialize_vm(vm, bytecode_file)";
print_line "class(vm_t), intent(out)::vm";
print_line "type(string_t), intent(in)::bytecode_file";
print_line "type(string_t)::version";
print_line "type(string_t)::model";
print_line ("version=_'" ^ List.nth rcs_tags 0 ^ "'");
print_line ("model=_'" ^ List.nth rcs_tags 1 ^ "'");
print_line "call_setup_couplings()";
print_line "call_vm%init(bytecode_file, version, model, verbose=.False., &";
print_line "coupl_cmplx=ovm_coupl_cmplx,&";
if arrays_to_set then
  print_line "coupl_cmplx2=ovm_coupl_cmplx2,&";
print_line ("mass=mass, width=width, openmp=" ^ (if !openmp then
  ".true." else ".false.") ^ ")");

```

```

    print_line "end_subroutine_initialize_vm";
    nl();
    print_md5sum !md5sum;
    print_inquiry_function_omp ();
    print_interface !whizard;
    print_lookup_functions ();

    print_line ("end_module_" ^ !wrapper_module);
    print_line "!0'Mega_revision_control_information:";
    ThoList.flatmap RCS.summary (M.rcs :: rcs_list) | >
        List.iter (fun s → printf "!%s" s; nl ())

let parameters_to_channel oc =
    parameters_to_fortran oc (CM.parameters ())

end

```

### 15.2.2 Fortran 90/95

#### *Dirac Fermions*

We factor out the code for fermions so that we can use the simpler implementation for Dirac fermions if the model contains no Majorana fermions.

```

module type Fermions =
sig
  open Coupling
  val psi_type : string
  val psibar_type : string
  val chi_type : string
  val grav_type : string
  val psi_incoming : string
  val brs_psi_incoming : string
  val psibar_incoming : string
  val brs_psibar_incoming : string
  val chi_incoming : string
  val brs_chi_incoming : string
  val grav_incoming : string
  val psi_outgoing : string
  val brs_psi_outgoing : string
  val psibar_outgoing : string
  val brs_psibar_outgoing : string
  val chi_outgoing : string
  val brs_chi_outgoing : string
  val grav_outgoing : string
  val psi_propagator : string
  val psibar_propagator : string
  val chi_propagator : string
  val grav_propagator : string
  val psi_projector : string
  val psibar_projector : string

```

```

val chi_projector : string
val grav_projector : string
val psi_gauss : string
val psibar_gauss : string
val chi_gauss : string
val grav_gauss : string
val print_current : int × fermionbar × boson × fermion →
  string → string → string → fuse2 → unit
val print_current_mom : int × fermionbar × boson × fermion →
  string → string → string → string → string → string
  → fuse2 → unit
val print_current_p : int × fermion × boson × fermion →
  string → string → string → fuse2 → unit
val print_current_b : int × fermionbar × boson × fermionbar →
  string → string → string → fuse2 → unit
val print_current_g : int × fermionbar × boson × fermion →
  string → string → string → string → string → string
  → fuse2 → unit
val print_current_g4 : int × fermionbar × boson2 × fermion →
  string → string → string → string → fuse3 → unit
val reverse_braket : lorentz → bool
val use_module : string
val require_library : string list
val rcs : RCS.t
end

module Fortran_Fermions : Fermions =
struct
  let rcs = RCS.rename rcs_file "Targets.Fortran_Fermions()"
    [ "generates_Fortran95_code_for_Dirac_fermions";
      "using_revision_2000_10_A_of_module_omega95" ]

  open Coupling
  open Format

  let psi_type = "spinor"
  let psibar_type = "conjspinor"
  let chi_type = "???"
  let grav_type = "???"

  let psi_incoming = "u"
  let brs_psi_incoming = "brs_u"
  let psibar_incoming = "vbar"
  let brs_psibar_incoming = "brs_vbar"
  let chi_incoming = "???"
  let brs_chi_incoming = "???"
  let grav_incoming = "???"
  let psi_outgoing = "v"
  let brs_psi_outgoing = "brs_v"
  let psibar_outgoing = "ubar"
  let brs_psibar_outgoing = "brs_ubar"
  let chi_outgoing = "???"

```

```

let brs_chi_outgoing = "???"
let grav_outgoing = "???"

let psi_propagator = "pr_psi"
let psibar_propagator = "pr_psibar"
let chi_propagator = "???"
let grav_propagator = "???"

let psi_projector = "pj_psi"
let psibar_projector = "pj_psibar"
let chi_projector = "???"
let grav_projector = "???"

let psi_gauss = "pg_psi"
let psibar_gauss = "pg_psibar"
let chi_gauss = "???"
let grav_gauss = "???"

let format_coupling coeff c =
  match coeff with
  | 1 → c
  | -1 → "(-" ^ c ^ ")"
  | coeff → string_of_int coeff ^ "*" ^ c

let format_coupling_2 coeff c =
  match coeff with
  | 1 → c
  | -1 → "-" ^ c
  | coeff → string_of_int coeff ^ "*" ^ c

```



JR's coupling constant HACK, necessitated by tho's bad design descition.

```

let fastener s i ?p ?q () =
  try
    let offset = (String.index s '(') in
    if ((String.get s (String.length s - 1)) ≠ ')') then
      failwith "fastener: wrong usage of parentheses"
    else
      let func_name = (String.sub s 0 offset) and
      tail =
        (String.sub s (succ offset) (String.length s - offset - 2)) in
      if (String.contains func_name ')') ∨
        (String.contains tail '(') ∨
        (String.contains tail ')') then
        failwith "fastener: wrong usage of parentheses"
      else
        func_name ^ "(" ^ string_of_int i ^ "," ^ tail ^ ")"
  with
  | Not_found →
    if (String.contains s ')') then
      failwith "fastener: wrong usage of parentheses"
    else

```

```

match p with
| None → s ^ "(" ^ string_of_int i ^ ")"
| Some p →
  match q with
  | None → s ^ "(" ^ p ^ "*" ^ p ^ "," ^ string_of_int i ^ ")"
  | Some q → s ^ "(" ^ p ^ "," ^ q ^ "," ^ string_of_int i ^ ")"

let print_fermion_current coeff f c wf1 wf2 fusion =
  let c = format_coupling coeff c in
  match fusion with
  | F13 → printf "%s_ff(%s,%s,%s)" f c wf1 wf2
  | F31 → printf "%s_ff(%s,%s,%s)" f c wf2 wf1
  | F23 → printf "f_%sf(%s,%s,%s)" f c wf1 wf2
  | F32 → printf "f_%sf(%s,%s,%s)" f c wf2 wf1
  | F12 → printf "f_f%s(%s,%s,%s)" f c wf1 wf2
  | F21 → printf "f_f%s(%s,%s,%s)" f c wf2 wf1

```



Using a two element array for the combined vector-axial and scalar-pseudo couplings helps to support HELAS as well. Since we will probably never support general boson couplings with HELAS, it might be retired in favor of two separate variables. For this *Model.constant\_symbol* has to be generalized.



NB: passing the array instead of two separate constants would be a *bad* idea, because the support for Majorana spinors below will have to flip signs!

```

let print_fermion_current2 coeff f c wf1 wf2 fusion =
  let c = format_coupling_2 coeff c in
  let c1 = fastener c 1 ()
  and c2 = fastener c 2 () in
  match fusion with
  | F13 → printf "%s_ff(%s,%s,%s,%s)" f c1 c2 wf1 wf2
  | F31 → printf "%s_ff(%s,%s,%s,%s)" f c1 c2 wf2 wf1
  | F23 → printf "f_%sf(%s,%s,%s,%s)" f c1 c2 wf1 wf2
  | F32 → printf "f_%sf(%s,%s,%s,%s)" f c1 c2 wf2 wf1
  | F12 → printf "f_f%s(%s,%s,%s,%s)" f c1 c2 wf1 wf2
  | F21 → printf "f_f%s(%s,%s,%s,%s)" f c1 c2 wf2 wf1

let print_fermion_current_mom_v1 coeff f c wf1 wf2 p1 p2 p12 fusion =
  let c = format_coupling coeff c in
  let c1 = fastener c 1 and
      c2 = fastener c 2 in
  match fusion with
  | F13 → printf "%s_ff(%s,%s,%s,%s)" f (c1 ~p : p12 ()) (c2 ~p :
p12 ()) wf1 wf2
  | F31 → printf "%s_ff(%s,%s,%s,%s)" f (c1 ~p : p12 ()) (c2 ~p :
p12 ()) wf2 wf1
  | F23 → printf "f_%sf(%s,%s,%s,%s)" f (c1 ~p : p1 ()) (c2 ~p :
p1 ()) wf1 wf2
  | F32 → printf "f_%sf(%s,%s,%s,%s)" f (c1 ~p : p2 ()) (c2 ~p :
p2 ()) wf2 wf1

```

```

| F12 → printf "f-f%s(%s,%s,%s,%s)" f (c1 ~p : p2 ()) (c2 ~p :
p2 ()) wf1 wf2
| F21 → printf "f-f%s(%s,%s,%s,%s)" f (c1 ~p : p1 ()) (c2 ~p :
p1 ()) wf2 wf1
let print_fermion_current_mom_v2 coeff f c wf1 wf2 p1 p2 p12 fusion =
  let c = format_coupling coeff c in
  let c1 = fastener c 1 and
      c2 = fastener c 2 in
  match fusion with
  | F13 → printf "%s_ff(%s,%s,@,%s,%s,%s)" f (c1 ~p : p12 ()) (c2 ~p :
p12 ()) wf1 wf2 p12
  | F31 → printf "%s_ff(%s,%s,@,%s,%s,%s)" f (c1 ~p : p12 ()) (c2 ~p :
p12 ()) wf2 wf1 p12
  | F23 → printf "f-%sf(%s,%s,@,%s,%s,%s)" f (c1 ~p : p1 ()) (c2 ~p :
p1 ()) wf1 wf2 p1
  | F32 → printf "f-%sf(%s,%s,@,%s,%s,%s)" f (c1 ~p : p2 ()) (c2 ~p :
p2 ()) wf2 wf1 p2
  | F12 → printf "f-f%s(%s,%s,@,%s,%s,%s)" f (c1 ~p : p2 ()) (c2 ~p :
p2 ()) wf1 wf2 p2
  | F21 → printf "f-f%s(%s,%s,@,%s,%s,%s)" f (c1 ~p : p1 ()) (c2 ~p :
p1 ()) wf2 wf1 p1
let print_fermion_current_mom_ff coeff f c wf1 wf2 p1 p2 p12 fusion =
  let c = format_coupling coeff c in
  let c1 = fastener c 1 and
      c2 = fastener c 2 in
  match fusion with
  | F13 → printf "%s_ff(%s,%s,%s,%s)" f (c1 ~p : p1 ~q : p2 ()) (c2 ~p :
p1 ~q : p2 ()) wf1 wf2
  | F31 → printf "%s_ff(%s,%s,%s,%s)" f (c1 ~p : p1 ~q : p2 ()) (c2 ~p :
p1 ~q : p2 ()) wf2 wf1
  | F23 → printf "f-%sf(%s,%s,%s,%s)" f (c1 ~p : p12 ~q : p2 ()) (c2 ~p :
p12 ~q : p2 ()) wf1 wf2
  | F32 → printf "f-%sf(%s,%s,%s,%s)" f (c1 ~p : p12 ~q : p1 ()) (c2 ~p :
p12 ~q : p1 ()) wf2 wf1
  | F12 → printf "f-f%s(%s,%s,%s,%s)" f (c1 ~p : p12 ~q : p1 ()) (c2 ~p :
p12 ~q : p1 ()) wf1 wf2
  | F21 → printf "f-f%s(%s,%s,%s,%s)" f (c1 ~p : p12 ~q : p2 ()) (c2 ~p :
p12 ~q : p2 ()) wf2 wf1
let print_current = function
| coeff, Psibar, VA, Psi → print_fermion_current2 coeff "va"
| coeff, Psibar, VA2, Psi → print_fermion_current coeff "va2"
| coeff, Psibar, VA3, Psi → print_fermion_current coeff "va3"
| coeff, Psibar, V, Psi → print_fermion_current coeff "v"
| coeff, Psibar, A, Psi → print_fermion_current coeff "a"
| coeff, Psibar, VL, Psi → print_fermion_current coeff "vl"
| coeff, Psibar, VR, Psi → print_fermion_current coeff "vr"
| coeff, Psibar, VLR, Psi → print_fermion_current2 coeff "vlr"
| coeff, Psibar, SP, Psi → print_fermion_current2 coeff "sp"
| coeff, Psibar, S, Psi → print_fermion_current coeff "s"

```

---

```

| coeff, Psibar, P, Psi → print_fermion_current coeff "p"
| coeff, Psibar, SL, Psi → print_fermion_current coeff "sl"
| coeff, Psibar, SR, Psi → print_fermion_current coeff "sr"
| coeff, Psibar, SLR, Psi → print_fermion_current2 coeff "slr"
| -, Psibar, -, Psi → invalid_arg
| "Targets.Fortran.Fermions:_no_superpotential_here"
| -, Chibar, -, - | -, -, -, Chi → invalid_arg
| "Targets.Fortran.Fermions:_Majorana_spinors_not_handled"
| -, Gravbar, -, - | -, -, -, Grav → invalid_arg
| "Targets.Fortran.Fermions:_Gravitinos_not_handled"

let print_current_mom = function
| coeff, Psibar, VLRM, Psi → print_fermion_current_mom_v1 coeff "vlr"
| coeff, Psibar, VAM, Psi → print_fermion_current_mom_ff coeff "va"
| coeff, Psibar, VA3M, Psi → print_fermion_current_mom_ff coeff "va3"
| coeff, Psibar, SPM, Psi → print_fermion_current_mom_v1 coeff "sp"
| coeff, Psibar, TVA, Psi → print_fermion_current_mom_v1 coeff "tva"
| coeff, Psibar, TVAM, Psi → print_fermion_current_mom_v2 coeff "tvam"
| coeff, Psibar, TLR, Psi → print_fermion_current_mom_v1 coeff "tlr"
| coeff, Psibar, TLRM, Psi → print_fermion_current_mom_v2 coeff "tlrm"
| coeff, Psibar, TRL, Psi → print_fermion_current_mom_v1 coeff "trl"
| coeff, Psibar, TRLM, Psi → print_fermion_current_mom_v2 coeff "trlm"
| -, Psibar, -, Psi → invalid_arg
| "Targets.Fortran.Fermions:_only_sigma_tensor_coupling_here"
| -, Chibar, -, - | -, -, -, Chi → invalid_arg
| "Targets.Fortran.Fermions:_Majorana_spinors_not_handled"
| -, Gravbar, -, - | -, -, -, Grav → invalid_arg
| "Targets.Fortran.Fermions:_Gravitinos_not_handled"

let print_current_p = function
| -, -, -, - → invalid_arg
| "Targets.Fortran.Fermions:_No_clashing_arrows_here"

let print_current_b = function
| -, -, -, - → invalid_arg
| "Targets.Fortran.Fermions:_No_clashing_arrows_here"

let print_current_g = function
| -, -, -, - → invalid_arg
| "Targets.Fortran.Fermions:_No_gravitinos_here"

let print_current_g4 = function
| -, -, -, - → invalid_arg
| "Targets.Fortran.Fermions:_No_gravitinos_here"

let reverse_braket = function
| Spinor → true
| - → false

let use_module = "omega95"
let require_library =
["omega-spinors-2010-01-A"; "omega-spinor-cpls-2010-01-A"]
end

```



*Main Functor*

```

module Make_Fortran (Fermions : Fermions)
  (Fusion_Maker : Fusion.Maker) (P : Momentum.T) (M : Model.T) =
struct
  let rcs_list =
    [ RCS.rename rcs_file "Targets.Make_Fortran()"
      [ "Interface_for_Whizard2.X";
        "NB: non-gauge vector couplings are not available yet" ];
      Fermions.rcs ]

  let require_library =
    Fermions.require_library @
    [ "omega_vectors_2010_01_A"; "omega_polarizations_2010_01_A";
      "omega_couplings_2010_01_A"; "omega_color_2010_01_A";
      "omega_utils_2010_01_A" ]

  module CM = Colorize.It(M)
  module F = Fusion_Maker(P)(M)

  module CF = Fusion.Multi(Fusion_Maker)(P)(M)
  type amplitudes = CF.amplitudes

  open Coupling
  open Format

  type output_mode =
    | Single_Function
    | Single_Module of int
    | Single_File of int
    | Multi_File of int

  let line_length = ref 80
  let continuation_lines = ref (-1) (* 255 *)
  let kind = ref "default"
  let fortran95 = ref true
  let module_name = ref "omega_amplitude"
  let output_mode = ref (Single_Module 10)
  let use_modules = ref []
  let whizard = ref false
  let parameter_module = ref ""
  let md5sum = ref None
  let no_write = ref false
  let km_write = ref false
  let km_pure = ref false
  let openmp = ref false
  let pure_unless_openmp = false

  let options = Options.create
    [ "90", Arg.Clear fortran95,
      "don't use Fortran95 features that are not in Fortran90";
      "kind", Arg.String (fun s → kind := s),
      "real and complex kind (default: " ^ !kind ^ ")";

```

```

"width", Arg.Int (fun w → line_length := w), "maximum_line_length";
"continuation", Arg.Int (fun l → continuation_lines := l),
"maximum_of_continuation_lines";
"module", Arg.String (fun s → module_name := s), "module_name";
"single_function", Arg.Unit (fun () → output_mode := Single_Function),
"compute_the_matrix_element(s)_in_a_monolithic_function";
"split_function", Arg.Int (fun n → output_mode := Single_Module n),
"split_the_matrix_element(s)_into_small_functions_[default, size=10]";
"split_module", Arg.Int (fun n → output_mode := Single_File n),
"split_the_matrix_element(s)_into_small_modules";
"split_file", Arg.Int (fun n → output_mode := Multi_File n),
"split_the_matrix_element(s)_into_small_files";
"use", Arg.String (fun s → use_modules := s :: !use_modules),
"use_module";
"parameter_module", Arg.String (fun s → parameter_module := s),
"parameter_module";
"md5sum", Arg.String (fun s → md5sum := Some s),
"transfer_MD5_checksum";
"whizard", Arg.Set whizard, "include_WHIZARD_interface";
"no_write", Arg.Set no_write, "no_write_statements";
"kmatrix_write", Arg.Set km_write, "write_K_matrix_functions";
"kmatrix_write_pure", Arg.Set km_pure, "write_K_matrix_pure_functions";
"openmp", Arg.Set openmp, "activate_OpenMP_support_in_generated_code"]

```

Fortran style line continuation:

Default function to output spaces (copied from `format.ml`).

```

let blank_line = String.make 80 ' '
let rec display_blanks oc n =
  if n > 0 then
    if n ≤ 80 then
      output oc blank_line 0 n
    else begin
      output oc blank_line 0 80;
      display_blanks oc (n - 80)
    end
  end

```

Default function to output new lines (copied from `format.ml`).

```

let display_newline oc () =
  output oc "\n" 0 1

```

*current\_continuation\_line*

- $\leq 0$ : not continuing: print a straight newline,
- $> 0$ : continuing: append "`&`" until we run up to `!continuation_lines`.  
NB: `!continuation_lines < 0` means *unlimited* continuation lines.

```

let current_continuation_line = ref 1
exception Continuation_Lines of int

```

```

let fortran_newline oc () =
  if !current_continuation_line > 0 then begin

```

```

    if !continuation_lines ≥ 0 ∧ !current_continuation_line > !continuation_lines then
      raise (Continuation_Lines !current_continuation_line)
    else begin
      output oc "␣&" 0 2;
      incr current_continuation_line
    end
  end;
  display_newline oc ()

let nl () =
  current_continuation_line := 0;
  print_newline ();
  current_continuation_line := 1

```

Make a formatter with default functions to output spaces and new lines.

```

let setup_fortran_formatter width oc =
  set_all_formatter_output_functions
    ~out : (output oc)
    ~flush : (fun () → flush oc)
    ~newline : (fortran_newline oc)
    ~spaces : (display_blanks oc);
  set_margin (width - 2)

let print_list = function
| [] → ()
| a :: rest →
  print_string a;
  List.iter (fun s → printf ",@␣%s" s) rest

```

### Variables and Declarations

"NC" is already used up in the module "constants":

```

let nc_parameter = "N_"
let omega_color_factor_abbrev = "OCF"
let openmp_tld_type = "thread_local_data"
let openmp_tld = "tld"

let flavors_symbol ?(decl = false) flavors =
  (if !openmp ∧ ¬ decl then openmp_tld ^ "%" else "" ) ^
  "oks_" ^ String.concat "" (List.map CM.flavor_symbol flavors)

let p2s p =
  if p ≥ 0 ∧ p ≤ 9 then
    string_of_int p
  else if p ≤ 36 then
    String.make 1 (Char.chr (Char.code 'A' + p - 10))
  else
    "_"

let format_momentum p =
  "p" ^ String.concat "" (List.map p2s p)

```

```

let format_p wf =
  String.concat "" (List.map p2s (F.momentum_list wf))

let ext_momentum wf =
  match F.momentum_list wf with
  | [n] → n
  | _ → invalid_arg "Targets.Fortran.ext_momentum"

module PSet = Set.Make (struct type t = int list let compare = compare end)
module WFSet = Set.Make (struct type t = F.wf let compare = compare end)

let add_tag wf name =
  match F.wf_tag wf with
  | None → name
  | Some tag → name ^ "-" ^ tag

let variable ?(decl = false) wf =
  (if !openmp ∧ ¬ decl then openmp_tld ^ "%" else "")
  ^ add_tag wf ("owf-" ^ CM.flavor_symbol (F.flavor wf) ^ "-" ^ format_p wf)

let momentum wf = "p" ^ format_p wf
let spin wf = "s(" ^ string_of_int (ext_momentum wf) ^ ")"

let format_multiple_variable ?(decl = false) wf i =
  variable ~decl : decl wf ^ "-X" ^ string_of_int i

let multiple_variable ?(decl = false) amplitude dictionary wf =
  try
    format_multiple_variable ~decl : decl wf (dictionary amplitude wf)
  with
  | Not_found → variable wf

let multiple_variables ?(decl = false) multiplicity wf =
  try
    List.map
      (format_multiple_variable ~decl : decl wf)
      (ThoList.range 1 (multiplicity wf))
  with
  | Not_found → [variable ~decl : decl wf]

let declaration_chunk_size = 64

let declare_list_chunk multiplicity t = function
| [] → ()
| wfs →
  printf "░░░░@ [<2>%s░ : :░" t;
  print_list (ThoList.flatmap (multiple_variables ~decl :true multiplicity) wfs); nl ()

let declare_list multiplicity t = function
| [] → ()
| wfs →
  List.iter
    (declare_list_chunk multiplicity t)
    (ThoList.chopn declaration_chunk_size wfs)

type declarations =

```

```

{ scalars : F.wf list;
  spinors : F.wf list;
  conjspinors : F.wf list;
  realspinors : F.wf list;
  ghostspinors : F.wf list;
  vectorspinors : F.wf list;
  vectors : F.wf list;
  ward_vectors : F.wf list;
  massive_vectors : F.wf list;
  tensors_1 : F.wf list;
  tensors_2 : F.wf list;
  brs_scalars : F.wf list;
  brs_spinors : F.wf list;
  brs_conjspinors : F.wf list;
  brs_realspinors : F.wf list;
  brs_vectorspinors : F.wf list;
  brs_vectors : F.wf list;
  brs_massive_vectors : F.wf list }

let rec classify_wfs' acc = function
| [] → acc
| wf :: rest →
  classify_wfs'
  (match CM.lorentz (F.flavor wf) with
  | Scalar → {acc with scalars = wf :: acc.scalars}
  | Spinor → {acc with spinors = wf :: acc.spinors}
  | ConjSpinor → {acc with conjspinors = wf :: acc.conjspinors}
  | Majorana → {acc with realspinors = wf :: acc.realspinors}
  | Maj_Ghost → {acc with ghostspinors = wf :: acc.ghostspinors}
  | Vectorspinor →
    {acc with vectorspinors = wf :: acc.vectorspinors}
  | Vector → {acc with vectors = wf :: acc.vectors}
  | Massive_Vector →
    {acc with massive_vectors = wf :: acc.massive_vectors}
  | Tensor_1 → {acc with tensors_1 = wf :: acc.tensors_1}
  | Tensor_2 → {acc with tensors_2 = wf :: acc.tensors_2}
  | BRS_Scalar → {acc with brs_scalars = wf :: acc.brs_scalars}
  | BRS_Spinor → {acc with brs_spinors = wf :: acc.brs_spinors}
  | BRS_ConjSpinor → {acc with brs_conjspinors =
    wf :: acc.brs_conjspinors}
  | BRS_Majorana → {acc with brs_realspinors =
    wf :: acc.brs_realspinors}
  | BRS_Vectorspinor → {acc with brs_vectorspinors =
    wf :: acc.brs_vectorspinors}
  | BRS_Vector → {acc with brs_vectors = wf :: acc.brs_vectors}
  | BRS_Massive_Vector → {acc with brs_massive_vectors =
    wf :: acc.brs_massive_vectors}
  | BRS _ → invalid_arg "Targets.wfs_classify': not needed here")
  rest

let classify_wfs wfs = classify_wfs'

```

```

{ scalars = []; spinors = []; conjspinors = []; realspinors = [];
  ghostspinors = []; vectorspinors = []; vectors = [];
  ward_vectors = [];
  massive_vectors = []; tensors_1 = []; tensors_2 = [];
  brs_scalars = []; brs_spinors = []; brs_conjspinors = [];
  brs_realspinors = []; brs_vectorspinors = [];
  brs_vectors = []; brs_massive_vectors = [] }
wfs

```

### Parameters

```

type  $\alpha$  parameters =
  { real_singles :  $\alpha$  list;
    real_arrays  : ( $\alpha \times \text{int}$ ) list;
    complex_singles :  $\alpha$  list;
    complex_arrays : ( $\alpha \times \text{int}$ ) list }

let rec classify_singles acc = function
| [] → acc
| Real p :: rest → classify_singles
  { acc with real_singles = p :: acc.real_singles } rest
| Complex p :: rest → classify_singles
  { acc with complex_singles = p :: acc.complex_singles } rest

let rec classify_arrays acc = function
| [] → acc
| (Real_Array p, rhs) :: rest → classify_arrays
  { acc with real_arrays =
    (p, List.length rhs) :: acc.real_arrays } rest
| (Complex_Array p, rhs) :: rest → classify_arrays
  { acc with complex_arrays =
    (p, List.length rhs) :: acc.complex_arrays } rest

let classify_parameters params =
  classify_arrays
    (classify_singles
      { real_singles = [];
        real_arrays = [];
        complex_singles = [];
        complex_arrays = [] }
      (List.map fst params.derived)) params.derived_arrays

```



Unify this with the other code using *ThoList.chopn*.

```

let rec schisma n l =
  if List.length l ≤ n then
    [l]
  else
    let a, b = ThoList.splitn n l in
    [a] @ (schisma n b)

```

```

let rec schisma_num i n l =
  if List.length l ≤ n then
    [(i, l)]
  else
    let a, b = ThoList.splitn n l in
    [(i, a)] @ (schisma_num (i + 1) n b)

let declare_parameters' t = function
| [] → ()
| plist →
  printf "%s@(<2>%s(kind=%s),_public,_save_::_)" t !kind;
  print_list (List.map CM.constant_symbol plist); nl ()

let declare_parameters t plist =
  List.iter (declare_parameters' t) plist

let declare_parameter_array t (p, n) =
  printf "%s@(<2>%s(kind=%s),_dimension(%d),_public,_save_::_)" t !kind n (CM.constant_symbol p); nl ()

let default_parameter (x, v) =
  printf "@_s=_g_%s" (CM.constant_symbol x) v !kind

let declare_default_parameters t = function
| [] → ()
| p :: plist →
  printf "%s@(<2>%s(kind=%s),_public,_save_::_)" t !kind;
  default_parameter p;
  List.iter (fun p' → printf ","; default_parameter p') plist;
  nl ()

let format_constant = function
| I → sprintf "cmplx_(0.0_%s,_1.0_%s)" !kind !kind
| Const c when c < 0 → sprintf "(%d.0_%s)" c !kind
| Const c → sprintf "%d.0_%s" c !kind
| _ → invalid_arg "format_constant"

let rec eval_parameter' = function
| I → printf "cmplx_(0.0_%s,_1.0_%s)" !kind !kind
| Const c when c < 0 → printf "(%d.0_%s)" c !kind
| Const c → printf "%d.0_%s" c !kind
| Atom x → printf "%s" (CM.constant_symbol x)
| Sum [] → printf "0.0_%s" !kind
| Sum [x] → eval_parameter' x
| Sum (x :: xs) →
  printf "@,("; eval_parameter' x;
  List.iter (fun x → printf "@,_+"; eval_parameter' x) xs;
  printf ")"
| Diff (x, y) →
  printf "@,("; eval_parameter' x;
  printf "_-"; eval_parameter' y; printf ")"
| Neg x → printf "@,(_-"; eval_parameter' x; printf ")"
| Prod [] → printf "1.0_%s" !kind
| Prod [x] → eval_parameter' x

```

```

| Prod (x :: xs) →
  printf "@,("; eval_parameter' x;
  List.iter (fun x → printf " * "; eval_parameter' x) xs;
  printf ")"
| Quot (x, y) →
  printf "@,("; eval_parameter' x;
  printf " / "; eval_parameter' y; printf ")"
| Rec x →
  printf "@,(1.0- %s / " !kind; eval_parameter' x; printf ")"
| Pow (x, n) →
  printf "@,("; eval_parameter' x; printf "**%d" n; printf ")"
| Sqrt x → printf "@,sqrt("; eval_parameter' x; printf ")"
| Sin x → printf "@,sin("; eval_parameter' x; printf ")"
| Cos x → printf "@,cos("; eval_parameter' x; printf ")"
| Tan x → printf "@,tan("; eval_parameter' x; printf ")"
| Cot x → printf "@,cot("; eval_parameter' x; printf ")"
| Atan2 (y, x) → printf "@,atan2("; eval_parameter' y;
  printf ",@("; eval_parameter' x; printf ")"
| Conj x → printf "@,conj("; eval_parameter' x; printf ")"

let strip_single_tag = function
| Real x → x
| Complex x → x

let strip_array_tag = function
| Real_Array x → x
| Complex_Array x → x

let eval_parameter (lhs, rhs) =
  let x = CM.constant_symbol (strip_single_tag lhs) in
  printf "~~~~@ [<2> %s = " x; eval_parameter' rhs; nl ()

let eval_para_list n l =
  printf "~~~~subroutine~~~~setup_parameters%s()" (string_of_int n); nl ();
  List.iter eval_parameter l;
  printf "~~~~end~~~~subroutine~~~~setup_parameters%s" (string_of_int n); nl ()

let eval_parameter_pair (lhs, rhs) =
  let x = CM.constant_symbol (strip_array_tag lhs) in
  let _ = List.fold_left (fun i rhs' →
    printf "~~~~@ [<2> %s (%d) = " x i; eval_parameter' rhs'; nl ();
    succ i) 1 rhs in
  ()

let eval_para_pair_list n l =
  printf "~~~~subroutine~~~~setup_parameters%s()" (string_of_int n); nl ();
  List.iter eval_parameter_pair l;
  printf "~~~~end~~~~subroutine~~~~setup_parameters%s" (string_of_int n); nl ()

let print_echo fmt p =
  let s = CM.constant_symbol p in
  printf "~~~~write~~~~(unit = ~~,fmt = ~%s) \\" %s\", ~%s"
    fmt s s; nl ()

```



```

let print_echo_array fmt (p, n) =
  let s = CM.constant_symbol p in
  for i = 1 to n do
    printf "~~~~write_(unit_=_,_fmt=_fmt_%s_array)_ " fmt ;
    printf "\"%s\",_%d,_%s(%d)" s i s i; nl ()
  done

let parameters_to_fortran oc params =
  setup_fortran_formatter !line_length oc;
  let declarations = classify_parameters params in
  printf "module_%s" !parameter_module; nl ();
  printf "~~use_kinds"; nl ();
  printf "~~use_constants"; nl ();
  printf "~~implicit_none"; nl ();
  printf "~~private"; nl ();
  printf "~~@[<2>public_:~setup_parameters";
  if !no_write then begin
    printf "!~No_print_parameters"; nl ();
  end else begin
    printf "@,~,~print_parameters"; nl ();
  end;
  declare_default_parameters "real" params.input;
  declare_parameters "real" (schisma 69 declarations.real_singles);
  List.iter (declare_parameter_array "real") declarations.real_arrays;
  declare_parameters "complex" (schisma 69 declarations.complex_singles);
  List.iter (declare_parameter_array "complex") declarations.complex_arrays;
  printf "contains"; nl ();
  printf "~~~~!~derived_parameters:"; nl ();
  let shredded = schisma_num 1 120 params.derived in
  let shredded_arrays = schisma_num 1 120 params.derived_arrays in
  let num_sub = List.length shredded in
  let num_sub_arrays = List.length shredded_arrays in
  printf "~~~~~!length:_%s" (string_of_int (List.length params.derived));
  nl ();
  printf "~~~~~!Num_Sub:_%s" (string_of_int num_sub); nl ();
  List.iter (fun (i, l) → eval_para_list i l) shredded;
  List.iter (fun (i, l) → eval_para_pair_list (num_sub + i) l)
    shredded_arrays;
  printf "~~subroutine~setup_parameters_()"; nl ();
  let sum_sub = num_sub + num_sub_arrays in
  for i = 1 to sum_sub do
    printf "~~~~call~setup_parameters%s" (string_of_int i); nl ();
  done;
  printf "~~end~subroutine~setup_parameters"; nl ();
  if !no_write then begin
    printf "!~No_print_parameters"; nl ();
  end else begin
    printf "~~subroutine~print_parameters_()"; nl ();
    printf "~~~~@[<2>character(len=*),~parameter_:~";
    printf "@_fmt_real=_\"(A12,4X,'_=',E25.18)\",~";

```

```

    printf "@_fmt_complex=_\"(A12,4X,'_=_',E25.18,'_+_i*',E25.18)\",";
    printf "@_fmt_real_array=_\"(A12,'(',I2.2,')', '_=_',E25.18)\",";
    printf "@_fmt_complex_array=_";
    printf "\"(A12,'(',I2.2,')', '_=_',E25.18,'_+_i*',E25.18)\","; nl ();
    printf "____@ [<2>write_(unit=_*,_fmt=_\"(A)\")_@,";
    printf "\"default_values_for_the_input_parameters:\""; nl ();
    List.iter (fun (p, _) → print_echo "real" p) params.input;
    printf "____@ [<2>write_(unit=_*,_fmt=_\"(A)\")_@,";
    printf "\"derived_parameters:\""; nl ();
    List.iter (print_echo "real") declarations.real_singles;
    List.iter (print_echo "complex") declarations.complex_singles;
    List.iter (print_echo_array "real") declarations.real_arrays;
    List.iter (print_echo_array "complex") declarations.complex_arrays;
    printf "____end_subroutine_print_parameters"; nl ();
end;

printf "end_module_%s" !parameter_module; nl ();
printf "!_0'Mega_revision_control_information:"; nl ();
List.iter (fun s → printf "!!!!_%s" s; nl ())
  (ThoList.flatmap RCS.summary (M.rcs :: rcs_list));
printf "!!!!_program_test_parameters"; nl ();
printf "!!!!_use_%s" !parameter_module; nl ();
printf "!!!!_call_setup_parameters_()"; nl ();
printf "!!!!_call_print_parameters_()"; nl ();
printf "!!!!_end_program_test_parameters"; nl ();

```

### Run-Time Diagnostics

```

type diagnostic = All | Arguments | Momenta | Gauge

type diagnostic_mode = Off | Warn | Panic

let warn mode =
  match !mode with
  | Off → false
  | Warn → true
  | Panic → true

let panic mode =
  match !mode with
  | Off → false
  | Warn → false
  | Panic → true

let suffix mode =
  if panic mode then
    "panic"
  else
    "warn"

let diagnose_arguments = ref Off
let diagnose_momenta = ref Off
let diagnose_gauge = ref Off

```

```

let rec parse_diagnostic = function
| All, panic →
    parse_diagnostic (Arguments, panic);
    parse_diagnostic (Momenta, panic);
    parse_diagnostic (Gauge, panic)
| Arguments, panic →
    diagnose_arguments := if panic then Panic else Warn
| Momenta, panic →
    diagnose_momenta := if panic then Panic else Warn
| Gauge, panic →
    diagnose_gauge := if panic then Panic else Warn

```

If diagnostics are required, we have to switch off Fortran95 features like pure functions.

```

let parse_diagnostics = function
| [] → ()
| diagnostics →
    fortran95 := false;
    List.iter parse_diagnostic diagnostics

```

#### *Amplitude*

```

let declare_momenta_chunk = function
| [] → ()
| momenta →
    printf "UUUU@ [<2>type(momentum)U: :U";
    print_list (List.map format_momentum momenta); nl ()

let declare_momenta = function
| [] → ()
| momenta →
    List.iter
        declare_momenta_chunk
        (ThoList.chopn declaration_chunk_size momenta)

let declare_wavefunctions multiplicity wfs =
let wfs' = classify_wfs wfs in
declare_list multiplicity ("complex(kind=" ^ !kind ^ ")")
    (wfs'.scalars @ wfs'.brs_scalars);
declare_list multiplicity ("type(" ^ Fermions.psi_type ^ ")")
    (wfs'.spinors @ wfs'.brs_spinors);
declare_list multiplicity ("type(" ^ Fermions.psibar_type ^ ")")
    (wfs'.conjspinors @ wfs'.brs_conjspinors);
declare_list multiplicity ("type(" ^ Fermions.chi_type ^ ")")
    (wfs'.realspinors @ wfs'.brs_realspinors @ wfs'.ghostspinors);
declare_list multiplicity ("type(" ^ Fermions.grav_type ^ ")") wfs'.vectorspinors;
declare_list multiplicity "type(vector)" (wfs'.vectors @ wfs'.massive_vectors @
    wfs'.brs_vectors @ wfs'.brs_massive_vectors @ wfs'.ward_vectors);
declare_list multiplicity "type(tensor2odd)" wfs'.tensors_1;
declare_list multiplicity "type(tensor)" wfs'.tensors_2

```

```

let flavors a = F.incoming a @ F.outgoing a
let declare_brackets_chunk = function
| [] → ()
| amplitudes →
    printf "░░░░@ [<2>complex(kind=%s)░: :░" !kind;
    print_list (List.map (fun a → flavors_symbol ~decl :true (flavors a)) amplitudes); nl ()
let declare_brackets = function
| [] → ()
| amplitudes →
    List.iter
        declare_brackets_chunk
        (ThoList.chopn declaration_chunk_size amplitudes)
let print_variable_declarations amplitudes =
    let multiplicity = CF.multiplicity amplitudes
    and processes = CF.processes amplitudes in
    declare_momenta
        (PSet.elements
            (List.fold_left
                (fun set a →
                    PSet.union set (List.fold_right
                        (fun wf → PSet.add (F.momentum_list wf))
                        (F.externals a) PSet.empty))
                    PSet.empty processes));
    declare_momenta
        (PSet.elements
            (List.fold_left
                (fun set a →
                    PSet.union set (List.fold_right
                        (fun wf → PSet.add (F.momentum_list wf))
                        (F.variables a) PSet.empty))
                    PSet.empty processes));
    if !openmp then begin
        printf "░░type░%s@ [<2>" openmp_tld_type;
        nl ();
    end ;
    declare_wavefunctions multiplicity
        (WFSet.elements
            (List.fold_left
                (fun set a →
                    WFSet.union set (List.fold_right WFSet.add (F.externals a) WFSet.empty))
                    WFSet.empty processes));
    declare_wavefunctions multiplicity
        (WFSet.elements
            (List.fold_left
                (fun set a →
                    WFSet.union set (List.fold_right WFSet.add (F.variables a) WFSet.empty))
                    WFSet.empty processes));
    declare_brackets processes;
    if !openmp then begin

```

```

    printf "@]end_type_%s\n" openmp_tld_type;
    printf "type(%s):_%s" openmp_tld_type openmp_tld;
    nl ();
end

```

*print\_current* is the most important function that has to match the functions in *omega95* (see appendix X). It offers plentiful opportunities for making mistakes, in particular those related to signs. We start with a few auxiliary functions:

```

let children2 rhs =
  match F.children rhs with
  | [wf1; wf2] → (wf1, wf2)
  | _ → failwith "Targets.children2: can't happen"

let children3 rhs =
  match F.children rhs with
  | [wf1; wf2; wf3] → (wf1, wf2, wf3)
  | _ → invalid_arg "Targets.children3: can't happen"

```

Note that it is (marginally) faster to multiply the two scalar products with the coupling constant than the four vector components.



This could be part of *omegalib* as well ...

```

let format_coeff = function
  | 1 → ""
  | -1 → "-"
  | coeff → "(" ^ string_of_int coeff ^ ")*"

let format_coupling coeff c =
  match coeff with
  | 1 → c
  | -1 → "(-" ^ c ^ ")"
  | coeff → string_of_int coeff ^ "*" ^ c

```



The following is error prone and should be generated automagically.

```

let print_vector4 c wf1 wf2 wf3 fusion (coeff, contraction) =
  match contraction, fusion with
  | C_12_34, (F341 | F431 | F342 | F432 | F123 | F213 | F124 | F214)
  | C_13_42, (F241 | F421 | F243 | F423 | F132 | F312 | F134 | F314)
  | C_14_23, (F231 | F321 | F234 | F324 | F142 | F412 | F143 |
F413) →
    printf "(%s%s)*(%s*s))*%s" (format_coeff coeff) c wf1 wf2 wf3
  | C_12_34, (F134 | F143 | F234 | F243 | F312 | F321 | F412 | F421)
  | C_13_42, (F124 | F142 | F324 | F342 | F213 | F231 | F413 | F431)
  | C_14_23, (F123 | F132 | F423 | F432 | F214 | F241 | F314 |
F341) →
    printf "(%s%s)*(%s*s))*%s" (format_coeff coeff) c wf2 wf3 wf1
  | C_12_34, (F314 | F413 | F324 | F423 | F132 | F231 | F142 | F241)
  | C_13_42, (F214 | F412 | F234 | F432 | F123 | F321 | F143 | F341)
  | C_14_23, (F213 | F312 | F243 | F342 | F124 | F421 | F134 |
F431) →

```

```

    printf "(%s%s)*(%s*s))*%s" (format_coeff coeff) c wf1 wf3 wf2
let print_add_vector4 c wf1 wf2 wf3 fusion (coeff, contraction) =
    printf "@_+";
    print_vector4 c wf1 wf2 wf3 fusion (coeff, contraction)

let print_vector4_km c pa pb wf1 wf2 wf3 fusion (coeff, contraction) =
    match contraction, fusion with
    | C_12_34, (F341 | F431 | F342 | F432 | F123 | F213 | F124 | F214)
    | C_13_42, (F241 | F421 | F243 | F423 | F132 | F312 | F134 | F314)
    | C_14_23, (F231 | F321 | F234 | F324 | F142 | F412 | F143 |
F413) →
        printf "(%s%s*s+%s))*(%s*s))*%s"
            (format_coeff coeff) c pa pb wf1 wf2 wf3
        | C_12_34, (F134 | F143 | F234 | F243 | F312 | F321 | F412 | F421)
        | C_13_42, (F124 | F142 | F324 | F342 | F213 | F231 | F413 | F431)
        | C_14_23, (F123 | F132 | F423 | F432 | F214 | F241 | F314 |
F341) →
            printf "(%s%s*s+%s))*(%s*s))*%s"
                (format_coeff coeff) c pa pb wf2 wf3 wf1
            | C_12_34, (F314 | F413 | F324 | F423 | F132 | F231 | F142 | F241)
            | C_13_42, (F214 | F412 | F234 | F432 | F123 | F321 | F143 | F341)
            | C_14_23, (F213 | F312 | F243 | F342 | F124 | F421 | F134 |
F431) →
                printf "(%s%s*s+%s))*(%s*s))*%s"
                    (format_coeff coeff) c pa pb wf1 wf3 wf2

let print_add_vector4_km c pa pb wf1 wf2 wf3 fusion (coeff, contraction) =
    printf "@_+";
    print_vector4_km c pa pb wf1 wf2 wf3 fusion (coeff, contraction)

let print_dscalar4 c wf1 wf2 wf3 p1 p2 p3 p123
    fusion (coeff, contraction) =
    match contraction, fusion with
    | C_12_34, (F341 | F431 | F342 | F432 | F123 | F213 | F124 | F214)
    | C_13_42, (F241 | F421 | F243 | F423 | F132 | F312 | F134 | F314)
    | C_14_23, (F231 | F321 | F234 | F324 | F142 | F412 | F143 |
F413) →
        printf "(%s%s)*(%s*s)*(%s*s))*%s*s*s*s"
            (format_coeff coeff) c p1 p2 p3 p123 wf1 wf2 wf3
        | C_12_34, (F134 | F143 | F234 | F243 | F312 | F321 | F412 | F421)
        | C_13_42, (F124 | F142 | F324 | F342 | F213 | F231 | F413 | F431)
        | C_14_23, (F123 | F132 | F423 | F432 | F214 | F241 | F314 |
F341) →
            printf "(%s%s)*(%s*s)*(%s*s))*%s*s*s*s"
                (format_coeff coeff) c p2 p3 p1 p123 wf1 wf2 wf3
        | C_12_34, (F314 | F413 | F324 | F423 | F132 | F231 | F142 | F241)
        | C_13_42, (F214 | F412 | F234 | F432 | F123 | F321 | F143 | F341)
        | C_14_23, (F213 | F312 | F243 | F342 | F124 | F421 | F134 |
F431) →
            printf "(%s%s)*(%s*s)*(%s*s))*%s*s*s*s"
                (format_coeff coeff) c p1 p3 p2 p123 wf1 wf2 wf3

```

---

```

let print_add_dscalar4 c wf1 wf2 wf3 p1 p2 p3 p123
  fusion (coeff, contraction) =
    printf "@_+";
    print_dscalar4 c wf1 wf2 wf3 p1 p2 p3 p123 fusion (coeff, contraction)
let print_dscalar2_vector2 c wf1 wf2 wf3 p1 p2 p3 p123
  fusion (coeff, contraction) =
    failwith "Targets.Fortran.print_dscalar2_vector2: incomplete!";
    match contraction, fusion with
    | C_12_34, (F134 | F143 | F234 | F243) →
      printf "((%s%s)*(%s*s)*(%s*s)*%s)"
        (format_coeff coeff) c p123 p1 wf2 wf3 wf1
    | C_12_34, (F312 | F321 | F412 | F421) →
      printf "((%s%s)*(%s*s)*%s*s)*%s)"
        (format_coeff coeff) c p2 p3 wf2 wf3 wf1
    | C_12_34, (F341 | F431 | F342 | F432 | F123 | F213 | F124 | F214)
    | C_13_42, (F241 | F421 | F243 | F423 | F132 | F312 | F134 | F314)
    | C_14_23, (F231 | F321 | F234 | F324 | F142 | F412 | F143 |
F413) →
      printf "((%s%s)*(%s*s)*(%s*s)*%s*s*s)"
        (format_coeff coeff) c p1 p2 p3 p123 wf1 wf2 wf3
    | C_13_42, (F124 | F142 | F324 | F342 | F213 | F231 | F413 | F431)
    | C_14_23, (F123 | F132 | F423 | F432 | F214 | F241 | F314 |
F341) →
      printf "((%s%s)*(%s*s)*(%s*s)*%s*s*s)"
        (format_coeff coeff) c p2 p3 p1 p123 wf1 wf2 wf3
    | C_12_34, (F314 | F413 | F324 | F423 | F132 | F231 | F142 | F241)
    | C_13_42, (F214 | F412 | F234 | F432 | F123 | F321 | F143 | F341)
    | C_14_23, (F213 | F312 | F243 | F342 | F124 | F421 | F134 |
F431) →
      printf "((%s%s)*(%s*s)*(%s*s)*%s*s*s)"
        (format_coeff coeff) c p1 p3 p2 p123 wf1 wf2 wf3
let print_add_dscalar2_vector2 c wf1 wf2 wf3 p1 p2 p3 p123
  fusion (coeff, contraction) =
    printf "@_+";
    print_dscalar2_vector2 c wf1 wf2 wf3 p1 p2 p3 p123
    fusion (coeff, contraction)
let print_current amplitude dictionary rhs =
  match F.coupling rhs with
  | V3 (vertex, fusion, constant) →
    let ch1, ch2 = children2 rhs in
    let wf1 = multiple_variable amplitude dictionary ch1
    and wf2 = multiple_variable amplitude dictionary ch2
    and p1 = momentum ch1
    and p2 = momentum ch2
    and m1 = CM.mass_symbol (F.flavor ch1)
    and m2 = CM.mass_symbol (F.flavor ch2) in
    let c = CM.constant_symbol constant in
    printf "@,%s" (if (F.sign rhs) < 0 then "-" else "+");
    begin match vertex with

```

Fermionic currents  $\bar{\psi}A\psi$  and  $\bar{\psi}\phi\psi$  are handled by the *Fermions* module, since they depend on the choice of Feynman rules: Dirac or Majorana.

```
| FBF (coeff, fb, b, f) →
  begin match coeff, fb, b, f with
  | -, Psibar, VLRM, Psi | -, Psibar, SPM, Psi
  | -, Psibar, VAM, Psi | -, Psibar, VA3M, Psi
  | -, Psibar, TVA, Psi | -, Psibar, TVAM, Psi
  | -, Psibar, TLR, Psi | -, Psibar, TLRM, Psi
  | -, Psibar, TRL, Psi | -, Psibar, TRLM, Psi →
    let p12 = Printf.sprintf "(-%s-%s)" p1 p2 in
    Fermions.print_current_mom (coeff, fb, b, f) c wf1 wf2 p1 p2
    p12 fusion
  | -, -, -, - →
    Fermions.print_current (coeff, fb, b, f) c wf1 wf2 fusion
  end
| PBP (coeff, f1, b, f2) →
  Fermions.print_current_p (coeff, f1, b, f2) c wf1 wf2 fusion
| BBB (coeff, fb1, b, fb2) →
  Fermions.print_current_b (coeff, fb1, b, fb2) c wf1 wf2 fusion
| GBG (coeff, fb, b, f) → let p12 =
  Printf.sprintf "(-%s-%s)" p1 p2 in
  Fermions.print_current_g (coeff, fb, b, f) c wf1 wf2 p1 p2
  p12 fusion
```

Table 9.13 is a bit misleading, since it includes totally antisymmetric structure constants. The space-time part alone is also totally antisymmetric:

```
| Gauge_Gauge_Gauge coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | (F23 | F31 | F12) →
    printf "g_gg(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | (F32 | F13 | F21) →
    printf "g_gg(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
  end
```

In *Aux\_Gauge\_Gauge*, we can not rely on antisymmetry alone, because of the different Lorentz representations of the auxiliary and the gauge field. Instead we have to provide the sign in

$$(V_2 \wedge V_3) \cdot T_1 = \begin{cases} V_2 \cdot (T_1 \cdot V_3) = -V_2 \cdot (V_3 \cdot T_1) \\ V_3 \cdot (V_2 \cdot T_1) = -V_3 \cdot (T_1 \cdot V_2) \end{cases} \quad (15.2)$$

ourselves. Alternatively, one could provide `g_xg` mirroring `g_gx`.

```
| Aux_Gauge_Gauge coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | F23 → printf "x_gg(%s,%s,%s)" c wf1 wf2
  | F32 → printf "x_gg(%s,%s,%s)" c wf2 wf1
  | F12 → printf "g_gx(%s,%s,%s)" c wf2 wf1
  | F21 → printf "g_gx(%s,%s,%s)" c wf1 wf2
```



```

| F13 → printf "(-1)*g_gx(%s,%s,%s)" c wf2 wf1
| F31 → printf "(-1)*g_gx(%s,%s,%s)" c wf1 wf2
end

```

These cases are symmetric and we just have to juxtapose the correct fields and provide parentheses to minimize the number of multiplications.

```

| Scalar_Vector_Vector coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | (F23 | F32) → printf "%s*(%s*%s)" c wf1 wf2
  | (F12 | F13) → printf "(%s*%s)*%s" c wf1 wf2
  | (F21 | F31) → printf "(%s*%s)*%s" c wf2 wf1
  end

| Aux_Vector_Vector coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | (F23 | F32) → printf "%s*(%s*%s)" c wf1 wf2
  | (F12 | F13) → printf "(%s*%s)*%s" c wf1 wf2
  | (F21 | F31) → printf "(%s*%s)*%s" c wf2 wf1
  end

```

Even simpler:

```

| Scalar_Scalar_Scalar coeff →
  printf "(%s*%s*%s)" (format_coupling coeff c) wf1 wf2

| Aux_Scalar_Scalar coeff →
  printf "(%s*%s*%s)" (format_coupling coeff c) wf1 wf2

| Aux_Scalar_Vector coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | (F13 | F31) → printf "%s*(%s*%s)" c wf1 wf2
  | (F23 | F21) → printf "(%s*%s)*%s" c wf1 wf2
  | (F32 | F12) → printf "(%s*%s)*%s" c wf2 wf1
  end

| Vector_Scalar_Scalar coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | F23 → printf "v_ss(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | F32 → printf "v_ss(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
  | F12 → printf "s_vs(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | F21 → printf "s_vs(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
  | F13 → printf "(-1)*s_vs(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | F31 → printf "(-1)*s_vs(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
  end

| Graviton_Scalar_Scalar coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | F12 → printf "s_gravs(%s,%s,-(%s+%s),%s,%s,%s)" c m2 p1 p2 p2 wf1 wf2
  | F21 → printf "s_gravs(%s,%s,-(%s+%s),%s,%s,%s)" c m1 p1 p2 p1 wf2 wf1

```

```

| F13 → printf "s_gravs(%s,%s,%s,-(%s+%s),%s,%s)" c m2 p2 p1 p2 wf1 wf2
| F31 → printf "s_gravs(%s,%s,%s,-(%s+%s),%s,%s)" c m1 p1 p1 p2 wf2 wf1
| F23 → printf "grav_ss(%s,%s,%s,%s,%s,%s)" c m1 p1 p2 wf1 wf2
| F32 → printf "grav_ss(%s,%s,%s,%s,%s,%s)" c m1 p2 p1 wf2 wf1
end

```

In producing a vector in the fusion we always contract the rightmost index with the vector wavefunction from *rhs*. So the first momentum is always the one of the vector boson produced in the fusion, while the second one is that from the *rhs*. This makes the cases *F12* and *F13* as well as *F21* and *F31* equal. In principle, we could have already done this for the *Graviton\_Scalar\_Scalar* case.

```

| Graviton_Vector_Vector coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | (F12 | F13) → printf "v_gravv(%s,%s,-(%s+%s),%s,%s,%s)" c m2 p1 p2 p2 wf1 wf2
  | (F21 | F31) → printf "v_gravv(%s,%s,-(%s+%s),%s,%s,%s)" c m1 p1 p2 p1 wf2 wf1
  | F23 → printf "grav_vv(%s,%s,%s,%s,%s,%s)" c m1 p1 p2 wf1 wf2
  | F32 → printf "grav_vv(%s,%s,%s,%s,%s,%s)" c m1 p2 p1 wf2 wf1
  end

| Graviton_Spinor_Spinor coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | F23 → printf "f_gravf(%s,%s,-(%s+%s),(-%s),%s,%s)" c m2 p1 p2 p2 wf1 wf2
  | F32 → printf "f_gravf(%s,%s,-(%s+%s),(-%s),%s,%s)" c m1 p1 p2 p1 wf2 wf1
  | F12 → printf "f_fgrav(%s,%s,%s,%s+%s,%s,%s)" c m1 p1 p1 p2 wf1 wf2
  | F21 → printf "f_fgrav(%s,%s,%s,%s+%s,%s,%s)" c m2 p2 p1 p2 wf2 wf1
  | F13 → printf "grav_ff(%s,%s,%s,(-%s),%s,%s)" c m1 p1 p2 wf1 wf2
  | F31 → printf "grav_ff(%s,%s,%s,(-%s),%s,%s)" c m1 p2 p1 wf2 wf1
  end

| Dim4_Vector_Vector_Vector_T coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | F23 → printf "tkv_vv(%s,%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | F32 → printf "tkv_vv(%s,%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
  | F12 → printf "tv_kv v(%s,%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | F21 → printf "tv_kv v(%s,%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
  | F13 → printf "(-1)*tv_kv v(%s,%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | F31 → printf "(-1)*tv_kv v(%s,%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
  end

| Dim4_Vector_Vector_Vector_L coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | F23 → printf "lkv_vv(%s,%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | F32 → printf "lkv_vv(%s,%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
  | F12 | F13 → printf "lv_kv v(%s,%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | F21 | F31 → printf "lv_kv v(%s,%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
  end

| Dim6_Gauge_Gauge_Gauge coeff →

```

```

let c = format_coupling coeff c in
begin match fusion with
| F23 | F31 | F12 →
    printf "kg_kgkg(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
| F32 | F13 | F21 →
    printf "kg_kgkg(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
end

| Dim4_Vector_Vector_Vector_T5 coeff →
    let c = format_coupling coeff c in
    begin match fusion with
    | F23 → printf "t5kv_vv(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
    | F32 → printf "t5kv_vv(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
    | F12 | F13 → printf "t5v_kv v(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
    | F21 | F31 → printf "t5v_kv v(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
    end

| Dim4_Vector_Vector_Vector_L5 coeff →
    let c = format_coupling coeff c in
    begin match fusion with
    | F23 → printf "l5kv_vv(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
    | F32 → printf "l5kv_vv(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
    | F12 → printf "l5v_kv v(%s,%s,%s,%s,%s)" c wf1 p1 wf2
    | F21 → printf "l5v_kv v(%s,%s,%s,%s,%s)" c wf2 p2 wf1
    | F13 → printf "(-1)*l5v_kv v(%s,%s,%s,%s,%s)" c wf1 p1 wf2
    | F31 → printf "(-1)*l5v_kv v(%s,%s,%s,%s,%s)" c wf2 p2 wf1
    end

| Dim6_Gauge_Gauge_Gauge_5 coeff →
    let c = format_coupling coeff c in
    begin match fusion with
    | F23 → printf "kg5_kgkg(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
    | F32 → printf "kg5_kgkg(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
    | F12 → printf "kg_kg5kg(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
    | F21 → printf "kg_kg5kg(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
    | F13 → printf "(-1)*kg_kg5kg(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
    | F31 → printf "(-1)*kg_kg5kg(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
    end

| Aux_DScalar_DScalar coeff →
    let c = format_coupling coeff c in
    begin match fusion with
    | (F23 | F32) →
        printf "%s*(%s*%s)*(%s*%s)" c p1 p2 wf1 wf2
    | (F12 | F13) →
        printf "%s*(-((%s+%s)*%s))*(%s*%s)" c p1 p2 p2 wf1 wf2
    | (F21 | F31) →
        printf "%s*(-((%s+%s)*%s))*(%s*%s)" c p1 p2 p1 wf1 wf2
    end

| Aux_Vector_DScalar coeff →
    let c = format_coupling coeff c in
    begin match fusion with

```

```

| F23 → printf "%s* (%s*%s)*%s" c wf1 p2 wf2
| F32 → printf "%s* (%s*%s)*%s" c wf2 p1 wf1
| F12 → printf "%s* (-(%s+%s)*%s)*%s" c p1 p2 wf2 wf1
| F21 → printf "%s* (-(%s+%s)*%s)*%s" c p1 p2 wf1 wf2
| (F13 | F31) → printf "(-(%s+%s))* (%s*%s*%s)" p1 p2 c wf1 wf2
end

| Dim5_Scalar_Gauge2_coeff →
  let c = format_coupling_coeff c in
  begin match fusion with
  | (F23 | F32) → printf "(%s)* (%s*%s)* (%s*%s)_- (%s*%s)* (%s*%s)"
    c p1 wf2 p2 wf1 p1 p2 wf2 wf1
  | (F12 | F13) → printf "(%s)*%s* (-(%s+%s)*%s)*%s_- ((-%s+%s)*%s)*%s"
    c wf1 p1 p2 wf2 p2 p1 p2 p2 wf2
  | (F21 | F31) → printf "(%s)*%s* (-(%s+%s)*%s)*%s_- ((-%s+%s)*%s)*%s"
    c wf2 p2 p1 wf1 p1 p1 p2 p1 wf1
  end

| Dim5_Scalar_Gauge2_Skew_coeff →
  let c = format_coupling_coeff c in
  begin match fusion with
  | (F23 | F32) → printf "(-_phi_vv_ (%s,_%s,_%s,_%s,_%s))" c p1 p2 wf1 wf2
  | (F12 | F13) → printf "(-_v_phiv_ (%s,_%s,_%s,_%s,_%s))" c wf1 p1 p2 wf2
  | (F21 | F31) → printf "v_phiv_ (%s,_%s,_%s,_%s,_%s)" c wf2 p1 p2 wf1
  end

| Dim5_Scalar_Vector_Vector_T_coeff →
  let c = format_coupling_coeff c in
  begin match fusion with
  | (F23 | F32) → printf "(%s)* (%s*%s)* (%s*%s)" c p1 wf2 p2 wf1
  | (F12 | F13) → printf "(%s)*%s* (-(%s+%s)*%s)*%s" c wf1 p1 p2 wf2 p2
  | (F21 | F31) → printf "(%s)*%s* (-(%s+%s)*%s)*%s" c wf2 p2 p1 wf1 p1
  end

| Dim5_Scalar_Vector_Vector_U_coeff →
  let c = format_coupling_coeff c in
  begin match fusion with
  | (F23 | F32) → printf "phi_u_vv_ (%s,_%s,_%s,_%s,_%s)" c p1 p2 wf1 wf2
  | (F12 | F13) → printf "v_u_phiv_ (%s,_%s,_%s,_%s,_%s)" c wf1 p1 p2 wf2
  | (F21 | F31) → printf "v_u_phiv_ (%s,_%s,_%s,_%s,_%s)" c wf2 p2 p1 wf1
  end

| Dim5_Scalar_Vector_Vector_TU_coeff →
  let c = format_coupling_coeff c in
  begin match fusion with
  | F23 → printf "(%s)* (%s*%s)* (-(%s+%s)*%s)_- ((-%s+%s)*%s)* (%s*%s)"
    c p1 wf2 p1 p2 wf1 p1 p2 p1 wf1 wf2
  | F32 → printf "(%s)* (%s*%s)* (-(%s+%s)*%s)_- ((-%s+%s)*%s)* (%s*%s)"
    c p2 wf1 p1 p2 wf2 p1 p2 p2 wf1 wf2
  | F12 → printf "(%s)*%s* (%s*%s)*%s_- (%s*%s)*%s"
    c wf1 p1 wf2 p2 p1 p2 wf2
  | F21 → printf "(%s)*%s* (%s*%s)*%s_- (%s*%s)*%s"
    c wf2 p2 wf1 p1 p1 p2 wf1
  end

```

```

| F13 → printf "(%s)*%s*((-(%s+%s)*%s)*%s_-(-(%s+%s)*%s)*%s)"
  c wf1 p1 p2 wf2 p1 p1 p2 p1 wf2
| F31 → printf "(%s)*%s*((-(%s+%s)*%s)*%s_-(-(%s+%s)*%s)*%s)"
  c wf2 p1 p2 wf1 p2 p1 p2 p2 wf1
end

| Scalar_Vector_Vector_t coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | (F23 | F32) → printf "s_vv_t(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | (F12 | F13) → printf "v_sv_t(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | (F21 | F31) → printf "v_sv_t(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
  end

| Dim6_Vector_Vector_Vector_T coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | F23 → printf "(%s)*(%s*%s)*(%s*%s)*(%s-%s)" c p2 wf1 p1 wf2 p1 p2
  | F32 → printf "(%s)*(%s*%s)*(%s*%s)*(%s-%s)" c p1 wf2 p2 wf1 p2 p1
  | (F12 | F13) → printf "(%s)*((%s+2*%s)*%s)*(-( (%s+%s)*%s))*%s"
    c p1 p2 wf1 p1 p2 wf2 p2
  | (F21 | F31) → printf "(%s)*(-( (%s+%s)*%s))*(%s+2*%s)*%s)*%s"
    c p2 p1 wf1 p2 p1 wf2 p1
  end

| Tensor_2_Vector_Vector coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | (F23 | F32) → printf "t2_vv(%s,%s,%s)" c wf1 wf2
  | (F12 | F13) → printf "v_t2v(%s,%s,%s)" c wf1 wf2
  | (F21 | F31) → printf "v_t2v(%s,%s,%s)" c wf2 wf1
  end

| Tensor_2_Vector_Vector_1 coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | (F23 | F32) → printf "t2_vv_1(%s,%s,%s)" c wf1 wf2
  | (F12 | F13) → printf "v_t2v_1(%s,%s,%s)" c wf1 wf2
  | (F21 | F31) → printf "v_t2v_1(%s,%s,%s)" c wf2 wf1
  end

| Dim5_Tensor_2_Vector_Vector_1 coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | (F23 | F32) → printf "t2_vv_d5_1(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | (F12 | F13) → printf "v_t2v_d5_1(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | (F21 | F31) → printf "v_t2v_d5_1(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
  end

| Tensor_2_Vector_Vector_t coeff →
  let c = format_coupling coeff c in
  begin match fusion with
  | (F23 | F32) → printf "t2_vv_t(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2

```

```

| (F12 | F13) → printf "v_t2v_t(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
| (F21 | F31) → printf "v_t2v_t(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
end

| Dim5_Tensor_2_Vector_Vector_2_coeff →
  let c = format_coupling_coeff c in
  begin match fusion with
  | F23 → printf "t2_vv_d5_2(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | F32 → printf "t2_vv_d5_2(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
  | (F12 | F13) → printf "v_t2v_d5_2(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | (F21 | F31) → printf "v_t2v_d5_2(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
  end

| Dim7_Tensor_2_Vector_Vector_T_coeff →
  let c = format_coupling_coeff c in
  begin match fusion with
  | F23 → printf "t2_vv_d7(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | F32 → printf "t2_vv_d7(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
  | (F12 | F13) → printf "v_t2v_d7(%s,%s,%s,%s,%s)" c wf1 p1 wf2 p2
  | (F21 | F31) → printf "v_t2v_d7(%s,%s,%s,%s,%s)" c wf2 p2 wf1 p1
  end

end

```

Flip the sign to account for the  $i^2$  relative to diagrams with only cubic couplings.

```

| V4 (vertex, fusion, constant) →
  let c = CM.constant_symbol constant
  and ch1, ch2, ch3 = children3 rhs in
  let wf1 = multiple_variable_amplitude_dictionary ch1
  and wf2 = multiple_variable_amplitude_dictionary ch2
  and wf3 = multiple_variable_amplitude_dictionary ch3
  and p1 = momentum ch1
  and p2 = momentum ch2
  and p3 = momentum ch3 in
  printf "@,%s" (if (F.sign rhs) < 0 then "+" else "-");
  begin match vertex with
  | Scalar4_coeff →
      printf "(%s*%s*%s*%s)" (format_coupling_coeff c) wf1 wf2 wf3
  | Scalar2_Vector2_coeff →
      let c = format_coupling_coeff c in
      begin match fusion with
      | F134 | F143 | F234 | F243 →
          printf "%s*%s*(%s*%s)" c wf1 wf2 wf3
      | F314 | F413 | F324 | F423 →
          printf "%s*%s*(%s*%s)" c wf2 wf1 wf3
      | F341 | F431 | F342 | F432 →
          printf "%s*%s*(%s*%s)" c wf3 wf1 wf2
      | F312 | F321 | F412 | F421 →
          printf "(%s*%s*%s)*%s" c wf2 wf3 wf1
      | F231 | F132 | F241 | F142 →
          printf "(%s*%s*%s)*%s" c wf1 wf3 wf2
      | F123 | F213 | F124 | F214 →

```

```

        printf "(%s*%s*%s)*%s" c wf1 wf2 wf3
    end
| Vector4_contractions →
    begin match contractions with
    | [] → invalid_arg "Targets.print_current:␣Vector4␣[]"
    | head :: tail →
        printf "(";
        print_vector4 c wf1 wf2 wf3 fusion head;
        List.iter (print_add_vector4 c wf1 wf2 wf3 fusion) tail;
        printf ")"
    end
| Vector4_K_Matrix_tho (_, poles) →
    let pa, pb =
        begin match fusion with
        | (F341 | F431 | F342 | F432 | F123 | F213 | F124 |
F214) → (p1, p2)
        | (F134 | F143 | F234 | F243 | F312 | F321 | F412 |
F421) → (p2, p3)
        | (F314 | F413 | F324 | F423 | F132 | F231 | F142 |
F241) → (p1, p3)
        end in
        printf "(%s*(%s*%s)*(%s*%s)*(%s*%s)@,%*("
            c p1 wf1 p2 wf2 p3 wf3;
        List.iter (fun (coeff, pole) →
            printf "+%s/((%s+%s)*(%s+%s)-%s)"
                (CM.constant_symbol coeff) pa pb pa pb
                (CM.constant_symbol pole))
            poles;
        printf ")*(-%s-%s-%s))" p1 p2 p3
    | Vector4_K_Matrix_jr (disc, contractions) →
        let pa, pb =
            begin match disc, fusion with
            | 3, (F143 | F413 | F142 | F412 | F321 | F231 | F324 |
F234) → (p1, p2)
            | 3, (F314 | F341 | F214 | F241 | F132 | F123 | F432 |
F423) → (p2, p3)
            | 3, (F134 | F431 | F124 | F421 | F312 | F213 | F342 |
F243) → (p1, p3)
            | -, (F341 | F431 | F342 | F432 | F123 | F213 | F124 |
F214) → (p1, p2)
            | -, (F134 | F143 | F234 | F243 | F312 | F321 | F412 |
F421) → (p2, p3)
            | -, (F314 | F413 | F324 | F423 | F132 | F231 | F142 |
F241) → (p1, p3)
            end in
            begin match contractions with
            | [] → invalid_arg "Targets.print_current:␣Vector4_K_Matrix_jr␣[]"
            | head :: tail →
                printf "(";
                print_vector4_km c pa pb wf1 wf2 wf3 fusion head;

```

```

        List.iter (print_add_vector4_km c pa pb wf1 wf2 wf3 fusion)
            tail;
        printf ")"
    end
| GBBG (coeff, fb, b, f) →
    Fermions.print_current_g4 (coeff, fb, b, f) c wf1 wf2 wf3
    fusion

```



In principle,  $p_4$  could be obtained from the left hand side ...

```

| DScalar4 contractions →
    let p123 = Printf.sprintf "(-%s-%s-%s)" p1 p2 p3 in
    begin match contractions with
    | [] → invalid_arg "Targets.print_current:_DScalar4_"
    | head :: tail →
        printf "(";
        print_dscalar4 c wf1 wf2 wf3 p1 p2 p3 p123 fusion head;
        List.iter (print_add_dscalar4
                    c wf1 wf2 wf3 p1 p2 p3 p123 fusion) tail;
        printf ")"
    end
| DScalar2_Vector2 contractions →
    let p123 = Printf.sprintf "(-%s-%s-%s)" p1 p2 p3 in
    begin match contractions with
    | [] → invalid_arg "Targets.print_current:_DScalar4_"
    | head :: tail →
        printf "(";
        print_dscalar2_vector2
            c wf1 wf2 wf3 p1 p2 p3 p123 fusion head;
        List.iter (print_add_dscalar2_vector2
                    c wf1 wf2 wf3 p1 p2 p3 p123 fusion) tail;
        printf ")"
    end
end
| Vn (_, -, -) →
    invalid_arg "Targets.print_current:_n-ary_fusion"

let print_propagator f p m gamma =
    let minus_third = "(-1.0_" ^ !kind ^ "/3.0_" ^ !kind ^ ")" in
    let w =
        begin match CM.width f with
        | Vanishing | Fudged → "0.0_" ^ !kind
        | Constant → gamma
        | Timelike → "wd_tl(" ^ p ^ ", " ^ gamma ^ ")"
        | Running →
            failwith "Targets.Fortran:_running_width_not_available"
        | Custom f → f ^ "(" ^ p ^ ", " ^ gamma ^ ")"
        end in
    match CM.propagator f with

```



---

```

| Prop_Scalar →
|   printf "pr_phi(%s,%s,%s," p m w
| Prop_Col_Scalar →
|   printf "%s*pr_phi(%s,%s,%s," minus_third p m w
| Prop_Ghost → printf "(0,1)*pr_phi(%s,%s,%s," p m w
| Prop_Spinor →
|   printf "%s(%s,%s,%s," Fermions.psi_propagator p m w
| Prop_ConjSpinor →
|   printf "%s(%s,%s,%s," Fermions.psibar_propagator p m w
| Prop_Majorana →
|   printf "%s(%s,%s,%s," Fermions.chi_propagator p m w
| Prop_Col_Majorana →
|   printf "%s*pr_phi(%s,%s,%s," minus_third Fermions.chi_propagator p m w
| Prop_Unitarity →
|   printf "pr_unitarity(%s,%s,%s," p m w
| Prop_Col_Unitarity →
|   printf "%s*pr_unitarity(%s,%s,%s," minus_third p m w
| Prop_Feynman →
|   printf "pr_feynman(%s," p
| Prop_Col_Feynman →
|   printf "%s*pr_feynman(%s," minus_third p
| Prop_Gauge_xi →
|   printf "pr_gauge(%s,%s," p (CM.gauge_symbol xi)
| Prop_Rxi_xi →
|   printf "pr_rxi(%s,%s,%s,%s," p m w (CM.gauge_symbol xi)
| Prop_Tensor_2 →
|   printf "pr_tensor(%s,%s,%s," p m w
| Prop_Vectorspinor →
|   printf "pr_grav(%s,%s,%s," p m w
| Aux_Scalar | Aux_Spinor | Aux_ConjSpinor | Aux_Majorana
| Aux_Vector | Aux_Tensor_1 → printf "("
| Aux_Col_Scalar | Aux_Col_Vector | Aux_Col_Tensor_1 →
printf "%s*pr_phi(%s,%s,%s," minus_third
| Only_Insertion → printf "("

let print_projector f p m gamma =
let minus_third = "(-1.0_ " ^ !kind ^ "/3.0_ " ^ !kind ^ ")" in
match CM.propagator f with
| Prop_Scalar →
|   printf "pj_phi(%s,%s," m gamma
| Prop_Col_Scalar →
|   printf "%s*pr_phi(%s,%s," minus_third m gamma
| Prop_Ghost →
|   printf "(0,1)*pr_phi(%s,%s," m gamma
| Prop_Spinor →
|   printf "%s(%s,%s,%s," Fermions.psi_projector p m gamma
| Prop_ConjSpinor →
|   printf "%s(%s,%s,%s," Fermions.psibar_projector p m gamma
| Prop_Majorana →
|   printf "%s(%s,%s,%s," Fermions.chi_projector p m gamma

```

```

| Prop_Col_Majorana →
|   printf "%s*%s(%s,%s,%s," minus_third Fermions.chi_projector p m gamma
| Prop_Unitarity →
|   printf "pj-unitarity(%s,%s,%s," p m gamma
| Prop_Col_Unitarity →
|   printf "%s*%s(%s,%s,%s," minus_third p m gamma
| Prop_Feynman | Prop_Col_Feynman →
|   invalid_arg "no_on-shell_Feynman_propagator!"
| Prop_Gauge →
|   invalid_arg "no_on-shell_massless_gauge_propagator!"
| Prop_Rxi →
|   invalid_arg "no_on-shell_Rxi_propagator!"
| Prop_Vectorspinor →
|   printf "pj-grav(%s,%s,%s," p m gamma
| Prop_Tensor_2 →
|   printf "pj-tensor(%s,%s,%s," p m gamma
| Aux_Scalar | Aux_Spinor | Aux_ConjSpinor | Aux_Majorana
| Aux_Vector | Aux_Tensor_1 → printf "("
| Aux_Col_Scalar | Aux_Col_Vector | Aux_Col_Tensor_1 →
printf "%s*%s(" minus_third
| Only_Insertion → printf "("

let print_gauss f p m gamma =
let minus_third = "(-1.0_" ^ !kind ^ "/3.0_" ^ !kind ^ ")" in
match CM.propagator f with
| Prop_Scalar →
|   printf "pg-phi(%s,%s,%s," p m gamma
| Prop_Ghost →
|   printf "(0,1)*%s(%s,%s,%s," p m gamma
| Prop_Spinor →
|   printf "%s(%s,%s,%s," Fermions.psi_projector p m gamma
| Prop_ConjSpinor →
|   printf "%s(%s,%s,%s," Fermions.psibar_projector p m gamma
| Prop_Majorana →
|   printf "%s(%s,%s,%s," Fermions.chi_projector p m gamma
| Prop_Col_Majorana →
|   printf "%s*%s(%s,%s,%s," minus_third Fermions.chi_projector p m gamma
| Prop_Unitarity →
|   printf "pg-unitarity(%s,%s,%s," p m gamma
| Prop_Feynman | Prop_Col_Feynman →
|   invalid_arg "no_on-shell_Feynman_propagator!"
| Prop_Gauge →
|   invalid_arg "no_on-shell_massless_gauge_propagator!"
| Prop_Rxi →
|   invalid_arg "no_on-shell_Rxi_propagator!"
| Prop_Tensor_2 →
|   printf "pg-tensor(%s,%s,%s," p m gamma
| Aux_Scalar | Aux_Spinor | Aux_ConjSpinor | Aux_Majorana
| Aux_Vector | Aux_Tensor_1 → printf "("
| Only_Insertion → printf "("

```

```

| - → invalid_arg "targets:print-gauss:_not_available"
let print_fusion_diagnostics amplitude dictionary fusion =
  if warn_diagnose_gauge then begin
    let lhs = F.lhs fusion in
    let f = F.flavor lhs
    and v = variable lhs
    and p = momentum lhs in
    let mass = CM.mass_symbol f in
    match CM.propagator f with
    | Prop_Gauge _ | Prop_Feynman
    | Prop_Rxi _ | Prop_Unitarity →
      printf "UUUUUU@ [<2>%s_=" v;
      List.iter (print_current amplitude dictionary) (F.rhs fusion); nl ();
      begin match CM.goldstone f with
      | None →
        printf "UUUUUUcall_omega_ward_%s(\"%s\",%s,%s,%s)"
          (suffix_diagnose_gauge) v mass p v; nl ()
      | Some (g, phase) →
        let gv = add_tag lhs (CM.flavor_symbol g ^ "-" ^ format_p lhs) in
        printf "UUUUUUcall_omega_slavnov_%s"
          (suffix_diagnose_gauge);
        printf "(@[\"%s\",%s,%s,%s,@,%s*%s)"
          v mass p v (format_constant phase) gv; nl ()
      end
    end
  | - → ()
end

let print_fusion amplitude dictionary fusion =
  let lhs = F.lhs fusion in
  let f = F.flavor lhs in
  printf "UUUUUU@ [<2>%s_=@,_" (multiple_variable amplitude dictionary lhs);
  if F.on_shell amplitude lhs then
    print_projector f (momentum lhs)
    (CM.mass_symbol f) (CM.width_symbol f)
  else
    if F.is_gauss amplitude lhs then
      print_gauss f (momentum lhs)
      (CM.mass_symbol f) (CM.width_symbol f)
    else
      print_propagator f (momentum lhs)
      (CM.mass_symbol f) (CM.width_symbol f);
    List.iter (print_current amplitude dictionary) (F.rhs fusion);
    printf ")"; nl ()
  end

let print_momenta_seen_momenta amplitude =
  List.fold_left (fun seen f →
    let wf = F.lhs f in
    let p = F.momentum_list wf in
    if ¬ (PSet.mem p seen) then begin
      let rhs1 = List.hd (F.rhs f) in
      printf "UUUU%s_=%s" (momentum wf)

```

```

        (String.concat "␣␣"
         (List.map momentum (F.children rhs1))); nl ()
    end;
    PSet.add p seen
    seen_momenta (F.fusions amplitude)

let print_fusions dictionary fusions =
  List.iter
    (fun (f, amplitude) →
      print_fusion_diagnostics amplitude dictionary f;
      print_fusion amplitude dictionary f)
    fusions

let print_braket amplitude dictionary name braket =
  let bra = F.bra braket
  and ket = F.ket braket in
  printf "␣␣␣␣␣␣@ [<2>%s␣=␣% s@,␣␣" name name;
  begin match Fermions.reverse_braket (CM.lorentz (F.flavor bra)) with
  | false →
      printf "%s*(@," (multiple_variable amplitude dictionary bra);
      List.iter (print_current amplitude dictionary) ket;
      printf ")"
    | true →
      printf "@,";
      List.iter (print_current amplitude dictionary) ket;
      printf ")*%s" (multiple_variable amplitude dictionary bra)
  end; nl ()

```

$$iT = i^{\# \text{vertices}} i^{\# \text{propagators}} \dots = i^{n-2} i^{n-3} \dots = -i(-1)^n \dots \quad (15.3)$$



*tho* : we write some brackets twice using different names. Is it useful to cache them?

```

let print_brackets dictionary amplitude =
  let name = flavors_symbol (flavors amplitude) in
  printf "␣␣␣␣␣␣% s␣=␣0" name; nl ();
  List.iter (print_braket amplitude dictionary name) (F.brackets amplitude);
  let n = List.length (F.externals amplitude) in
  if n mod 2 = 0 then begin
    printf "␣␣␣␣␣␣@ [<2>% s␣=@,␣␣-% s␣!␣% d␣vertices,␣% d␣propagators"
      name name (n - 2) (n - 3); nl ()
  end else begin
    printf "␣␣␣␣␣␣!␣% s␣=␣% s␣!␣% d␣vertices,␣% d␣propagators"
      name name (n - 2) (n - 3); nl ()
  end;
  let s = F.symmetry amplitude in
  if s > 1 then
    printf "␣␣␣␣␣␣@ [<2>% s␣=@,␣% s␣,␣/␣sqrt(% d.0-% s)␣!␣symmetry␣factor" name name s !kind
  else
    printf "␣␣␣␣␣␣!␣unit␣symmetry␣factor";

```

```

nl ()

let print_incoming wf =
  let p = momentum wf
  and s = spin wf
  and f = F.flavor wf in
  let m = CM.mass_symbol f in
  match CM.lorentz f with
  | Scalar → printf "1"
  | BRS Scalar → printf "(0,-1)⊔*(%s⊔%s⊔%s**2)" p p m
  | Spinor →
    printf "%s⊔(%s,⊔%s,⊔%s)" Fermions.psi_incoming m p s
  | BRS Spinor →
    printf "%s⊔(%s,⊔%s,⊔%s)" Fermions.brs_psi_incoming m p s
  | ConjSpinor →
    printf "%s⊔(%s,⊔%s,⊔%s)" Fermions.psibar_incoming m p s
  | BRS ConjSpinor →
    printf "%s⊔(%s,⊔%s,⊔%s)" Fermions.brs_psibar_incoming m p s
  | Majorana →
    printf "%s⊔(%s,⊔%s,⊔%s)" Fermions.chi_incoming m p s
  | Maj_Ghost → printf "ghost⊔(%s,⊔%s,⊔%s)" m p s
  | BRS Majorana →
    printf "%s⊔(%s,⊔%s,⊔%s)" Fermions.brs_chi_incoming m p s
  | Vector | Massive_Vector →
    printf "eps⊔(%s,⊔%s,⊔%s)" m p s
  | BRS Vector | BRS Massive_Vector → printf
    "(0,1)⊔*(%s⊔%s⊔%s**2)⊔*eps⊔(%s,⊔%s,⊔%s)" p p m p s
  | Vectorspinor | BRS Vectorspinor →
    printf "%s⊔(%s,⊔%s,⊔%s)" Fermions.grav_incoming m p s
  | Tensor_1 → invalid_arg "Tensor_1⊔only⊔internal"
  | Tensor_2 → printf "eps2⊔(%s,⊔%s,⊔%s)" m p s
  | _ → invalid_arg "no⊔such⊔BRST⊔transformations"

let print_outgoing wf =
  let p = momentum wf
  and s = spin wf
  and f = F.flavor wf in
  let m = CM.mass_symbol f in
  match CM.lorentz f with
  | Scalar → printf "1"
  | BRS Scalar → printf "(0,-1)⊔*(%s⊔%s⊔%s**2)" p p m
  | Spinor →
    printf "%s⊔(%s,⊔%s,⊔%s)" Fermions.psi_outgoing m p s
  | BRS Spinor →
    printf "%s⊔(%s,⊔%s,⊔%s)" Fermions.brs_psi_outgoing m p s
  | ConjSpinor →
    printf "%s⊔(%s,⊔%s,⊔%s)" Fermions.psibar_outgoing m p s
  | BRS ConjSpinor →
    printf "%s⊔(%s,⊔%s,⊔%s)" Fermions.brs_psibar_outgoing m p s
  | Majorana →
    printf "%s⊔(%s,⊔%s,⊔%s)" Fermions.chi_outgoing m p s

```

```

| BRS Majorana →
  printf "%s_(%s,%s,%s)" Fermions.brs_chi_outgoing m p s
| Maj_Ghost → printf "ghost_(%s,%s,%s)" m p s
| Vector | Massive_Vector →
  printf "conjg_(eps_(%s,%s,%s))" m p s
| BRS Vector | BRS Massive_Vector → printf
  "(0,1)_(%s*%s-%s**2)_(conjg_(eps_(%s,%s,%s)))" p p m m p s
| Vectorspinor | BRS Vectorspinor →
  printf "%s_(%s,%s,%s)" Fermions.grav_incoming m p s
| Tensor_1 → invalid_arg "Tensor_1_only_internal"
| Tensor_2 → printf "conjg_(eps2_(%s,%s,%s))" m p s
| BRS _ → invalid_arg "no_such_BRST_transformations"

let print_external_momenta amplitude =
  let externals =
    List.combine
      (F.externals amplitude)
      (List.map (fun _ → true) (F.incoming amplitude) @
        List.map (fun _ → false) (F.outgoing amplitude)) in
    List.iter (fun (wf, incoming) →
      if incoming then
        printf "%%%s_=%_k(,%d)!_incoming"
          (momentum wf) (ext_momentum wf)
      else
        printf "%%%s_=%_k(,%d)!_outgoing"
          (momentum wf) (ext_momentum wf); nl ()) externals

let print_externals_seen_wfs amplitude =
  let externals =
    List.combine
      (F.externals amplitude)
      (List.map (fun _ → true) (F.incoming amplitude) @
        List.map (fun _ → false) (F.outgoing amplitude)) in
    List.fold_left (fun seen (wf, incoming) →
      if ¬ (WFSet.mem wf seen) then begin
        printf "%%%%%%%%@ [<2>%s_=@,%d]" (variable wf);
        (if incoming then print_incoming else print_outgoing) wf; nl ()
      end;
      WFSet.add wf seen) seen_wfs externals

let flavors_sans_color_to_string flavors =
  String.concat "_" (List.map M.flavor_to_string flavors)

let process_sans_color_to_string (fin, fout) =
  flavors_sans_color_to_string fin ^ "_->" ^
  flavors_sans_color_to_string fout

let print_fudge_factor amplitude =
  let name = flavors_symbol (flavors amplitude) in
  List.iter (fun wf →
    let p = momentum wf
    and f = F.flavor wf in
    match CM.width f with

```

```

| Fudged →
  let m = CM.mass_symbol f
  and w = CM.width_symbol f in
  printf "~~~~~if_ (%s>0.0_%s) then" w !kind; nl ();
  printf "~~~~~@[<2>%s=%s@_*(%s*%s-_%s**2)"
    name name p p m;
  printf "@/_cmplx_ (%s*%s-_%s**2,_%s*%s,_%s,kind=%s)"
    p p m m w !kind; nl ();
  printf "~~~~~end_if"; nl ()
| - → () (F.s_channel amplitude)

let num_helicities amplitudes =
  List.length (CF.helicities amplitudes)

```

### Spin, Flavor & Color Tables

The following abomination is required to keep the number of continuation lines as low as possible. FORTRAN77-style **DATA** statements are actually a bit nicer here, but they are not available for *constant* arrays.



We used to have a more elegant design with a sentinel 0 added to each initializer, but some revisions of the Compaq/Digital Compiler have a bug that causes it to reject this variant.



The actual table writing code using **reshape** should be factored, since it's the same algorithm every time.

```

let print_integer_parameter name value =
  printf "~~~@[<2>integer,parameter_::_%s=%d" name value; nl ()

let print_real_parameter name value =
  printf "~~~@[<2>real(kind=%s),parameter_::_%s=%d"
    !kind name value; nl ()

let print_logical_parameter name value =
  printf "~~~@[<2>logical,parameter_::_%s=_%s."
    name (if value then "true" else "false"); nl ()

let num_particles_in amplitudes =
  match CF.flavors amplitudes with
  | [] → 0
  | (fin, _) :: _ → List.length fin

let num_particles_out amplitudes =
  match CF.flavors amplitudes with
  | [] → 0
  | (_, fout) :: _ → List.length fout

let num_particles amplitudes =
  match CF.flavors amplitudes with
  | [] → 0
  | (fin, fout) :: _ → List.length fin + List.length fout

```

```

module CFlow = Color.Flow

let num_color_flows amplitudes =
  List.length (CF.color_flows amplitudes)

let num_color_indices_default = 2 (* Standard model *)

let num_color_indices amplitudes =
  try CFlow.rank (List.hd (CF.color_flows amplitudes)) with _ → num_color_indices_default

let color_to_string c =
  "(" ^ (String.concat "," (List.map (Printf.sprintf "%3d") c)) ^ ")"

let cflow_to_string cflow =
  String.concat "_" (List.map color_to_string (CFlow.in_to_lists cflow)) ^ "_->" ^
  String.concat "_" (List.map color_to_string (CFlow.out_to_lists cflow))

let protected = ",_protected" (* Fortran 2003! *)

let print_spin_table name tuples =
  printf "%s@[%d>integer,%dimension(n_prt,n_hel),_save%s:_table_spin-%s"
    protected name; nl ();
  match tuples with
  | [] → ()
  | _ →
    ignore (List.fold_left (fun i (tuple1, tuple2) →
      printf "%s@[%d>data,_table_spin-%s(:,%4d)/_s/_/" name i
        (String.concat "," (List.map (Printf.sprintf "%2d") (tuple1 @ tuple2)));
      nl (); succ i) 1 tuples)

let print_spin_tables amplitudes =
  (* print_spin_table_old "s" "states_old" (CF.helicities amplitudes);
*)
  print_spin_table "states" (CF.helicities amplitudes);
  nl ()

let print_flavor_table name tuples =
  printf "%s@[%d>integer,%dimension(n_prt,n_flv),_save%s:_table_flavor-%s"
    protected name; nl ();
  match tuples with
  | [] → ()
  | _ →
    ignore (List.fold_left (fun i tuple →
      printf "%s@[%d>data,_table_flavor-%s(:,%4d)/_s/_!_s" name i
        (String.concat ","
          (List.map (fun f → Printf.sprintf "%3d" (M.pdg f)) tuple))
        (String.concat "_" (List.map M.flavor_to_string tuple)));
      nl (); succ i) 1 tuples)

let print_flavor_tables amplitudes =
  (* let n = num_particles amplitudes in *)
  (* print_flavor_table_old n "f" "states_old" (List.map (fun (fin, fout) →
  fin @ fout) (CF.flavors amplitudes)); *)
  print_flavor_table "states"
    (List.map (fun (fin, fout) → fin @ fout) (CF.flavors amplitudes));

```



```

    nl ()

let num_flavors amplitudes =
    List.length (CF.flavors amplitudes)

let print_color_flows_table tuples =
    printf
        "%u@ [<2>integer, dimension(n_cindex,n_prt,n_cflow), save%s::table_color_flows"
        protected; nl ();
    match tuples with
    | [] → ()
    | - :: - as tuples →
        ignore (List.fold_left (fun i tuple →
            begin match CFlow.to_lists tuple with
            | [] → ()
            | cf1 :: cf_n →
                printf "%u@ [<2>data_table_color_flows(:,%4d)/" i;
                printf "@%s" (String.concat " " (List.map string_of_int cf1));
                List.iter (function cf →
                    printf ",@%s" (String.concat " " (List.map string_of_int cf))) cf_n;
                printf "@_/"; nl ()
            end;
            succ i) 1 tuples)

let print_ghost_flags_table tuples =
    printf
        "%u@ [<2>logical, dimension(n_prt,n_cflow), save%s::table_ghost_flags"
        protected; nl ();
    match tuples with
    | [] → ()
    | - →
        ignore (List.fold_left (fun i tuple →
            begin match CFlow.ghost_flags tuple with
            | [] → ()
            | gf1 :: gf_n →
                printf "%u@ [<2>data_table_ghost_flags(:,%4d)/" i;
                printf "@%s" (if gf1 then "T" else "F");
                List.iter (function gf → printf ",@%s" (if gf then "T" else "F")) gf_n;
                printf "_/";
                nl ()
            end;
            succ i) 1 tuples)

let format_power_of x
    { Color.Flow.num = num; Color.Flow.den = den; Color.Flow.power = pwr } =
    match num, den, pwr with
    | -, 0, - → invalid_arg "format_power_of::zero denominator"
    | 0, -, - → "+zero"
    | 1, 1, 0 | -1, -1, 0 → "+one"
    | -1, 1, 0 | 1, -1, 0 → "-one"
    | 1, 1, 1 | -1, -1, 1 → "+" ^ x
    | -1, 1, 1 | 1, -1, 1 → "-" ^ x

```

```

| 1, 1, -1 | -1, -1, -1 → "+1/" ^ x
| -1, 1, -1 | 1, -1, -1 → "-1/" ^ x
| 1, 1, p | -1, -1, p →
  "+" ^ (if p > 0 then "" else "1/") ^ x ^ "*" ^ string_of_int (abs p)
| -1, 1, p | 1, -1, p →
  "-" ^ (if p > 0 then "" else "1/") ^ x ^ "*" ^ string_of_int (abs p)
| n, 1, 0 →
  (if n < 0 then "-" else "+") ^ string_of_int (abs n) ^ ".0_" ^ !kind
| n, d, 0 →
  (if n × d < 0 then "-" else "+") ^
  string_of_int (abs n) ^ ".0_" ^ !kind ^ "/" ^
  string_of_int (abs d)
| n, 1, 1 →
  (if n < 0 then "-" else "+") ^ string_of_int (abs n) ^ "*" ^ x
| n, 1, -1 →
  (if n < 0 then "-" else "+") ^ string_of_int (abs n) ^ "/" ^ x
| n, d, 1 →
  (if n × d < 0 then "-" else "+") ^
  string_of_int (abs n) ^ ".0_" ^ !kind ^ "/" ^
  string_of_int (abs d) ^ "*" ^ x
| n, d, -1 →
  (if n × d < 0 then "-" else "+") ^
  string_of_int (abs n) ^ ".0_" ^ !kind ^ "/" ^
  string_of_int (abs d) ^ "/" ^ x
| n, 1, p →
  (if n < 0 then "-" else "+") ^ string_of_int (abs n) ^
  (if p > 0 then "*" else "/") ^ x ^ "*" ^ string_of_int (abs p)
| n, d, p →
  (if n × d < 0 then "-" else "+") ^
  string_of_int (abs n) ^ ".0_" ^ !kind ^ "/" ^
  string_of_int (abs d) ^
  (if p > 0 then "*" else "/") ^ x ^ "*" ^ string_of_int (abs p)

let format_powers_of x = function
| [] → "zero"
| powers → String.concat "" (List.map (format_power_of x) powers)

```



We can optimize the following slightly by reusing common color factor parameters.

```

let print_color_factor_table table =
  let n_cflow = Array.length table in
  let n_cfactors = ref 0 in
  for c1 = 0 to pred n_cflow do
    for c2 = 0 to pred n_cflow do
      match table.(c1).(c2) with
      | [] → ()
      | - → incr n_cfactors
    done
  done;

```

---

```

print_integer_parameter "n_cfactors" !n_cfactors;
printf "%%@ [<2>type(%s),_dimension(n_cfactors),_save%s_::"
      omega_color_factor_abbrev protected;
printf "@_table_color_factors"; nl ();
let i = ref 1 in
if n_cflow > 0 then begin
  for c1 = 0 to pred n_cflow do
    for c2 = 0 to pred n_cflow do
      match table.(c1).(c2) with
      | [] → ()
      | cf →
        printf "%%@ [<2>real(kind=%s),_parameter,_private_::_color_factor_%06d=_%s"
              !kind !i (format_powers_of nc_parameter cf);
        nl ();
        printf "%%@ [<2>data_table_color_factors(%6d)_/_%s(%d,%d,color_factor_%06d)_\n"
              !i omega_color_factor_abbrev (succ c1) (succ c2) !i;
        incr i;
        nl ();
      done
    done
  end

let print_color_tables amplitudes =
  let cflows = CF.color_flows amplitudes
  and cfactors = CF.color_factors amplitudes in
  (* print_color_flows_table_old "c" cflows; nl (); *)
  print_color_flows_table cflows; nl ();
  (* print_ghost_flags_table_old "g" cflows; nl (); *)
  print_ghost_flags_table cflows; nl ();
  (* print_color_factor_table_old cfactors; nl (); *)
  print_color_factor_table cfactors; nl ()

let option_to_logical = function
| Some _ → "T"
| None → "F"

let print_flavor_color_table n_flv n_cflow table =
  printf
    "%%@ [<2>logical,_dimension(n_flv,_n_cflow),_save%s_::@_flv_col_is_allowed"
    protected; nl ();
  if n_flv > 0 then begin
    for c = 0 to pred n_cflow do
      printf
        "%%@ [<2>data_flv_col_is_allowed(:,%4d)_/" (succ c);
      printf "@_%s" (option_to_logical table.(0).(c));
      for f = 1 to pred n_flv do
        printf ",@_%s" (option_to_logical table.(f).(c))
      done;
      printf "@_/"; nl ()
    done;
  end
end

```

```

let print_amplitude_table a =
  (* print_flavor_color_table_old "a" (num_flavors a) (List.length (CF.color_flows a)) (CF.process_table a) *)
  print_flavor_color_table
    (num_flavors a) (List.length (CF.color_flows a)) (CF.process_table a);
  nl ();
  printf
    "%%@ [<2>complex(kind=%s), dimension(n_flg, n_cflow, n_hel), save:: amp" !kind;
  nl ();
  nl ()

let print_helicity_selection_table () =
  printf "%%@ [<2>logical, dimension(n_hel), save:: ";
  printf "hel_is_allowed=T"; nl ();
  printf "%%@ [<2>real(kind=%s), dimension(n_hel), save:: " !kind;
  printf "hel_max_abs=0"; nl ();
  printf "%%@ [<2>real(kind=%s), save:: " !kind;
  printf "hel_sum_abs=0, ";
  printf "hel_threshold=1E10"; nl ();
  printf "%%@ [<2>integer, save:: ";
  printf "hel_count=0, ";
  printf "hel_cutoff=100"; nl ();
  printf "%%@ [<2>integer:: ";
  printf "i"; nl ();
  printf "%%@ [<2>integer, save, dimension(n_hel):: ";
  printf "hel_map=(i, i=1, n_hel)"; nl ();
  printf "%%@ [<2>integer, save:: hel_finite=n_hel"; nl ();
  nl ()

```

#### Optional MD5 sum function

```

let print_md5sum_functions = function
| Some s →
  printf "%%@ [<5>"; if !fortran95 then printf "pure ";
  printf "function_md5sum()"; nl ();
  printf "character(len=32):: md5sum"; nl ();
  printf "DONT EVEN THINK of modifying the following line!"; nl ();
  printf "md5sum=\"%s\" s"; nl ();
  printf "end_function_md5sum"; nl ();
  nl ()
| None → ()

```

#### Maintenance & Inquiry Functions

```

let print_maintenance_functions () =
  if !whizard then begin
    printf "subroutine_init(par)"; nl ();
    printf "real(kind=%s), dimension(*), intent(in):: par" !kind; nl ();
    printf "call import_from_whizard(par)"; nl ();
  end

```

```

        printf "end_subroutine_init"; nl ();
        nl ();
        printf "subroutine_final()"; nl ();
        printf "end_subroutine_final"; nl ();
        nl ();
        printf "subroutine_update_alpha_s(alpha_s)"; nl ();
        printf "real(kind=%s),intent(in)::alpha_s" !kind; nl ();
        printf "call_model_update_alpha_s(alpha_s)"; nl ();
        printf "end_subroutine_update_alpha_s"; nl ();
        nl ();
    end

let print_inquiry_function_omp () = begin
    printf "pure_function_omp_supported() result(status)"; nl ();
    printf "logical::status"; nl ();
    printf "status=%s" (if !omp then ".true." else ".false."); nl ();
    printf "end_function_omp_supported"; nl ();
    nl ();
end

let print_numeric_inquiry_functions (f, v) =
    printf "@[<5>"; if !fortran95 then printf "pure";
    printf "function_s() result(n)" f; nl ();
    printf "integer::n"; nl ();
    printf "n=%s" v; nl ();
    printf "end_function_s" f; nl ();
    nl ();

let print_inquiry_functions name =
    printf "@[<5>"; if !fortran95 then printf "pure";
    printf "function_number_s() result(n)" name; nl ();
    printf "integer::n"; nl ();
    printf "n=size(table_s,dim=2)" name; nl ();
    printf "end_function_number_s" name; nl ();
    nl ();
    printf "@[<5>"; if !fortran95 then printf "pure";
    printf "subroutine_s(a)" name; nl ();
    printf "integer,dimension(:,:),intent(out)::a"; nl ();
    printf "a=table_s" name; nl ();
    printf "end_subroutine_s" name; nl ();
    nl ();

let print_color_flows () =
    printf "@[<5>"; if !fortran95 then printf "pure";
    printf "function_number_color_indices() result(n)"; nl ();
    printf "integer::n"; nl ();
    printf "n=size(table_color_flows,dim=1)"; nl ();
    printf "end_function_number_color_indices"; nl ();
    nl ();
    printf "@[<5>"; if !fortran95 then printf "pure";
    printf "function_number_color_flows() result(n)"; nl ();
    printf "integer::n"; nl ();

```

```

    printf "uuuuun=size(table_color_flows,dim=3); nl ();
    printf "uuendfunctionnumber_color_flows"; nl ();
    nl ();
    printf "uu@ [<5>"; if !fortran95 then printf "pure ";
    printf "subroutine color_flows (a,ug)"; nl ();
    printf "uuuuinteger, dimension(:,:,:), intent(out) u:: a"; nl ();
    printf "uuuulogical, dimension(:,:,:), intent(out) u:: g"; nl ();
    printf "uuuua= table_color_flows"; nl ();
    printf "uuuug= table_ghost_flags"; nl ();
    printf "uuendsubroutine color_flows"; nl ();
    nl ();

let print_color_factors () =
    printf "uu@ [<5>"; if !fortran95 then printf "pure ";
    printf "function number_color_factors ( ) result (n)"; nl ();
    printf "uuuuinteger :: u"; nl ();
    printf "uuuun=size(table_color_factors)"; nl ();
    printf "uuendfunction number_color_factors"; nl ();
    nl ();
    printf "uu@ [<5>"; if !fortran95 then printf "pure ";
    printf "subroutine color_factors (cf)"; nl ();
    printf "uuuutype(%s), dimension(:), intent(out) u:: cf"
        omega_color_factor_abbrev; nl ();
    printf "uuuucf= table_color_factors"; nl ();
    printf "uuendsubroutine color_factors"; nl ();
    nl ();
    printf "uu@ [<5>"; if !fortran95  $\wedge$  pure_unless_openmp then printf "pure ";
    printf "function color_sum (flv, hel) result (amp2)"; nl ();
    printf "uuuuinteger, intent(in) u:: flv, hel"; nl ();
    printf "uuuureal(kind=%s) :: amp2" !kind; nl ();
    printf "uuuuamp2= real (omega_color_sum (flv, hel, amp, table_color_factors))"; nl ();
    printf "uuendfunction color_sum"; nl ();
    nl ();

let print_dispatch_functions () =
    printf "uu@ [<5>";
    printf "subroutine new_event (p)"; nl ();
    printf "uuuureal(kind=%s), dimension(0:3,*), intent(in) u:: p" !kind; nl ();
    printf "uuuulogical :: mask_dirty"; nl ();
    printf "uuuuinteger :: hel"; nl ();
    printf "uuuucall calculate_amplitudes (amp, p, hel_is_allowed)"; nl ();
    printf "uuuuif ((hel_threshold .gt. 0) .and. (hel_count .le. hel_cutoff)) then"; nl ();
    printf "uuuuuucall@ [<3>omega_update_helicity_selection@ (hel_count,@amp,@u";
    printf "hel_max_abs,@hel_sum_abs,@hel_is_allowed,@hel_threshold,@hel_cutoff,@mask";
    printf "uuuuuuif (mask_dirty) then"; nl ();
    printf "uuuuuuuuhel_finite = 0"; nl ();
    printf "uuuuuuuudo hel= 1, n_hel"; nl ();
    printf "uuuuuuuuuuif (hel_is_allowed(hel)) then"; nl ();
    printf "uuuuuuuuuuuuhel_finite = hel_finite+1"; nl ();
    printf "uuuuuuuuuuuuhel_map(hel_finite) = hel"; nl ();
    printf "uuuuuuuuuuuuend if"; nl ();

```

```

printf "UUUUUUUUend_do"; nl ();
printf "UUUUUUend_if"; nl ();
printf "UUUUend_if"; nl ();
printf "UUend_subroutine_new_event"; nl ();
nl ();
printf "UU@ [<5>";
printf "subroutine_reset_helicity_selection(threshold,cutoff)"; nl ();
printf "UUUUreal(kind=%s),intent(in)U::threshold" !kind; nl ();
printf "UUUUinteger,intent(in)U::cutoff"; nl ();
printf "UUUUintegerU::i"; nl ();
printf "UUUUhel_is_allowedU=T"; nl ();
printf "UUUUhel_max_absU=0"; nl ();
printf "UUUUhel_sum_absU=0"; nl ();
printf "UUUUhel_countU=0"; nl ();
printf "UUUUhel_thresholdU=threshold"; nl ();
printf "UUUUhel_cutoffU=cutoff"; nl ();
printf "UUUUhel_mapU=/(i,iU=1,U_nhel)/"; nl ();
printf "UUUUhel_finiteU=n_hel"; nl ();
printf "UUend_subroutine_reset_helicity_selection"; nl ();
nl ();
printf "UU@ [<5>"; if !fortran95 then printf "pureU";
printf "function_is_allowed(flv,Uhel,Ucol)UresultU(yorn)"; nl ();
printf "UUUUlogicalU::yorn"; nl ();
printf "UUUUinteger,intent(in)U::flv,Uhel,Ucol"; nl ();
printf "UUUUyornU=hel_is_allowed(hel)U.and.U";
printf "flv_col_is_allowed(flv,col)"; nl ();
printf "UUend_function_is_allowed"; nl ();
nl ();
printf "UU@ [<5>"; if !fortran95 then printf "pureU";
printf "function_get_amplitude(flv,Uhel,Ucol)UresultU(amp_result)"; nl ();
printf "UUUUcomplex(kind=%s)U::amp_result" !kind; nl ();
printf "UUUUinteger,intent(in)U::flv,Uhel,Ucol"; nl ();
printf "UUUUamp_resultU=amp(flv,Ucol,Uhel)"; nl ();
printf "UUend_function_get_amplitude"; nl ();
nl ();

```

### Main Function

```

let format_power_of_nc
{ Color.Flow.num = num; Color.Flow.den = den; Color.Flow.power = pwr } =
match num, den, pwr with
| -, 0, - → invalid_arg "format_power_of_nc: zero_denominator"
| 0, -, - → ""
| 1, 1, 0 | -1, -1, 0 → "+_1"
| -1, 1, 0 | 1, -1, 0 → "-_1"
| 1, 1, 1 | -1, -1, 1 → "+_N"
| -1, 1, 1 | 1, -1, 1 → "-_N"
| 1, 1, -1 | -1, -1, -1 → "+_1/N"
| -1, 1, -1 | 1, -1, -1 → "-_1/N"

```

```

| 1, 1, p | -1, -1, p →
  "+" ^ (if p > 0 then "" else "1/") ^ "N" ^ string_of_int (abs p)
| -1, 1, p | 1, -1, p →
  "-" ^ (if p > 0 then "" else "1/") ^ "N" ^ string_of_int (abs p)
| n, 1, 0 →
  (if n < 0 then "-" else "+") ^ string_of_int (abs n)
| n, d, 0 →
  (if n × d < 0 then "-" else "+") ^
  string_of_int (abs n) ^ "/" ^ string_of_int (abs d)
| n, 1, 1 →
  (if n < 0 then "-" else "+") ^ string_of_int (abs n) ^ "N"
| n, 1, -1 →
  (if n < 0 then "-" else "+") ^ string_of_int (abs n) ^ "/N"
| n, d, 1 →
  (if n × d < 0 then "-" else "+") ^
  string_of_int (abs n) ^ "/" ^ string_of_int (abs d) ^ "N"
| n, d, -1 →
  (if n × d < 0 then "-" else "+") ^
  string_of_int (abs n) ^ "/" ^ string_of_int (abs d) ^ "/N"
| n, 1, p →
  (if n < 0 then "-" else "+") ^ string_of_int (abs n) ^
  (if p > 0 then "*" else "/") ^ "N" ^ string_of_int (abs p)
| n, d, p →
  (if n × d < 0 then "-" else "+") ^ string_of_int (abs n) ^ "/" ^
  string_of_int (abs d) ^ (if p > 0 then "*" else "/") ^ "N" ^ string_of_int (abs p)

let format_powers_of_nc = function
| [] → "0"
| powers → String.concat "_" (List.map format_power_of_nc powers)

let print_description cmdline amplitudes () =
  printf "!_File_generated_automatically_by_0'Mega"; nl ();
  printf "!"; nl ();
  printf "!_{}_s" cmdline; nl ();
  printf "!"; nl ();
  printf "!_with_all_scattering_amplitudes_for_the_process(es)"; nl ();
  printf "!"; nl ();
  printf "!_{}_flavor_combinations:"; nl ();
  printf "!"; nl ();
  ThoList.iteri
    (fun i process →
      printf "!_{}_3d:_s" i (process_sans_color_to_string process); nl ())
    1 (CF.flavors amplitudes);
  printf "!"; nl ();
  printf "!_{}_color_flows:"; nl ();
  printf "!"; nl ();
  ThoList.iteri
    (fun i cflow →
      printf "!_{}_3d:_s" i (cflow_to_string cflow); nl ())
    1 (CF.color_flows amplitudes);
  printf "!"; nl ();

```



```

printf "!NB: i.g. not all color flows contribute to all flavor"; nl ();
printf "!combinations. Consult the array FLV_COL_IS_ALLOWED"; nl ();
printf "below for the allowed combinations."; nl ();
printf "!"; nl ();
printf "!Color_Factors:"; nl ();
printf "!"; nl ();
let cfactors = CF.color_factors amplitudes in
for c1 = 0 to pred (Array.length cfactors) do
  for c2 = 0 to c1 do
    match cfactors.(c1).(c2) with
    | [] → ()
    | cfactor →
      printf "!(%3d,%3d): %s"
        (succ c1) (succ c2) (format_powers_of_nc cfactor); nl ()
  done
done;
printf "!"; nl ();
printf "!vanishing or redundant flavor combinations:"; nl ();
printf "!"; nl ();
List.iter (fun process →
  printf "!!!!!!!!!! %s" (process_sans_color_to_string process); nl ())
  (CF.vanishing_flavors amplitudes);
printf "!"; nl ();
begin
  match CF.constraints amplitudes with
  | None → ()
  | Some s →
    printf
      "!!diagram_selection_(MIGHT_BREAK_GAUGE_INVARIANCE!!!):"; nl ();
    printf "!"; nl ();
    printf "!! %s" s; nl ();
    printf "!"; nl ()
end;
begin match RCS.description M.rcs with
| line1 :: lines →
  printf "!\nin %s" line1; nl ();
  List.iter (fun s → printf "!!!! %s" s; nl ()) lines
| [] → printf "!\nin %s" (RCS.name M.rcs); nl ()
end;
printf "!"; nl ()

let print_version () =
  printf "!\0'Mega_revision_control_information:"; nl ();
  List.iter (fun s → printf "!!!! %s" s; nl ())
    (ThoList.flatmap RCS.summary (M.rcs :: rcs_list @ F.rcs_list))

```

### Printing Modules

```

type accessibility =
| Public

```

```

| Private
| Protected (* Fortran 2003 *)

let accessibility_to_string = function
| Public → "public"
| Private → "private"
| Protected → "protected"

type used_symbol =
| As_Is of string
| Aliased of string × string

let print_used_symbol = function
| As_Is name → printf "%s" name
| Aliased (orig, alias) → printf "%s_=>%s" alias orig

type used_module =
| Full of string
| Full_Aliased of string × (string × string) list
| Subset of string × used_symbol list

let print_used_module = function
| Full name
| Full_Aliased (name, [])
| Subset (name, []) →
  printf "_use_%s" name;
  nl ()
| Full_Aliased (name, aliases) →
  printf "_@ [<5>use_%s" name;
  List.iter
    (fun (orig, alias) → printf ",_%s_=>%s" alias orig)
    aliases;
  nl ()
| Subset (name, used_symbol :: used_symbols) →
  printf "_@ [<5>use_%s,only:_ " name;
  print_used_symbol used_symbol;
  List.iter (fun s → printf ",_"; print_used_symbol s) used_symbols;
  nl ()

type fortran_module =
{ module_name : string;
  default_accessibility : accessibility;
  used_modules : used_module list;
  public_symbols : string list;
  print_declarations : (unit → unit) list;
  print_implementations : (unit → unit) list }

let print_public = function
| name1 :: names →
  printf "_@ [<2>public:_%s" name1;
  List.iter (fun n → printf ",_@_%s" n) names; nl ()
| [] → ()

let print_module m =

```

```

    printf "module_%s" m.module_name; nl ();
    List.iter print_used_module m.used_modules;
    printf "implicit_none"; nl ();
    printf "_%s" (accessibility_to_string m.default_accessibility); nl ();
    print_public m.public_symbols; nl ();
    begin match m.print_declarations with
    | [] → ()
    | print_declarations →
        List.iter (fun f → f ()) print_declarations; nl ()
    end;
    begin match m.print_implementations with
    | [] → ()
    | print_implementations →
        printf "contains"; nl (); nl ();
        List.iter (fun f → f ()) print_implementations; nl ()
    end;
    printf "end_module_%s" m.module_name; nl ()

let print_modules modules =
    List.iter print_module modules;
    print_version ();
    print_flush ()

let module_to_file line_length oc prelude m =
    output_string oc (m.module_name ^ "\n");
    let filename = m.module_name ^ ".f90" in
    let channel = open_out filename in
    setup_fortran_formatter line_length channel;
    prelude ();
    print_modules [m];
    close_out channel

let modules_to_file line_length oc prelude = function
| [] → ()
| m :: mlist →
    module_to_file line_length oc prelude m;
    List.iter (module_to_file line_length oc (fun () → ())) mlist

```

### Chopping Up Amplitudes

```

let num_fusions_brackets size amplitudes =
    let num_fusions =
        max 1 size in
    let count_brackets =
        List.fold_left
            (fun sum process → sum + List.length (F.brackets process))
            0 (CF.processes amplitudes)
    and count_processes =
        List.length (CF.processes amplitudes) in
    if count_brackets > 0 then
        let num_brackets =

```

```

      max 1 ((num_fusions × count_processes) / count_brackets) in
      (num_fusions, num_brackets)
    else
      (num_fusions, 1)
  let chop_amplitudes size amplitudes =
    let num_fusions, num_brackets = num_fusions_brackets size amplitudes in
    (ThoList.enumerate 1 (ThoList.chopn num_fusions (CF.fusions amplitudes)),
     ThoList.enumerate 1 (ThoList.chopn num_brackets (CF.processes amplitudes)))
  let print_compute_fusions1 dictionary (n, fusions) =
    if !openmp then begin
      printf "subroutine_compute_fusions_%04d(%s)" n openmp_tld; nl ();
      printf "type(%s), intent(inout): %s" openmp_tld_type openmp_tld; nl ();
    end else begin
      printf "subroutine_compute_fusions_%04d()" n; nl ();
    end;
    print_fusions dictionary fusions;
    printf "end_subroutine_compute_fusions_%04d" n; nl ()
  and print_compute_brackets1 dictionary (n, processes) =
    if !openmp then begin
      printf "subroutine_compute_brackets_%04d(%s)" n openmp_tld; nl ();
      printf "type(%s), intent(inout): %s" openmp_tld_type openmp_tld; nl ();
    end else begin
      printf "subroutine_compute_brackets_%04d()" n; nl ();
    end;
    List.iter (print_brackets dictionary) processes;
    printf "end_subroutine_compute_brackets_%04d" n; nl ()

```

### Common Stuff

```

let omega_public_symbols =
  ["number_particles_in"; "number_particles_out";
   "number_color_indices";
   "reset_helicity_selection"; "new_event";
   "is_allowed"; "get_amplitude"; "color_sum"; "openmp_supported"] @
  ThoList.flatmap
    (fun n → ["number_" ^ n; n])
  ["spin_states"; "flavor_states"; "color_flows"; "color_factors"]
let whizard_public_symbols md5sum =
  ["init"; "final"; "update_alpha_s"] @
  (match md5sum with Some _ → ["md5sum"] | None → [])
let used_modules () =
  [Full "kinds";
   Full Fermions.use_module;
   Full_Aliased ("omega_color", ["omega_color_factor", omega_color_factor_abbrev])] @
  List.map
    (fun m → Full m)

```

```

      (match !parameter_module with "" → !use_modules | pm →
pm :: !use_modules)
let public_symbols () =
  if !whizard then
    omega_public_symbols @ (whizard_public_symbols !md5sum)
  else
    omega_public_symbols
let print_constants amplitudes =
  printf "!!DON'T EVEN THINK of removing the following!"; nl ();
  printf "!!If the compiler complains about undeclared"; nl ();
  printf "!!or undefined variables, you are compiling"; nl ();
  printf "!!against an incompatible omega95 module!"; nl ();
  printf "!!@[<2>integer, dimension(%d), parameter, private::"
    (List.length require_library);
  printf "require=@(/@";
  print_list require_library;
  printf ")/"; nl (); nl ();

```

Using these parameters makes sense for documentation, but in practice, there is no need to ever change them.

```

List.iter
  (function name, value → print_integer_parameter name (value amplitudes))
  [ ("n_prt", num_particles);
    ("n_in", num_particles_in);
    ("n_out", num_particles_out);
    ("n_cflow", num_color_flows); (* Number of different color ampli-
tudes. *)
    ("n_cindex", num_color_indices); (* Maximum rank of color ten-
sors. *)
    ("n_flv", num_flavors); (* Number of different flavor amplitudes.
*)
    ("n_hel", num_helicities) (* Number of different helicity amplitudes.
*) ];
  nl ();

```

Abbreviations.

```

printf "!!NB: you MUST NOT change the value of %s here!!" nc_parameter;
nl ();
printf "!!It is defined here for convenience only and must be"; nl ();
printf "!!compatible with hardcoded values in the amplitude!"; nl ();
print_real_parameter nc_parameter (CM.nc ()); (* NC *)
List.iter
  (function name, value → print_logical_parameter name value)
  [ ("F", false); ("T", true) ]; nl ();

print_spin_tables amplitudes;
print_flavor_tables amplitudes;
print_color_tables amplitudes;
print_amplitude_table amplitudes;

```

```

    print_helicity_selection_table ()

let print_interface () =
  print_md5sum_functions !md5sum;
  print_maintenance_functions ();
  List.iter print_numeric_inquiry_functions
    [("number_particles_in", "n_in");
     ("number_particles_out", "n_out")];
  List.iter print_inquiry_functions
    ["spin_states", "flavor_states"];
  print_inquiry_function_openmp ();
  print_color_flows ();
  print_color_factors ();
  print_dispatch_functions ();
  nl ();
  current_continuation_line := 0;
  if !km_write ∨ !km_pure then (Targets_Kmatrix.Fortran.print !km_pure);
  current_continuation_line := 1;
  nl ()

let print_calculate_amplitudes_declarations_computations_amplitudes =
  printf "%@<5>subroutine_calculate_amplitudes(amp,k,mask)"; nl ();
  printf "      complex(kind=%s), dimension(:, :, :), intent(out) :: amp" !kind; nl ();
  printf "      real(kind=%s), dimension(0:3, *), intent(in) :: k" !kind; nl ();
  printf "      logical, dimension(:), intent(in) :: mask"; nl ();
  printf "      integer, dimension(n_prt) :: s"; nl ();
  printf "      integer :: h, hi"; nl ();
  declarations ();
  begin match CF.processes_amplitudes with
  | p :: _ → print_external_momenta p
  | _ → ()
  end;
  ignore (List.fold_left print_momenta PSet.empty (CF.processes_amplitudes));
  printf "      amp = 0"; nl ();
  if num_helicities_amplitudes > 0 then begin
    printf "      if (hel_finite == 0) return"; nl ();
    if !openmp then begin
      printf "!$OMP_PARALLEL DO DEFAULT(SHARED) PRIVATE(s, h, %s) SCHEDULE(STATIC)" openmp;
    end;
    printf "      do hi = 1, hel_finite"; nl ();
    printf "        h = hel_map(hi)"; nl ();
    printf "        s = table_spin_states(:, h)"; nl ();
    ignore (List.fold_left print_externals WFS.empty (CF.processes_amplitudes));
    computations ();
    List.iter print_fudge_factor (CF.processes_amplitudes);
    (* This sorting should slightly improve cache locality. *)
    let triple_snd = fun (_, x, _) → x
    in let triple_fst = fun (x, _, _) → x
    in let rec builder1 flvi flowi flows = match flows with
    | (Some a) :: tl → (flvi, flowi, flavors_symbol (flavors a)) :: (builder1 flvi (flowi + 1) tl)
    | None :: tl → builder1 flvi (flowi + 1) tl

```

```

| [] → []
in let rec builder2 flvi flvs = match flvs with
| flv :: tl → (builder1 flvi 1 flv) @ (builder2 (flvi + 1) tl)
| [] → []
in let unsorted = builder2 1 (List.map Array.to_list (Array.to_list (CF.process_table amplitudes)))
in let sorted = List.sort (fun a b →
if (triple_snd a ≠ triple_snd b) then triple_snd a - triple_snd b else (triple_fst a - triple_fst b))
unsorted
in List.iter (fun (flvi, flowi, flv) →
(printf "UUUUUUamp(%d,%d,h)U=U%s" flvi flowi flv; nl ());) sorted;

printf "UUUUend_Udo"; nl ();
if !openmp then begin
printf " !$OMP_END_PARALLEL_DO"; nl ();
end;
end;
printf "UUend_Usubroutine_Ucalculate_amplitudes"; nl ()

let print_compute_chops chopped_fusions chopped_brackets () =
List.iter
(fun (i, _) → printf "UUUUUUcall_Ucompute_fusions_%04d_U(%s)" i
(if !openmp then openmp_tld else ""); nl ())
chopped_fusions;
List.iter
(fun (i, _) → printf "UUUUUUcall_Ucompute_brackets_%04d_U(%s)" i
(if !openmp then openmp_tld else ""); nl ())
chopped_brackets

```

### Single Function

```

let amplitudes_to_channel_single_function cmdline oc amplitudes =

let print_declarations () =
print_constants amplitudes

and print_implementations () =
print_interface ();
print_calculate_amplitudes
(fun () → print_variable_declarations amplitudes)
(fun () →
print_fusions (CF.dictionary amplitudes) (CF.fusions amplitudes);
List.iter
(print_brackets (CF.dictionary amplitudes))
(CF.processes amplitudes))
amplitudes in

let fortran_module =
{ module_name = !module_name;
used_modules = used_modules ();
default_accessibility = Private;
public_symbols = public_symbols ();
print_declarations = [print_declarations];

```

```

    print_implementations = [print_implementations] } in
  setup_fortran_formatter !line_length oc;
  print_description cmdline amplitudes ();
  print_modules [fortran_module]

```

### Single Module

```

let amplitudes_to_channel_single_module cmdline oc size amplitudes =
  let print_declarations () =
    print_constants amplitudes;
    print_variable_declarations amplitudes
  and print_implementations () =
    print_interface () in
  let chopped_fusions, chopped_brackets =
    chop_amplitudes size amplitudes in
  let dictionary = CF.dictionary amplitudes in
  let print_compute_amplitudes () =
    print_calculate_amplitudes
    (fun () → ())
    (print_compute_chops chopped_fusions chopped_brackets)
    amplitudes
  and print_compute_fusions () =
    List.iter (print_compute_fusions1 dictionary) chopped_fusions
  and print_compute_brackets () =
    List.iter (print_compute_brackets1 dictionary) chopped_brackets in
  let fortran_module =
    { module_name = !module_name;
      used_modules = used_modules ();
      default_accessibility = Private;
      public_symbols = public_symbols ();
      print_declarations = [print_declarations];
      print_implementations = [print_implementations;
                               print_compute_amplitudes;
                               print_compute_fusions;
                               print_compute_brackets] } in
  setup_fortran_formatter !line_length oc;
  print_description cmdline amplitudes ();
  print_modules [fortran_module]

```

### Multiple Modules

```

let modules_of_amplitudes _ _ size amplitudes =
  let name = !module_name in

```



```

let print_declarations () =
  print_constants amplitudes
and print_variables () =
  print_variable_declarations amplitudes in

let constants_module =
  { module_name = name ^ "_constants";
    used_modules = used_modules ();
    default_accessibility = Public;
    public_symbols = [];
    print_declarations = [print_declarations];
    print_implementations = [] } in

let variables_module =
  { module_name = name ^ "_variables";
    used_modules = used_modules ();
    default_accessibility = Public;
    public_symbols = [];
    print_declarations = [print_variables];
    print_implementations = [] } in

let dictionary = CF.dictionary amplitudes in

let print_compute_fusions (n, fusions) () =
  if !openmp then begin
    printf "▯▯subroutine▯compute_fusions_%04d▯(%s)" n openmp_tld; nl ();
    printf "▯▯@<5>type(%s),▯intent(inout)▯:▯%s" openmp_tld-type openmp_tld; nl ();
  end else begin
    printf "▯▯@<5>subroutine▯compute_fusions_%04d▯()" n; nl ();
  end;
  print_fusions dictionary fusions;
  printf "▯▯end▯subroutine▯compute_fusions_%04d" n; nl () in

let print_compute_brackets (n, processes) () =
  if !openmp then begin
    printf "▯▯subroutine▯compute_brackets_%04d▯(%s)" n openmp_tld; nl ();
    printf "▯▯@<5>type(%s),▯intent(inout)▯:▯%s" openmp_tld-type openmp_tld; nl ();
  end else begin
    printf "▯▯@<5>subroutine▯compute_brackets_%04d▯()" n; nl ();
  end;
  List.iter (print_brackets dictionary) processes;
  printf "▯▯end▯subroutine▯compute_brackets_%04d" n; nl () in

let fusions_module (n, _ as fusions) =
  let tag = Printf.sprintf "_fusions_%04d" n in
  { module_name = name ^ tag;
    used_modules = (used_modules () @
      [Full constants_module.module_name;
       Full variables_module.module_name]);
    default_accessibility = Private;
    public_symbols = ["compute" ^ tag];
    print_declarations = [];
    print_implementations = [print_compute_fusions fusions] } in

```

```

let brackets_module (n, _ as processes) =
  let tag = Printf.sprintf "_brackets_%04d" n in
  { module_name = name ^ tag;
    used_modules = (used_modules () @
      [Full constants_module.module_name;
       Full variables_module.module_name]);
    default_accessibility = Private;
    public_symbols = ["compute" ^ tag];
    print_declarations = [];
    print_implementations = [print_compute_brackets processes] } in

let chopped_fusions, chopped_brackets =
  chop_amplitudes size amplitudes in

let fusions_modules =
  List.map fusions_module chopped_fusions in

let brackets_modules =
  List.map brackets_module chopped_brackets in

let print_implementations () =
  print_interface ();
  print_calculate_amplitudes
    (fun () → ())
    (print_compute_chops chopped_fusions chopped_brackets)
    amplitudes in

let public_module =
  { module_name = name;
    used_modules = (used_modules () @
      [Full constants_module.module_name;
       Full variables_module.module_name ] @
      List.map
        (fun m → Full m.module_name)
        (fusions_modules @ brackets_modules));
    default_accessibility = Private;
    public_symbols = public_symbols ();
    print_declarations = [];
    print_implementations = [print_implementations] }
and private_modules =
  [constants_module; variables_module] @ fusions_modules @ brackets_modules in

(public_module, private_modules)

let amplitudes_to_channel_single_file cmdline oc size amplitudes =
  let public_module, private_modules =
    modules_of_amplitudes cmdline oc size amplitudes in
  setup_fortran_formatter !line_length oc;
  print_description cmdline amplitudes ();
  print_modules (private_modules @ [public_module])

let amplitudes_to_channel_multi_file cmdline oc size amplitudes =
  let public_module, private_modules =
    modules_of_amplitudes cmdline oc size amplitudes in

```

```

modules_to_file !line_length oc
  (print_description cmdline amplitudes)
  (public_module :: private_modules)

```

### Dispatch

```

let amplitudes_to_channel cmdline oc diagnostics amplitudes =
  parse_diagnostics diagnostics;
  match !output_mode with
  | Single_Function →
    amplitudes_to_channel_single_function cmdline oc amplitudes
  | Single_Module size →
    amplitudes_to_channel_single_module cmdline oc size amplitudes
  | Single_File size →
    amplitudes_to_channel_single_file cmdline oc size amplitudes
  | Multi_File size →
    amplitudes_to_channel_multi_file cmdline oc size amplitudes

let parameters_to_channel oc =
  parameters_to_fortran oc (CM.parameters ())

end

module Fortran = Make_Fortran(Fortran_Fermions)

```

### Majorana Fermions



*JR sez' (regarding the Majorana Feynman rules):* For this function we need a different approach due to our aim of implementing the fermion vertices with the right line as ingoing (in a calculational sense) and the left line in a fusion as outgoing. In defining all external lines and the fermionic wavefunctions built out of them as ingoing we have to invert the left lines to make them outgoing. This happens by multiplying them with the inverse charge conjugation matrix in an appropriate representation and then transposing it. We must distinguish whether the direction of calculation and the physical direction of the fermion number flow are parallel or antiparallel. In the first case we can use the "normal" Feynman rules for Dirac particles, while in the second, according to the paper of Denner et al., we have to reverse the sign of the vector and antisymmetric bilinears of the Dirac spinors, cf. the *Coupling* module.

Note the subtlety for the left- and righthanded couplings: Only the vector part of these couplings changes in the appropriate cases its sign, changing the chirality to the negative of the opposite. (*JR's probably right, but I need to check myself ...*)

```

module Fortran_Majorana_Fermions : Fermions =
  struct
    let rcs = RCS.rename rcs_file "Targets.Fortran_Majorana_Fermions()"
    [ "generates_Fortran95_code_for_Dirac_and_Majorana_fermions";

```

```

    "using_revision_2003_03_A_of_module_omega95_bispinors" ]

open Coupling
open Format

let psi_type = "bispinor"
let psibar_type = "bispinor"
let chi_type = "bispinor"
let grav_type = "vectorspinor"

```



*JR sez' (regarding the Majorana Feynman rules):* Because of our rules for fermions we are going to give all incoming fermions a  $u$  spinor and all outgoing fermions a  $v$  spinor, no matter whether they are Dirac fermions, antifermions or Majorana fermions. (*JR's probably right, but I need to check myself ...*)

```

let psi_incoming = "u"
let brs_psi_incoming = "brs_u"
let psibar_incoming = "u"
let brs_psibar_incoming = "brs_u"
let chi_incoming = "u"
let brs_chi_incoming = "brs_u"
let grav_incoming = "ueps"

let psi_outgoing = "v"
let brs_psi_outgoing = "brs_v"
let psibar_outgoing = "v"
let brs_psibar_outgoing = "brs_v"
let chi_outgoing = "v"
let brs_chi_outgoing = "brs_v"
let grav_outgoing = "veps"

let psi_propagator = "pr_psi"
let psibar_propagator = "pr_psi"
let chi_propagator = "pr_psi"
let grav_propagator = "pr_grav"

let psi_projector = "pj_psi"
let psibar_projector = "pj_psi"
let chi_projector = "pj_psi"
let grav_projector = "pj_grav"

let psi_gauss = "pg_psi"
let psibar_gauss = "pg_psi"
let chi_gauss = "pg_psi"
let grav_gauss = "pg_grav"

let format_coupling_coeff c =
  match coeff with
  | 1 → c
  | -1 → "(-" ^ c ^ ")"
  | coeff → string_of_int coeff ^ "*" ^ c

let format_coupling_2 coeff c =

```

```

match coeff with
| 1 → c
| -1 → "-" ^ c
| coeff → string_of_int coeff ^ "*" ^ c

```



JR's coupling constant HACK, necessitated by tho's bad design descition.

```

let fastener s i =
  try
    let offset = (String.index s '(') in
    if ((String.get s (String.length s - 1)) ≠ ')') then
      failwith "fastener: wrong usage of parentheses"
    else
      let func_name = (String.sub s 0 offset) and
      tail =
        (String.sub s (succ offset) (String.length s - offset - 2)) in
      if (String.contains func_name '(') ∨
        (String.contains tail '(') ∨
        (String.contains tail ')') then
        failwith "fastener: wrong usage of parentheses"
      else
        func_name ^ "(" ^ string_of_int i ^ ", " ^ tail ^ ")"
  with
  | Not_found →
    if (String.contains s '(') then
      failwith "fastener: wrong usage of parentheses"
    else
      s ^ "(" ^ string_of_int i ^ ")"

let print_fermion_current coeff f c wf1 wf2 fusion =
  let c = format_coupling coeff c in
  match fusion with
  | F13 | F31 → printf "%s_ff(%s,%s,%s)" f c wf1 wf2
  | F23 | F21 → printf "f_%sf(%s,%s,%s)" f c wf1 wf2
  | F32 | F12 → printf "f_%sf(%s,%s,%s)" f c wf2 wf1

let print_fermion_current2 coeff f c wf1 wf2 fusion =
  let c = format_coupling_2 coeff c in
  let c1 = fastener c 1 and
  c2 = fastener c 2 in
  match fusion with
  | F13 | F31 → printf "%s_ff(%s,%s,%s,%s)" f c1 c2 wf1 wf2
  | F23 | F21 → printf "f_%sf(%s,%s,%s,%s)" f c1 c2 wf1 wf2
  | F32 | F12 → printf "f_%sf(%s,%s,%s,%s)" f c1 c2 wf2 wf1

let print_fermion_current_vector coeff f c wf1 wf2 fusion =
  let c = format_coupling coeff c in
  match fusion with
  | F13 → printf "%s_ff(%s,%s,%s)" f c wf1 wf2
  | F31 → printf "%s_ff(-%s,%s,%s)" f c wf1 wf2
  | F23 → printf "f_%sf(%s,%s,%s)" f c wf1 wf2

```

```

| F32 → printf "f_%sf(%s,%s,%s)" f c wf2 wf1
| F12 → printf "f_%sf(-(s),%s,%s,%s)" f c wf2 wf1
| F21 → printf "f_%sf(-(s),%s,%s,%s)" f c wf1 wf2

let print_fermion_current2_vector coeff f c wf1 wf2 fusion =
  let c = format_coupling_2 coeff c in
  let c1 = fastener c 1 and
      c2 = fastener c 2 in
  match fusion with
  | F13 → printf "%s_ff(%s,%s,%s,%s)" f c1 c2 wf1 wf2
  | F31 → printf "%s_ff(-(s),%s,%s,%s)" f c1 c2 wf1 wf2
  | F23 → printf "f_%sf(%s,%s,%s,%s)" f c1 c2 wf1 wf2
  | F32 → printf "f_%sf(%s,%s,%s,%s)" f c1 c2 wf2 wf1
  | F12 → printf "f_%sf(-(s),%s,%s,%s)" f c1 c2 wf2 wf1
  | F21 → printf "f_%sf(-(s),%s,%s,%s)" f c1 c2 wf1 wf2

let print_fermion_current_chiral coeff f1 f2 c wf1 wf2 fusion =
  let c = format_coupling_2 coeff c in
  match fusion with
  | F13 → printf "%s_ff(%s,%s,%s,%s)" f1 c wf1 wf2
  | F31 → printf "%s_ff(-(s),%s,%s,%s)" f2 c wf1 wf2
  | F23 → printf "f_%sf(%s,%s,%s,%s)" f1 c wf1 wf2
  | F32 → printf "f_%sf(%s,%s,%s,%s)" f1 c wf2 wf1
  | F12 → printf "f_%sf(-(s),%s,%s,%s)" f2 c wf2 wf1
  | F21 → printf "f_%sf(-(s),%s,%s,%s)" f2 c wf1 wf2

let print_fermion_current2_chiral coeff f c wf1 wf2 fusion =
  let c = format_coupling_2 coeff c in
  let c1 = fastener c 1 and
      c2 = fastener c 2 in
  match fusion with
  | F13 → printf "%s_ff(%s,%s,%s,%s)" f c1 c2 wf1 wf2
  | F31 → printf "%s_ff(-(s),-(s),%s,%s)" f c2 c1 wf1 wf2
  | F23 → printf "f_%sf(%s,%s,%s,%s)" f c1 c2 wf1 wf2
  | F32 → printf "f_%sf(%s,%s,%s,%s)" f c1 c2 wf2 wf1
  | F12 → printf "f_%sf(-(s),-(s),%s,%s)" f c2 c1 wf2 wf1
  | F21 → printf "f_%sf(-(s),-(s),%s,%s)" f c2 c1 wf1 wf2

let print_current = function
| coeff, -, VA, - → print_fermion_current2_vector coeff "va"
| coeff, -, V, - → print_fermion_current_vector coeff "v"
| coeff, -, A, - → print_fermion_current coeff "a"
| coeff, -, VL, - → print_fermion_current_chiral coeff "vl" "vr"
| coeff, -, VR, - → print_fermion_current_chiral coeff "vr" "vl"
| coeff, -, VLR, - → print_fermion_current2_chiral coeff "vlr"
| coeff, -, SP, - → print_fermion_current2 coeff "sp"
| coeff, -, S, - → print_fermion_current coeff "s"
| coeff, -, P, - → print_fermion_current coeff "p"
| coeff, -, SL, - → print_fermion_current coeff "sl"
| coeff, -, SR, - → print_fermion_current coeff "sr"
| coeff, -, SLR, - → print_fermion_current2 coeff "slr"
| coeff, -, POT, - → print_fermion_current_vector coeff "pot"

```

```

| -, -, -, - → invalid_arg
| "Targets.Fortran-Majorana-Fermions:_Not_needed_in_the_models"

let print_current_p = function
| coeff, Psi, SL, Psi → print_fermion_current coeff "sl"
| coeff, Psi, SR, Psi → print_fermion_current coeff "sr"
| coeff, Psi, SLR, Psi → print_fermion_current2 coeff "slr"
| -, -, -, - → invalid_arg
| "Targets.Fortran-Majorana-Fermions:_Not_needed_in_the_used_models"

let print_current_b = function
| coeff, Psibar, SL, Psibar → print_fermion_current coeff "sl"
| coeff, Psibar, SR, Psibar → print_fermion_current coeff "sr"
| coeff, Psibar, SLR, Psibar → print_fermion_current2 coeff "slr"
| -, -, -, - → invalid_arg
| "Targets.Fortran-Majorana-Fermions:_Not_needed_in_the_used_models"

```

This function is for the vertices with three particles including two fermions but also a momentum, therefore with a dimensionful coupling constant, e.g. the gravitino vertices. One has to distinguish between the two kinds of canonical orders in the string of gamma matrices. Of course, the direction of the string of gamma matrices is reversed if one goes from the *Gravbar*,  $-$ , *Psi* to the *Psibar*,  $-$ , *Grav* vertices, and the same is true for the couplings of the gravitino to the Majorana fermions. For more details see the tables in the *coupling* implementation.

We now have to fix the directions of the momenta. For making the compiler happy and because we don't want to make constructions of infinite complexity we list the momentum including vertices without gravitinos here; the pattern matching says that's better. Perhaps we have to find a better name now.

For the cases of *MOM*, *MOM5*, *MOML* and *MOMR* which arise only in BRST transformations we take the mass as a coupling constant. For *VMOM* we don't need a mass either. These vertices are like kinetic terms and so need not have a coupling constant. By this we avoid a strange and awful construction with a new variable. But be careful with a generalization if you want to use these vertices for other purposes.

```

let format_coupling_mom coeff c =
  match coeff with
  | 1 → c
  | -1 → "(-" ^ c ^ ")"
  | coeff → string_of_int coeff ^ "*" ^ c

let commute_proj f =
  match f with
  | "moml" → "lmom"
  | "momr" → "rmom"
  | "lmom" → "moml"
  | "rmom" → "momr"
  | "svl" → "svr"
  | "svr" → "svl"
  | "sl" → "sr"
  | "sr" → "sl"
  | "s" → "s"

```

```

| "p" → "p"
| - → invalid_arg "Targets:Fortran-Majorana-Fermions: wrong case"

let print_fermion_current_mom coeff f c wf1 wf2 p1 p2 p12 fusion =
  let c = format_coupling_mom coeff c in
  let c1 = fastener c 1 and
      c2 = fastener c 2 in
  match fusion with
  | F13 → printf "%s_ff(%s,%s,%s,%s,%s)" f c1 c2 wf1 wf2 p12
  | F31 → printf "%s_ff(%s,%s,%s,%s,%s)" f c1 c2 wf1 wf2 p12
  | F23 → printf "f_%sf(%s,%s,%s,%s,%s)" f c1 c2 wf1 wf2 p1
  | F32 → printf "f_%sf(%s,%s,%s,%s,%s)" f c1 c2 wf2 wf1 p2
  | F12 → printf "f_%sf(%s,%s,%s,%s,%s)" f c1 c2 wf2 wf1 p2
  | F21 → printf "f_%sf(%s,%s,%s,%s,%s)" f c1 c2 wf1 wf2 p1

let print_fermion_current_mom_sign coeff f c wf1 wf2 p1 p2 p12 fusion =
  let c = format_coupling_mom coeff c in
  let c1 = fastener c 1 and
      c2 = fastener c 2 in
  match fusion with
  | F13 → printf "%s_ff(%s,%s,%s,%s,%s)" f c1 c2 wf1 wf2 p12
  | F31 → printf "%s_ff(%s,%s,%s,%s,-(%s))" f c1 c2 wf1 wf2 p12
  | F23 → printf "f_%sf(%s,%s,%s,%s,%s)" f c1 c2 wf1 wf2 p1
  | F32 → printf "f_%sf(%s,%s,%s,%s,%s)" f c1 c2 wf2 wf1 p2
  | F12 → printf "f_%sf(%s,%s,%s,%s,-(%s))" f c1 c2 wf2 wf1 p2
  | F21 → printf "f_%sf(%s,%s,%s,%s,-(%s))" f c1 c2 wf1 wf2 p1

let print_fermion_current_mom_sign_1 coeff f c wf1 wf2 p1 p2 p12 fusion =
  let c = format_coupling coeff c in
  match fusion with
  | F13 → printf "%s_ff(%s,%s,%s,%s)" f c wf1 wf2 p12
  | F31 → printf "%s_ff(%s,%s,%s,-(%s))" f c wf1 wf2 p12
  | F23 → printf "f_%sf(%s,%s,%s,%s)" f c wf1 wf2 p1
  | F32 → printf "f_%sf(%s,%s,%s,%s)" f c wf2 wf1 p2
  | F12 → printf "f_%sf(%s,%s,%s,-(%s))" f c wf2 wf1 p2
  | F21 → printf "f_%sf(%s,%s,%s,-(%s))" f c wf1 wf2 p1

let print_fermion_current_mom_chiral coeff f c wf1 wf2 p1 p2 p12 fusion =
  let c = format_coupling_mom coeff c and
      cf = commute_proj f in
  let c1 = fastener c 1 and
      c2 = fastener c 2 in
  match fusion with
  | F13 → printf "%s_ff(%s,%s,%s,%s,%s)" f c1 c2 wf1 wf2 p12
  | F31 → printf "%s_ff(%s,%s,%s,%s,-(%s))" cf c1 c2 wf1 wf2 p12
  | F23 → printf "f_%sf(%s,%s,%s,%s,%s)" f c1 c2 wf1 wf2 p1
  | F32 → printf "f_%sf(%s,%s,%s,%s,%s)" f c1 c2 wf2 wf1 p2
  | F12 → printf "f_%sf(%s,%s,%s,%s,-(%s))" cf c1 c2 wf2 wf1 p2
  | F21 → printf "f_%sf(%s,%s,%s,%s,-(%s))" cf c1 c2 wf1 wf2 p1

let print_fermion_g_current coeff f c wf1 wf2 p1 p2 p12 fusion =
  let c = format_coupling coeff c in
  match fusion with

```



```

| F13 → printf "%s_grf(%s,%s,%s,%s)" f c wf1 wf2 p12
| F31 → printf "%s_fgr(%s,%s,%s,%s)" f c wf1 wf2 p12
| F23 → printf "gr_%sf(%s,%s,%s,%s)" f c wf1 wf2 p1
| F32 → printf "gr_%sf(%s,%s,%s,%s)" f c wf2 wf1 p2
| F12 → printf "f_%sgr(%s,%s,%s,%s)" f c wf2 wf1 p2
| F21 → printf "f_%sgr(%s,%s,%s,%s)" f c wf1 wf2 p1

let print_fermion_g_2_current coeff f c wf1 wf2 p1 p2 p12 fusion =
  let c = format_coupling coeff c in
  match fusion with
  | F13 → printf "%s_grf(%s(1),%s(2),%s,%s,%s)" f c c wf1 wf2 p12
  | F31 → printf "%s_fgr(%s(1),%s(2),%s,%s,%s)" f c c wf1 wf2 p12
  | F23 → printf "gr_%sf(%s(1),%s(2),%s,%s,%s)" f c c wf1 wf2 p1
  | F32 → printf "gr_%sf(%s(1),%s(2),%s,%s,%s)" f c c wf2 wf1 p2
  | F12 → printf "f_%sgr(%s(1),%s(2),%s,%s,%s)" f c c wf2 wf1 p2
  | F21 → printf "f_%sgr(%s(1),%s(2),%s,%s,%s)" f c c wf1 wf2 p1

let print_fermion_g_current_rev coeff f c wf1 wf2 p1 p2 p12 fusion =
  let c = format_coupling coeff c in
  match fusion with
  | F13 → printf "%s_fgr(%s,%s,%s,%s)" f c wf1 wf2 p12
  | F31 → printf "%s_grf(%s,%s,%s,%s)" f c wf1 wf2 p12
  | F23 → printf "f_%sgr(%s,%s,%s,%s)" f c wf1 wf2 p1
  | F32 → printf "f_%sgr(%s,%s,%s,%s)" f c wf2 wf1 p2
  | F12 → printf "gr_%sf(%s,%s,%s,%s)" f c wf2 wf1 p2
  | F21 → printf "gr_%sf(%s,%s,%s,%s)" f c wf1 wf2 p1

let print_fermion_g_2_current_rev coeff f c wf1 wf2 p1 p2 p12 fusion =
  let c = format_coupling coeff c in
  match fusion with
  | F13 → printf "%s_fgr(%s(1),%s(2),%s,%s,%s)" f c c wf1 wf2 p12
  | F31 → printf "%s_grf(%s(1),%s(2),%s,%s,%s)" f c c wf1 wf2 p12
  | F23 → printf "f_%sgr(%s(1),%s(2),%s,%s,%s)" f c c wf1 wf2 p1
  | F32 → printf "f_%sgr(%s(1),%s(2),%s,%s,%s)" f c c wf2 wf1 p2
  | F12 → printf "gr_%sf(%s(1),%s(2),%s,%s,%s)" f c c wf2 wf1 p2
  | F21 → printf "gr_%sf(%s(1),%s(2),%s,%s,%s)" f c c wf1 wf2 p1

let print_fermion_g_current_vector coeff f c wf1 wf2 - - fusion =
  let c = format_coupling coeff c in
  match fusion with
  | F13 → printf "%s_grf(%s,%s,%s)" f c wf1 wf2
  | F31 → printf "%s_fgr(-%s,%s,%s)" f c wf1 wf2
  | F23 → printf "gr_%sf(%s,%s,%s)" f c wf1 wf2
  | F32 → printf "gr_%sf(%s,%s,%s)" f c wf2 wf1
  | F12 → printf "f_%sgr(-%s,%s,%s)" f c wf2 wf1
  | F21 → printf "f_%sgr(-%s,%s,%s)" f c wf1 wf2

let print_fermion_g_current_vector_rev coeff f c wf1 wf2 - - fusion =
  let c = format_coupling coeff c in
  match fusion with
  | F13 → printf "%s_fgr(%s,%s,%s)" f c wf1 wf2
  | F31 → printf "%s_grf(-%s,%s,%s)" f c wf1 wf2
  | F23 → printf "f_%sgr(%s,%s,%s)" f c wf1 wf2

```

```

| F32 → printf "f-%sgr(%s,%s,%s)" f c wf2 wf1
| F12 → printf "gr-%sf(-%s,%s,%s)" f c wf2 wf1
| F21 → printf "gr-%sf(-%s,%s,%s)" f c wf1 wf2

let print_current_g = function
| coeff, -, MOM, - → print_fermion_current_mom_sign coeff "mom"
| coeff, -, MOM5, - → print_fermion_current_mom coeff "mom5"
| coeff, -, MOML, - → print_fermion_current_mom_chiral coeff "moml"
| coeff, -, MOMR, - → print_fermion_current_mom_chiral coeff "momr"
| coeff, -, LMOM, - → print_fermion_current_mom_chiral coeff "lmom"
| coeff, -, RMOM, - → print_fermion_current_mom_chiral coeff "rmom"
| coeff, -, VMOM, - → print_fermion_current_mom_sign_1 coeff "vmom"
| coeff, Gravbar, S, - → print_fermion_g_current coeff "s"
| coeff, Gravbar, SL, - → print_fermion_g_current coeff "sl"
| coeff, Gravbar, SR, - → print_fermion_g_current coeff "sr"
| coeff, Gravbar, SLR, - → print_fermion_g_2_current coeff "slr"
| coeff, Gravbar, P, - → print_fermion_g_current coeff "p"
| coeff, Gravbar, V, - → print_fermion_g_current coeff "v"
| coeff, Gravbar, VLR, - → print_fermion_g_2_current coeff "vlr"
| coeff, Gravbar, POT, - → print_fermion_g_current_vector coeff "pot"
| coeff, -, S, Grav → print_fermion_g_current_rev coeff "s"
| coeff, -, SL, Grav → print_fermion_g_current_rev coeff "sl"
| coeff, -, SR, Grav → print_fermion_g_current_rev coeff "sr"
| coeff, -, SLR, Grav → print_fermion_g_2_current_rev coeff "slr"
| coeff, -, P, Grav → print_fermion_g_current_rev (-coeff) "p"
| coeff, -, V, Grav → print_fermion_g_current_rev coeff "v"
| coeff, -, VLR, Grav → print_fermion_g_2_current_rev coeff "vlr"
| coeff, -, POT, Grav → print_fermion_g_current_vector_rev coeff "pot"
| -, -, -, - → invalid_arg
    "Targets.Fortran-Majorana-Fermions: not used in the models"

let print_current_mom = function
| -, -, -, - → invalid_arg
    "Targets.Fortran-Majorana-Fermions: Not needed in the models"

```

We need support for dimension-5 vertices with two fermions and two bosons, appearing in theories of supergravity and also together with in insertions of the supersymmetric current. There is a canonical order *fermionbar*, *boson\_1*, *boson\_2*, *fermion*, so what one has to do is a mapping from the fusions *F123* etc. to the order of the three wave functions *wf1*, *wf2* and *wf3*.

The function *d\_p* (for distinct the particle) distinguishes which particle (scalar or vector) must be fused to in the special functions.

```

let d_p = function
| 1, ("sv" | "pv" | "svl" | "svr" | "slrv") → "1"
| 1, - → ""
| 2, ("sv" | "pv" | "svl" | "svr" | "slrv") → "2"
| 2, - → ""
| -, - → invalid_arg "Targets.Fortran-Majorana-Fermions: not used"

let wf_of_f wf1 wf2 wf3 f =
  match f with
  | (F123 | F423) → [wf2; wf3; wf1]

```

```

| (F213 | F243 | F143 | F142 | F413 | F412) → [wf1; wf3; wf2]
| (F132 | F432) → [wf3; wf2; wf1]
| (F231 | F234 | F134 | F124 | F431 | F421) → [wf1; wf2; wf3]
| (F312 | F342) → [wf3; wf1; wf2]
| (F321 | F324 | F314 | F214 | F341 | F241) → [wf2; wf1; wf3]
let print_fermion_g4_brs_vector_current coeff f c wf1 wf2 wf3 fusion =
  let cf = commute_proj f and
    cp = format_coupling coeff c and
    cm = if f = "pv" then
      format_coupling coeff c
    else
      format_coupling (-coeff) c
  and
    d1 = d_p (1, f) and
    d2 = d_p (2, f) and
    f1 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 0) and
    f2 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 1) and
    f3 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 2) in
  match fusion with
  | (F123 | F213 | F132 | F231 | F312 | F321) →
    printf "f_%sf(%s,%s,%s,%s)" cf cm f1 f2 f3
  | (F423 | F243 | F432 | F234 | F342 | F324) →
    printf "f_%sf(%s,%s,%s,%s)" f cp f1 f2 f3
  | (F134 | F143 | F314) → printf "%s%s_ff(%s,%s,%s,%s)" f d1 cp f1 f2 f3
  | (F124 | F142 | F214) → printf "%s%s_ff(%s,%s,%s,%s)" f d2 cp f1 f2 f3
  | (F413 | F431 | F341) → printf "%s%s_ff(%s,%s,%s,%s)" cf d1 cm f1 f2 f3
  | (F241 | F412 | F421) → printf "%s%s_ff(%s,%s,%s,%s)" cf d2 cm f1 f2 f3
let print_fermion_g4_svlr_current coeff c wf1 wf2 wf3 fusion =
  let c = format_coupling_2 coeff c and
    f1 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 0) and
    f2 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 1) and
    f3 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 2) in
  let c1 = fastener c 1 and
    c2 = fastener c 2 in
  match fusion with
  | (F123 | F213 | F132 | F231 | F312 | F321) →
    printf "f_svlrf(-(s),-(s),%s,%s,%s)" c2 c1 f1 f2 f3
  | (F423 | F243 | F432 | F234 | F342 | F324) →
    printf "f_svlrf(%s,%s,%s,%s,%s)" c1 c2 f1 f2 f3
  | (F134 | F143 | F314) →
    printf "svlr2_ff(%s,%s,%s,%s,%s)" c1 c2 f1 f2 f3
  | (F124 | F142 | F214) →
    printf "svlr1_ff(%s,%s,%s,%s,%s)" c1 c2 f1 f2 f3
  | (F413 | F431 | F341) →
    printf "svlr2_ff(-(s),-(s),%s,%s,%s)" c2 c1 f1 f2 f3
  | (F241 | F412 | F421) →
    printf "svlr1_ff(-(s),-(s),%s,%s,%s)" c2 c1 f1 f2 f3
let print_fermion_s2_current coeff f c wf1 wf2 wf3 fusion =
  let cp = format_coupling coeff c and

```

```

    cm = if f = "p" then
      format_coupling (-coeff) c
    else
      format_coupling coeff c
  and
    cf = commute_proj f and
    f1 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 0) and
    f2 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 1) and
    f3 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 2) in
  match fusion with
  | (F123 | F213 | F132 | F231 | F312 | F321) →
    printf "%s*%f-%sf(%s,%s,%s)" f1 cf cm f2 f3
  | (F423 | F243 | F432 | F234 | F342 | F324) →
    printf "%s*%f-%sf(%s,%s,%s)" f1 f cp f2 f3
  | (F134 | F143 | F314) →
    printf "%s*%s-ff(%s,%s,%s)" f2 f cp f1 f3
  | (F124 | F142 | F214) →
    printf "%s*%s-ff(%s,%s,%s)" f2 f cp f1 f3
  | (F413 | F431 | F341) →
    printf "%s*%s-ff(%s,%s,%s)" f2 cf cm f1 f3
  | (F241 | F412 | F421) →
    printf "%s*%s-ff(%s,%s,%s)" f2 cf cm f1 f3
let print_fermion_s2p_current coeff f c wf1 wf2 wf3 fusion =
  let c = format_coupling_2 coeff c and
    f1 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 0) and
    f2 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 1) and
    f3 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 2) in
  let c1 = fastener c 1 and
    c2 = fastener c 2 in
  match fusion with
  | (F123 | F213 | F132 | F231 | F312 | F321) →
    printf "%s*%f-%sf(%s,-(%s),%s,%s)" f1 f c1 c2 f2 f3
  | (F423 | F243 | F432 | F234 | F342 | F324) →
    printf "%s*%f-%sf(%s,%s,%s,%s)" f1 f c1 c2 f2 f3
  | (F134 | F143 | F314) →
    printf "%s*%s-ff(%s,%s,%s,%s)" f2 f c1 c2 f1 f3
  | (F124 | F142 | F214) →
    printf "%s*%s-ff(%s,%s,%s,%s)" f2 f c1 c2 f1 f3
  | (F413 | F431 | F341) →
    printf "%s*%s-ff(%s,-(%s),%s,%s)" f2 f c1 c2 f1 f3
  | (F241 | F412 | F421) →
    printf "%s*%s-ff(%s,-(%s),%s,%s)" f2 f c1 c2 f1 f3
let print_fermion_s2lr_current coeff f c wf1 wf2 wf3 fusion =
  let c = format_coupling_2 coeff c and
    f1 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 0) and
    f2 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 1) and
    f3 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 2) in
  let c1 = fastener c 1 and
    c2 = fastener c 2 in

```

```

match fusion with
| (F123 | F213 | F132 | F231 | F312 | F321) →
  printf "%s*f-%sf(%s,%s,%s,%s)" f1 f c2 c1 f2 f3
| (F423 | F243 | F432 | F234 | F342 | F324) →
  printf "%s*f-%sf(%s,%s,%s,%s)" f1 f c1 c2 f2 f3
| (F134 | F143 | F314) →
  printf "%s*s-%s-ff(%s,%s,%s,%s)" f2 f c1 c2 f1 f3
| (F124 | F142 | F214) →
  printf "%s*s-%s-ff(%s,%s,%s,%s)" f2 f c1 c2 f1 f3
| (F413 | F431 | F341) →
  printf "%s*s-%s-ff(%s,%s,%s,%s)" f2 f c2 c1 f1 f3
| (F241 | F412 | F421) →
  printf "%s*s-%s-ff(%s,%s,%s,%s)" f2 f c2 c1 f1 f3
let print_fermion_g4_current coeff f c wf1 wf2 wf3 fusion =
  let c = format_coupling coeff c and
    f1 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 0) and
    f2 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 1) and
    f3 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 2) in
  match fusion with
  | (F123 | F213 | F132 | F231 | F312 | F321) →
    printf "f-%sgr(-%s,%s,%s,%s)" f c f1 f2 f3
  | (F423 | F243 | F432 | F234 | F342 | F324) →
    printf "gr-%sf(%s,%s,%s,%s)" f c f1 f2 f3
  | (F134 | F143 | F314 | F124 | F142 | F214) →
    printf "%s-grf(%s,%s,%s,%s)" f c f1 f2 f3
  | (F413 | F431 | F341 | F241 | F412 | F421) →
    printf "%s-fgr(-%s,%s,%s,%s)" f c f1 f2 f3
let print_fermion_2_g4_current coeff f c wf1 wf2 wf3 fusion =
  let f1 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 0) and
    f2 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 1) and
    f3 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 2) in
  let c = format_coupling_2 coeff c in
  let c1 = fastener c 1 and
    c2 = fastener c 2 in
  match fusion with
  | (F123 | F213 | F132 | F231 | F312 | F321) →
    printf "f-%sgr(-(s),-(s),%s,%s,%s)" f c2 c1 f1 f2 f3
  | (F423 | F243 | F432 | F234 | F342 | F324) →
    printf "gr-%sf(%s,%s,%s,%s,%s)" f c1 c2 f1 f2 f3
  | (F134 | F143 | F314 | F124 | F142 | F214) →
    printf "%s-grf(%s,%s,%s,%s,%s)" f c1 c2 f1 f2 f3
  | (F413 | F431 | F341 | F241 | F412 | F421) →
    printf "%s-fgr(-(s),-(s),%s,%s,%s)" f c2 c1 f1 f2 f3
let print_fermion_g4_current_rev coeff f c wf1 wf2 wf3 fusion =
  let c = format_coupling coeff c and
    f1 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 0) and
    f2 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 1) and
    f3 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 2) in
  match fusion with

```

```

| (F123 | F213 | F132 | F231 | F312 | F321) →
  printf "f-%sgr(%s,%s,%s,%s)" f c f1 f2 f3
| (F423 | F243 | F432 | F234 | F342 | F324) →
  printf "gr-%sf(-%s,%s,%s,%s)" f c f1 f2 f3
| (F134 | F143 | F314 | F124 | F142 | F214) →
  printf "%s-grf(-%s,%s,%s,%s)" f c f1 f2 f3
| (F413 | F431 | F341 | F241 | F412 | F421) →
  printf "%s-fgr(%s,%s,%s,%s)" f c f1 f2 f3

```

Here we have to distinguish which of the two bosons is produced in the fusion of three particles which include both fermions.

```

let print_fermion_g4_vector_current coeff f c wf1 wf2 wf3 fusion =
  let c = format_coupling coeff c and
    d1 = d_p (1,f) and
    d2 = d_p (2,f) and
    f1 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 0) and
    f2 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 1) and
    f3 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 2) in
  match fusion with
  | (F123 | F213 | F132 | F231 | F312 | F321) →
    printf "f-%sgr(%s,%s,%s,%s)" f c f1 f2 f3
  | (F423 | F243 | F432 | F234 | F342 | F324) →
    printf "gr-%sf(%s,%s,%s,%s)" f c f1 f2 f3
  | (F134 | F143 | F314) → printf "%s%s-grf(%s,%s,%s,%s)" f d1 c f1 f2 f3
  | (F124 | F142 | F214) → printf "%s%s-grf(%s,%s,%s,%s)" f d2 c f1 f2 f3
  | (F413 | F431 | F341) → printf "%s%s-fgr(%s,%s,%s,%s)" f d1 c f1 f2 f3
  | (F241 | F412 | F421) → printf "%s%s-fgr(%s,%s,%s,%s)" f d2 c f1 f2 f3

let print_fermion_2_g4_vector_current coeff f c wf1 wf2 wf3 fusion =
  let d1 = d_p (1,f) and
    d2 = d_p (2,f) and
    f1 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 0) and
    f2 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 1) and
    f3 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 2) in
  let c = format_coupling_2 coeff c in
  let c1 = fastener c 1 and
    c2 = fastener c 2 in
  match fusion with
  | (F123 | F213 | F132 | F231 | F312 | F321) →
    printf "f-%sgr(%s,%s,%s,%s,%s,%s)" f c1 c2 f1 f2 f3
  | (F423 | F243 | F432 | F234 | F342 | F324) →
    printf "gr-%sf(%s,%s,%s,%s,%s,%s)" f c1 c2 f1 f2 f3
  | (F134 | F143 | F314) → printf "%s%s-grf(%s,%s,%s,%s,%s,%s)" f d1 c1 c2 f1 f2 f3
  | (F124 | F142 | F214) → printf "%s%s-grf(%s,%s,%s,%s,%s,%s)" f d2 c1 c2 f1 f2 f3
  | (F413 | F431 | F341) → printf "%s%s-fgr(%s,%s,%s,%s,%s,%s)" f d1 c1 c2 f1 f2 f3
  | (F241 | F412 | F421) → printf "%s%s-fgr(%s,%s,%s,%s,%s,%s)" f d2 c1 c2 f1 f2 f3

let print_fermion_g4_vector_current_rev coeff f c wf1 wf2 wf3 fusion =
  let c = format_coupling coeff c and
    d1 = d_p (1,f) and
    d2 = d_p (2,f) and

```

```

    f1 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 0) and
    f2 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 1) and
    f3 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 2) in
  match fusion with
  | (F123 | F213 | F132 | F231 | F312 | F321) →
    printf "gr-%sf(%s,%s,%s,%s)" f c f1 f2 f3
  | (F423 | F243 | F432 | F234 | F342 | F324) →
    printf "f-%sgr(%s,%s,%s,%s)" f c f1 f2 f3
  | (F134 | F143 | F314) → printf "%s%s_fgr(%s,%s,%s,%s)" f d1 c f1 f2 f3
  | (F124 | F142 | F214) → printf "%s%s_fgr(%s,%s,%s,%s)" f d2 c f1 f2 f3
  | (F413 | F431 | F341) → printf "%s%s_grf(%s,%s,%s,%s)" f d1 c f1 f2 f3
  | (F241 | F412 | F421) → printf "%s%s_grf(%s,%s,%s,%s)" f d2 c f1 f2 f3

let print_fermion_2_g4_current_rev coeff f c wf1 wf2 wf3 fusion =
  let c = format_coupling_2 coeff c in
  let c1 = fastener c 1 and
    c2 = fastener c 2 and
    d1 = d_p (1, f) and
    d2 = d_p (2, f) in
  let f1 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 0) and
    f2 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 1) and
    f3 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 2) in
  match fusion with
  | (F123 | F213 | F132 | F231 | F312 | F321) →
    printf "gr-%sf(%s,%s,%s,%s,%s)" f c1 c2 f1 f2 f3
  | (F423 | F243 | F432 | F234 | F342 | F324) →
    printf "f-%sgr(-(s),-(s),%s,%s,%s)" f c1 c2 f1 f2 f3
  | (F134 | F143 | F314) →
    printf "%s%s_fgr(-(s),-(s),%s,%s,%s)" f d1 c1 c2 f1 f2 f3
  | (F124 | F142 | F214) →
    printf "%s%s_fgr(-(s),-(s),%s,%s,%s)" f d2 c1 c2 f1 f2 f3
  | (F413 | F431 | F341) →
    printf "%s%s_grf(%s,%s,%s,%s,%s)" f d1 c1 c2 f1 f2 f3
  | (F241 | F412 | F421) →
    printf "%s%s_grf(%s,%s,%s,%s,%s)" f d2 c1 c2 f1 f2 f3

let print_fermion_2_g4_vector_current_rev coeff f c wf1 wf2 wf3 fusion =
  (* Here we put in the extra minus sign from the coeff. *)
  let c = format_coupling coeff c in
  let c1 = fastener c 1 and
    c2 = fastener c 2 in
  let d1 = d_p (1, f) and
    d2 = d_p (2, f) and
    f1 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 0) and
    f2 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 1) and
    f3 = (List.nth (wf_of_f wf1 wf2 wf3 fusion) 2) in
  match fusion with
  | (F123 | F213 | F132 | F231 | F312 | F321) →
    printf "gr-%sf(%s,%s,%s,%s,%s)" f c1 c2 f1 f2 f3
  | (F423 | F243 | F432 | F234 | F342 | F324) →
    printf "f-%sgr(%s,%s,%s,%s,%s)" f c1 c2 f1 f2 f3

```

```

| (F134 | F143 | F314) → printf "%s%s_fgr(%s,%s,%s,%s,%s)" f d1 c1 c2 f1 f2 f3
| (F124 | F142 | F214) → printf "%s%s_fgr(%s,%s,%s,%s,%s)" f d2 c1 c2 f1 f2 f3
| (F413 | F431 | F341) → printf "%s%s_grf(%s,%s,%s,%s,%s)" f d1 c1 c2 f1 f2 f3
| (F241 | F412 | F421) → printf "%s%s_grf(%s,%s,%s,%s,%s)" f d2 c1 c2 f1 f2 f3

let print_current_g4 = function
| coeff, Gravbar, S2, - → print_fermion_g4_current coeff "s2"
| coeff, Gravbar, SV, - → print_fermion_g4_vector_current coeff "sv"
| coeff, Gravbar, SLV, - → print_fermion_g4_vector_current coeff "slv"
| coeff, Gravbar, SRV, - → print_fermion_g4_vector_current coeff "srv"
| coeff, Gravbar, SLRV, - → print_fermion_2_g4_vector_current coeff "slrv"
| coeff, Gravbar, PV, - → print_fermion_g4_vector_current coeff "pv"
| coeff, Gravbar, V2, - → print_fermion_g4_current coeff "v2"
| coeff, Gravbar, V2LR, - → print_fermion_2_g4_current coeff "v2lr"
| -, Gravbar, -, - → invalid_arg "print_current_g4: not implemented"
| coeff, -, S2, Grav → print_fermion_g4_current_rev coeff "s2"
| coeff, -, SV, Grav → print_fermion_g4_vector_current_rev (-coeff) "sv"
| coeff, -, SLV, Grav → print_fermion_g4_vector_current_rev (-coeff) "slv"
| coeff, -, SRV, Grav → print_fermion_g4_vector_current_rev (-coeff) "srv"
| coeff, -, SLRV, Grav → print_fermion_2_g4_vector_current_rev coeff "slrv"
| coeff, -, PV, Grav → print_fermion_g4_vector_current_rev coeff "pv"
| coeff, -, V2, Grav → print_fermion_g4_vector_current_rev coeff "v2"
| coeff, -, V2LR, Grav → print_fermion_2_g4_current_rev coeff "v2lr"
| -, -, -, Grav → invalid_arg "print_current_g4: not implemented"
| coeff, -, S2, - → print_fermion_s2_current coeff "s"
| coeff, -, P2, - → print_fermion_s2_current coeff "p"
| coeff, -, S2P, - → print_fermion_s2p_current coeff "sp"
| coeff, -, S2L, - → print_fermion_s2_current coeff "sl"
| coeff, -, S2R, - → print_fermion_s2_current coeff "sr"
| coeff, -, S2LR, - → print_fermion_s2lr_current coeff "slr"
| coeff, -, V2, - → print_fermion_g4_brs_vector_current coeff "v2"
| coeff, -, SV, - → print_fermion_g4_brs_vector_current coeff "sv"
| coeff, -, PV, - → print_fermion_g4_brs_vector_current coeff "pv"
| coeff, -, SLV, - → print_fermion_g4_brs_vector_current coeff "svl"
| coeff, -, SRV, - → print_fermion_g4_brs_vector_current coeff "svr"
| coeff, -, SLRV, - → print_fermion_g4_svlr_current coeff "svlr"
| -, -, V2LR, - → invalid_arg "Targets.print_current: not available"

let reverse_braket _ = false

let use_module = "omega95_bispinors"
let require_library =
["omega_bispinors_2010_01_A"; "omega_bispinor_cpls_2010_01_A"]
end

module Fortran_Majorana = Make_Fortran(Fortran_Majorana_Fermions)

FORTRAN 77

module Fortran77 = Dummy

```



### 15.2.3 C

```
module C = Dummy
```

### C++

```
module Cpp = Dummy
```

### Java

```
module Java = Dummy
```

### 15.2.4 O'Caml

```
module Ocaml = Dummy
```

### 15.2.5 L<sup>A</sup>T<sub>E</sub>X

```
module LaTeX = Dummy
```

## 15.3 Interface of *Targets\_Kmatrix*

```
module Fortran : sig val print : bool → unit end
```

## 15.4 Implementation of *Targets\_Kmatrix*

```
let rcs_file = RCS.parse "Targets_Kmatrix" ["K-Matrix_Support_routines"]
  { RCS.revision = "$Revision: 5697$";
    RCS.date = "$Date: 2014-04-17 13:01:21 +0200 (Thu, 17 Apr 2014)$";
    RCS.author = "$Author: msekulla$";
    RCS.source
      = "$URL: svn+ssh://jr-reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/s";
  }
module Fortran =
  struct
    open Format
    let nl = print_newline
```

Special functions for the K matrix approach. This might be generalized to other functions that have to have access to the parameters and coupling constants. At the moment, this is hardcoded.

```
let print_pure_functions =
  let pure =
    if pure_functions then
```

```

    "pure_"
    else
        "" in
        printf "%%!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!"; nl ();
        printf "%%!!_Special_K_matrix_functions"; nl ();
        printf "%%!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!"; nl ();
        nl();
        printf "%%_sfunction_width_res_(z,res,w_wkm,m,g)_result_(w)" pure; nl ();
        printf "%%_real(kind=default),_intent(in)_::_z,_w_wkm,_m,_g"; nl ();
        printf "%%_integer,_intent(in)_::_res"; nl ();
        printf "%%_real(kind=default)_::_w"; nl ();
        printf "%%_if_(z.eq.0_.AND._w_wkm.eq.0_)_then"; nl ();
        printf "%%_w_wkm=0"; nl ();
        printf "%%_else"; nl ();
        printf "%%_if_(w_wkm.eq.0)_then"; nl ();
        printf "%%_select_case_(res)"; nl ();
        printf "%%_case_(1)%%!!_Scalar_isosinglet"; nl ();
        printf "%%_w_wkm=3.*g**2/32./Pi*_m**3/vev**2"; nl ();
        printf "%%_case_(2)%%!!_Scalar_isoquintet"; nl ();
        printf "%%_w_wkm=g**2/64./Pi*_m**3/vev**2"; nl ();
        printf "%%_case_(3)%%!!_Vector_isotriplet"; nl ();
        printf "%%_w_wkm=g**2/48./Pi*_m"; nl ();
        printf "%%_case_(4)%%!!_Tensor_isosinglet"; nl ();
        printf "%%_w_wkm=g**2/320./Pi*_m**3/vev**2"; nl ();
        printf "%%_case_(5)%%!!_Tensor_isoquintet"; nl ();
        printf "%%_w_wkm=g**2/1920./Pi*_m**3/vev**2"; nl ();
        printf "%%_case_default"; nl ();
        printf "%%_w_wkm=0"; nl ();
        printf "%%_end_select"; nl ();
        printf "%%_else"; nl ();
        printf "%%_w_wkm=w_wkm"; nl ();
        printf "%%_end_if"; nl ();
        printf "%%_end_if"; nl ();
        printf "%%_end_function_width_res"; nl ();
        nl ();
        printf "%%_sfunction_s0stu_(s,m)_result_(s0)" pure; nl ();
        printf "%%_real(kind=default),_intent(in)_::_s,_m"; nl ();
        printf "%%_real(kind=default)_::_s0"; nl ();
        printf "%%_if_(m.ge.1.0e08)_then"; nl ();
        printf "%%_s0=0"; nl ();
        printf "%%_else"; nl ();
        printf "%%_s0=m**2*_s/2+_m**4/_s*_log(m**2/(s+m**2))"; nl ();
        printf "%%_end_if"; nl ();
        printf "%%_end_function_s0stu"; nl ();
        nl ();
        printf "%%_sfunction_s1stu_(s,m)_result_(s1)" pure; nl ();
        printf "%%_real(kind=default),_intent(in)_::_s,_m"; nl ();
        printf "%%_real(kind=default)_::_s1"; nl ();
        printf "%%_if_(m.ge.1.0e08)_then"; nl ();
        printf "%%_s1=0"; nl ();

```

```

printf "        else"; nl ();
printf "        s1=_2*m**4/s+_s/6+_m**4/s**2*(2*m**2+s)"; nl();
printf "        *log(m**2/(s+m**2))"; nl ();
printf "    end_if"; nl ();
printf "end_function_s1stu"; nl();
nl ();
printf "%sfunction_s2stu(s,_m)_result(s2)" pure; nl ();
printf "        real(kind=default),intent(in):_s,_m"; nl ();
printf "        real(kind=default):_s2"; nl ();
printf "        if(m.ge.1.0e08)then"; nl ();
printf "            s2=_0"; nl ();
printf "        else"; nl ();
printf "            s2=_m**4/s**2*_ (6*m**2+_3*s)"; nl();
printf "            m**4/s**3*_ (6*m**4+_6*m**2*s+_s**2)"; nl();
printf "            *log(m**2/(s+m**2))"; nl ();
printf "        end_if"; nl ();
printf "end_function_s2stu"; nl();
nl ();
printf "%sfunction_s3stu(s,_m)_result(s3)" pure; nl ();
printf "        real(kind=default),intent(in):_s,_m"; nl ();
printf "        real(kind=default):_s3"; nl ();
printf "        if(m.ge.1.0e08)then"; nl ();
printf "            s3=_0"; nl ();
printf "        else"; nl ();
printf "            s3=_m**4/s**3*_ (60*m**4+_60*m**2*s+11*s**2)"; nl();
printf "            m**4/s**4*_ (2*m**2+s)_(10*m**4+_10*m**2*s+_s**2)"; nl();
printf "            *log(m**2/(s+m**2))"; nl ();
printf "        end_if"; nl ();
printf "%sfunction_s3stu"; nl();
nl ();
printf "%sfunction_p0stu(s,_m)_result(p0)" pure; nl ();
printf "        real(kind=default),intent(in):_s,_m"; nl ();
printf "        real(kind=default):_p0"; nl ();
printf "        if(m.ge.1.0e08)then"; nl ();
printf "            p0=_0"; nl ();
printf "        else"; nl ();
printf "            p0=_1+_ (2*s+m**2)*log(m**2/(s+m**2))/s"; nl ();
printf "        end_if"; nl ();
printf "end_function_p0stu"; nl();
nl ();
printf "%sfunction_p1stu(s,_m)_result(p1)" pure; nl ();
printf "        real(kind=default),intent(in):_s,_m"; nl ();
printf "        real(kind=default):_p1"; nl ();
printf "        if(m.ge.1.0e08)then"; nl ();
printf "            p1=_0"; nl ();
printf "        else"; nl ();
printf "            p1=_ (m**2+_2*s)/s**2*_ (2*s+(2*m**2+s)"; nl();
printf "            *log(m**2/(s+m**2)))"; nl ();
printf "        end_if"; nl ();
printf "end_function_p1stu"; nl();

```

```

nl ();
printf "%sfunction_d0stu(s,m)result(d0)" pure; nl ();
printf "real(kind=default),intent(in)::s,m"; nl ();
printf "real(kind=default)::d0"; nl ();
printf "if(m.ge.1.0e08)then"; nl ();
printf "d0=0"; nl ();
printf "else"; nl ();
printf "d0=(2*m**2+11*s)/2+(m**4+6*m**2*s+6*s**2)"; nl ();
printf "s*log(m**2/(s+m**2))"; nl ();
printf "endif"; nl ();
printf "endfunction_d0stu"; nl ();
nl ();
printf "%sfunction_d1stu(s,m)result(d1)" pure; nl ();
printf "real(kind=default),intent(in)::s,m"; nl ();
printf "real(kind=default)::d1"; nl ();
printf "if(m.ge.1.0e08)then"; nl ();
printf "d1=0"; nl ();
printf "else"; nl ();
printf "d1=(s*(12*m**4+72*m**2*s+73*s**2)+6*(2*m**2+s)*(m**4+6*m**2*s+6*s**2)"; nl ();
printf "+6*(2*m**2+s)*(m**4+6*m**2*s+6*s**2)"; nl ();
printf "s*log(m**2/(s+m**2)))/6/s**2"; nl ();
printf "endif"; nl ();
printf "endfunction_d1stu"; nl ();
nl ();
printf "%sfunction_da00(cc,s,m)result(amp_00)" pure; nl ();
printf "real(kind=default),intent(in)::s"; nl ();
printf "real(kind=default),dimension(1:12),intent(in)::cc"; nl ();
printf "real(kind=default),dimension(1:5),intent(in)::m"; nl ();
printf "complex(kind=default)::a00_0,a00_1,a00_a,a00_f"; nl ();
printf "complex(kind=default),dimension(1:7)::a00"; nl ();
printf "complex(kind=default)::ii,jj,amp_00"; nl ();
printf "real(kind=default)::kappal,kappam,kappat"; nl ();
printf "ii=cplx(0.0,1.0/32.0/Pi,default)"; nl ();
printf "jj=s**2/vev**4*ii"; nl ();
printf "kappal=cc(12)*((mass(23)**2+mass(24)**2)/m(4)**2-2*mass(23)**2*mass(24)"; nl ();
printf "kappam=cc(12)*((mass(23)**4+mass(24)**4)/m(4)**2/(mass(23)**2+mass(24)"; nl ();
printf "2*mass(23)**2*mass(24)**2/m(4)**4)"; nl ();
printf "kappat=cc(12)*mass(23)**2*mass(24)**2/m(4)**4"; nl ();
printf "Longitudinal"; nl ();
printf "Scalarisosinglet"; nl ();
printf "a00(1)=-2.0*cc(1)**2/vev**2*s0stu(s,m(1))"; nl ();
printf "if(cc(1)/=0)then"; nl ();
printf "a00(1)=a00(1)-3.0*cc(1)**2/vev**2*&"; nl ();
printf "s**2/cplx(s-m(1)**2,m(1)*wkm(1,default))"; nl ();
printf "endif"; nl ();
printf "Scalarisoquintet"; nl ();
printf "a00(2)=-5.0*cc(2)**2/vev**2*s0stu(s,m(2))-3.0"; nl ();
printf "Vectorisotriplet"; nl ();
printf "a00(3)=-cc(3)**2*(4.0*p0stu(s,m(3))+6.0*s/m(3)**2)"; nl ();
printf "Tensorisosinglet"; nl ();

```

```

printf "a00(4)=cc(4)**2/vev**2/3*(d0stu(s,m(4)))&"; nl ();
printf "a00(4)=2*kappal*s0stu(s,m(4))&"; nl ();
printf "if(cc(4)/=0).and.(kappal/=0)then"; nl ();
printf "a00(4)=a00(4)-cc(4)**2/vev**2*kappal*&"; nl ();
printf "a00(4)=s**2/cmplx(s-m(4)**2,m(4)*wkm(4),default)&"; nl ();
printf "endif"; nl ();
printf "!!!TensorIsoquintet"; nl ();
printf "a00(5)=-5.0*cc(5)**2/vev**2*(d0stu(s,m(5)))&"; nl ();
printf "a00(5)=3.0/6.0"; nl ();
printf "!!!TensorTransversal"; nl ();
printf "!!!TensorIsosinglet"; nl ();
printf "a00(6)=cc(9)**2/Pi/vev**6*mass(23)**2*mass(24)**2/4*s**2*&"; nl ();
printf "a00(6)=*(2-2*s/m(4)**2+s**2/m(4)**4)+kappat/2"; nl ();
printf "if(a00(6)/=0)then"; nl ();
printf "a00(6)=a00(6)/cmplx(s-m(4)**2,-w-res/32/Pi*real(a00(6),default),&"; nl ();
printf "endif"; nl ();
printf "a00(6)=a00(6)-cc(9)**2/Pi/vev**6*mass(23)**2*mass(24)**2/12*(s0stu(s,m(4))&"; nl ();
printf "a00(6)=*(3*(1+2*s/m(4)**2+2*s**2/m(4)**4)+kappat)"; nl ();
printf "!!!Mixed"; nl ();
printf "!!!TensorIsosinglet"; nl ();
printf "a00(7)=cc(11)*cc(9)*cc(4)/Pi/vev**4*(mass(23)**2+mass(24)**2)/4*s**2*&"; nl ();
printf "a00(7)=*(1-4*s/m(4)**2+2*s**2/m(4)**4)+kappam"; nl ();
printf "if(a00(7)/=0)then"; nl ();
printf "a00(7)=a00(7)/cmplx(s-m(4)**2,-w-res/32/Pi*real(a00(7),default),&"; nl ();
printf "endif"; nl ();
printf "a00(7)=a00(7)-cc(11)*cc(9)*cc(4)/Pi/vev**4*(mass(23)**2+mass(24)**2)&"; nl ();
printf "a00(7)=*(12*s/m(4)**2+12*s**2/m(4)**4+2*kappam)"; nl ();
printf "!!!Fudge-Higgs"; nl ();
printf "a00_f=2.*fudge_higgs*s/vev**2"; nl ();
printf "a00_f=a00_f!!!-0*5.*(1-ghvva)**2/vev**2*mass(25)**2"; nl ();
printf "!!!Lowenergytheoryalphas"; nl ();
printf "a00_0=8.*(7.*a4+a11.*a5)/3.*s**2/vev**4"; nl ();
printf "a00_1=(25.*log(lam-reg**2/s)/9+a11./54.0-default)*s**2/vev**4"; nl ();
printf "a00_a=a00_0!!!+a00_1/16./Pi**2"; nl ();
printf "!!!Unitarize"; nl ();
printf "if(fudge_km/=0)then"; nl ();
printf "amp_00=sum(a00)+a00_f+a00_a"; nl ();
printf "if(amp_00/=0)then"; nl ();
printf "amp_00=-a00_a-a00_f-part_r*(sum(a00)-a00(3))+1/(real(1/amp_00)+&"; nl ();
printf "endif"; nl ();
printf "else"; nl ();
printf "amp_00=(1-part_r)*sum(a00)+part_r*a00(3)"; nl ();
printf "endif"; nl ();
printf "amp_00=vev**4/s**2*amp_00"; nl ();
printf "endfunctionda00"; nl ();
nl ();
printf "%sfunctionda02(cc,s,m)result(amp_02)" pure; nl ();
printf "real(kind=default),intent(in):s"; nl ();
printf "real(kind=default),dimension(1:12),intent(in):cc"; nl ();
printf "real(kind=default),dimension(1:5),intent(in):m"; nl ();

```

```

printf "uuuuuucomplex(kind=default)_: _a02_0,_a02_1,_a02_a"; nl ();
printf "uuuuuucomplex(kind=default),_dimension(1:7)_:_a02"; nl ();
printf "uuuuuucomplex(kind=default)_:_ii,_jj,_amp_02"; nl ();
printf "uuuuuu real(kind=default)_:_kappal,_kappam,_kappat"; nl ();
printf "uuuuuu ii=_cplx(0.0,1.0/32.0/Pi,default)"; nl ();
printf "uuuuuu jj=_s**2/vev**4*ii"; nl ();
printf "uuuuuu kappal=_cc(12)*((mass(23)**2+mass(24)**2)/m(4)**2-2*mass(23)**2*mass(24)";
printf "uuuuuu kappam=_cc(12)*((mass(23)**4+mass(24)**4)/m(4)**2/(mass(23)**2+mass(24)";
printf "uuuuuuuuuuuu-2*mass(23)**2*mass(24)**2/m(4)**4)"; nl ();
printf "uuuuuu kappat=_cc(12)*mass(23)**2*mass(24)**2/m(4)**4"; nl ();
printf "uuuuuu!!!_Longitudinal"; nl ();
printf "uuuuuu!!!_Scalar_u_isinglet"; nl ();
printf "uuuuuu a02(1)_=-2.0*cc(1)**2/vev**2*_s2stu(s,m(1))"; nl ();
printf "uuuuuu!!!_Scalar_isoquintet"; nl ();
printf "uuuuuu a02(2)_=-5.0*cc(2)**2/vev**2*_s2stu(s,m(2))/_3.0"; nl ();
printf "uuuuuu!!!_Vector_isotriplet"; nl ();
printf "uuuuuu a02(3)_=-4.0*cc(3)**2*(2*s+m(3)**2)*s2stu(s,m(3))/m(3)**4"; nl ();
printf "uuuuuu!!!_Tensor_isinglet"; nl ();
printf "uuuuuu a02(4)_=_cc(4)**2/vev**2/3*_u_&"; nl ();
printf "uuuuuuuuuuuuuuuu((1.+6.*s/m(4)**2+6.*s**2/m(4)**4)-2*kappal)*_s2stu(s,m(4))";
printf "uuuuuu if(_cc(4)/=_0)_then"; nl ();
printf "uuuuuu a02(4)_=_a02(4)-_cc(4)**2/vev**2/10._u_&"; nl ();
printf "uuuuuuuuuuuuuuuu*_s**2/cplx(s-m(4)**2,m(4)*wkm(4),default)"; nl ();
printf "uuuuuu end_if"; nl ();
printf "uuuuuu!!!_Tensor_isoquintet"; nl ();
printf "uuuuuu a02(5)_=_cc(5)**2/vev**2*(5.0*(1.0+6.0*_u_&"; nl ();
printf "uuuuuuuuuuuuuuuu s/m(5)**2+6.0*s**2/m(5)**4)*s2stu(s,m(5))/3.0_u_&"; nl ();
printf "uuuuuuuuuuuuuuuu)/6.0"; nl ();
printf "uuuuuu!!!_Transversal"; nl ();
printf "uuuuuu!!!_Tensor_isinglet"; nl ();
printf "uuuuuu a02(6)_=_cc(9)**2/Pi/vev**6*mass(23)**2*mass(24)**2/40*_s**2"; nl ();
printf "uuuuuu if(_a02(6)/=_0)_then"; nl ();
printf "uuuuuu a02(6)_=_a02(6)/cplx(s-m(4)**2,_w-res/32/Pi*_real(a02(6),default),";
printf "uuuuuu end_if"; nl ();
printf "uuuuuu a02(6)_=_a02(6)-_cc(9)**2/Pi/vev**6*mass(23)**2*mass(24)**2/12*_s2stu";
printf "uuuuuuuuuuuuuuuu*_u(12*s/m(4)**2+12*s**2/m(4)**4+2*kappam_u)"; nl ();
printf "uuuuuu!!!_Low_energy_theory_alphas"; nl ();
printf "uuuuuu a02_0=_u(8.*(2.*a4+_a5)/15.)*_u_s**2/vev**4"; nl ();
printf "uuuuuu a02_1=_u(log(lam_reg**2/s)/9._u_7./135.0_default)*_u_s**2/vev**4"; nl ();
printf "uuuuuu a02_a=_a02_0!!!+_a02_1/16/Pi**2"; nl ();
printf "uuuuuu!!!_Unitarize"; nl ();

```

```

printf "#####if_(fudge_km/=0)_then"; nl ();
printf "#####amp_02=_sum(a02)+a02_a"; nl ();
printf "#####if_(amp_02/=0)_then"; nl ();
printf "#####amp_02=_a02_a_part_r*_sum(a02)_a02(3))_+1/(real(1/amp_02,d
printf "#####endif"; nl ();
printf "#####else"; nl ();
printf "#####amp_02=(1-part_r)*_sum(a02)+_part_r*_a02(3)"; nl ();
printf "#####endif"; nl ();
printf "#####amp_02=vev**4/s**2*_amp_02"; nl ();
printf "##_end_function_da02"; nl ();
nl ();
printf "##_sfunction_da11_(cc,s,m)_result_(amp_11)" pure; nl ();
printf "#####real(kind=default),_intent(in):_s"; nl ();
printf "#####real(kind=default),_dimension(1:12),_intent(in):_cc"; nl ();
printf "#####real(kind=default),_dimension(1:5),_intent(in):_m"; nl ();
printf "#####complex(kind=default):_a11_0,_a11_1,_a11_a,_a11_f"; nl ();
printf "#####complex(kind=default),_dimension(1:7):_a11"; nl ();
printf "#####complex(kind=default):_ii,_jj,_amp_11"; nl ();
printf "#####real(kind=default):_kappal,_kappam,_kappat"; nl ();
printf "#####ii=_cmplx(0.0,1.0/32.0/Pi,default)"; nl ();
printf "#####jj=_s**2/vev**4*ii"; nl ();
printf "#####kappal=_cc(12)*((mass(23)**2+mass(24)**2)/m(4)**2-2*mass(23)**2*mass(24)
printf "#####kappam=_cc(12)*((mass(23)**4+mass(24)**4)/m(4)**2/(mass(23)**2+mass(24)
printf "#####-2*mass(23)**2*mass(24)**2/m(4)**4)"; nl ();
printf "#####kappat=_cc(12)*mass(23)**2*mass(24)**2/m(4)**4"; nl ();
printf "#####!!!_Longitudinal"; nl ();
printf "#####!!!_Scalar_isosinglet"; nl ();
printf "#####a11(1)=_2.0*cc(1)**2/vev**2*_s1stu(s,m(1))"; nl ();
printf "#####!!!_Scalar_isoquintet"; nl ();
printf "#####a11(2)=_5.0*cc(2)**2/vev**2*_s1stu(s,m(2))/_6.0"; nl ();
printf "#####!!!_Vector_isotriplet"; nl ();
printf "#####a11(3)=_cc(3)**2*_u&"; nl ();
printf "#####(s/m(3)**2+_2.0*_p1stu(s,m(3)))"; nl ();
printf "#####if_(cc(3)/=0)_then"; nl ();
printf "#####a11(3)=_a11(3)-2./3.0*_cc(3)**2*_u&"; nl ();
printf "#####s/cmplx(s-m(3)**2,m(3)*wkm(3),default)"; nl ();
printf "#####endif"; nl ();
printf "#####!!!_Tensor_isosinglet"; nl ();
printf "#####a11(4)=_cc(4)**2/vev**2*(d1stu(s,m(4))-2*kappal*s1stu(s,m(4)))_u&"; nl ();
printf "#####/3.0"; nl ();
printf "#####!!!_Tensor_isoquintet"; nl ();
printf "#####a11(5)=_5.0*cc(5)**2/vev**2*(d1stu(s,m(5)))_u&"; nl ();
printf "#####/36.0"; nl ();
printf "#####!!!_Transversal"; nl ();
printf "#####!!!_Tensor_isosinglet"; nl ();
printf "#####a11(6)=_cc(9)**2/Pi/vev**6*mass(23)**2*mass(24)**2/12*_s1stu(s,m(4))
printf "#####(3*(1+2*s/m(4)**2+2*s**2/m(4)**4)+kappat)_u(s/m(4)**2+s**2/m(4)
printf "#####!!!_Mixed"; nl ();
printf "#####!!!_Tensor_isosinglet"; nl ();
printf "#####a11(7)=_cc(11)*cc(9)*cc(4)/Pi/vev**4*(mass(23)**2+mass(24)**2)/12*_s1stu(s,m(4))

```

```

printf "!!!!!!!!!!!!!!!!!!!!*(12*s/m(4)**2+12*s**2/m(4)**4+2*kappam)*_u2*(s/m(4)**2+s**2/vev**2); nl ();
printf "!!!!!!!!!!Fudge-Higgs"; nl ();
printf "!!!!!!!!a11_f=fudge_higgs*s/3./vev**2"; nl ();
printf "!!!!!!!!!!Low-energy-theory-alphas"; nl ();
printf "!!!!!!!!a11_0=4.*(a4_u2*a5)/3.*s**2/vev**4"; nl ();
printf "!!!!!!!!a11_1=1.0/54.0_default*s**2/vev**4"; nl ();
printf "!!!!!!!!a11_a=a11_0!!!!+a11_1/16/Pi**2"; nl ();
printf "!!!!!!!!!!Unitarize"; nl ();
printf "!!!!!!!!if(fudge_km/=0)then"; nl ();
printf "!!!!!!!!amp_11=sum(a11)+a11_f+a11_a"; nl ();
printf "!!!!!!!!if(amp_11/=0)then"; nl ();
printf "!!!!!!!!amp_11=-a11_a-part_r*(sum(a11)-a11(3))+1/(real(1/amp_11,d0)); nl ();
printf "!!!!!!!!end_if"; nl ();
printf "!!!!!!!!else"; nl ();
printf "!!!!!!!!amp_11=(1-part_r)*sum(a11)+part_r*a11(3)"; nl ();
printf "!!!!!!!!end_if"; nl ();
printf "!!!!!!amp_11=vev**4/s**2*amp_11"; nl ();
printf "!!end_function_da11"; nl ();
nl ();
printf "!!%sfunction_da20(cc,s,m)result(amp_20)" pure; nl ();
printf "!!!!!!real(kind=default),intent(in):_s"; nl ();
printf "!!!!!!real(kind=default),dimension(1:12),intent(in):_cc"; nl ();
printf "!!!!!!real(kind=default),dimension(1:5),intent(in):_m"; nl ();
printf "!!!!!!complex(kind=default):_a20_0,_a20_1,_a20_a,_a20_f"; nl ();
printf "!!!!!!complex(kind=default),dimension(1:7):_a20"; nl ();
printf "!!!!!!complex(kind=default):_ii,_jj,_amp_20"; nl ();
printf "!!!!!!real(kind=default):_kappal,_kappam,_kappat"; nl ();
printf "!!!!!!ii=cplx(0.0,1.0/32.0/Pi,default)"; nl ();
printf "!!!!!!jj=s**2/vev**4*ii"; nl ();
printf "!!!!!!!!Scalar-isosinglet"; nl ();
printf "!!!!!!kappal=cc(12)*((mass(23)**2+mass(24)**2)/m(4)**2-2*mass(23)**2*mass(24)**2/m(4)**2); nl ();
printf "!!!!!!kappam=cc(12)*((mass(23)**4+mass(24)**4)/m(4)**2/(mass(23)**2+mass(24)**2)); nl ();
printf "!!!!!!kappat=cc(12)*mass(23)**2*mass(24)**2/m(4)**4"; nl ();
printf "!!!!!!!!Longitudinal"; nl ();
printf "!!!!!!a20(1)=-2.0*cc(1)**2/vev**2*_s0stu(s,m(1))"; nl ();
printf "!!!!!!!!Scalar-isoquintet"; nl ();
printf "!!!!!!a20(2)=-cc(2)**2/vev**2/6.*_s0stu(s,m(2))"; nl ();
printf "!!!!!!if(cc(2)/=0)then"; nl ();
printf "!!!!!!a20(2)=a20(2)-cc(2)**2/vev**2/2.*&"; nl ();
printf "!!!!!!s**2/cplx(s-m(2)**2,m(2)*wkm(2),default)"; nl ();
printf "!!!!!!end_if"; nl ();
printf "!!!!!!!!Vector-isotriplet"; nl ();
printf "!!!!!!a20(3)=cc(3)**2*(2.0*p0stu(s,m(3))+3.0*s/m(3)**2)"; nl ();
printf "!!!!!!!!Tensor-isosinglet"; nl ();
printf "!!!!!!a20(4)=-cc(4)**2/vev**2*(d0stu(s,m(4))-2*kappal*s0stu(s,m(4)))&"; nl ();
printf "!!!!!!/3.0"; nl ();
printf "!!!!!!!!Tensor-isoquintet"; nl ();
printf "!!!!!!a20(5)=-cc(5)**2/vev**2*(d0stu(s,m(5)))&"; nl ();
printf "!!!!!!/36.0"; nl ();

```



```

printf "!!!!_Transversal"; nl ();
printf "!!!!_Tensor_isosinglet"; nl ();
printf "!!!!a20(6)=-cc(9)**2/Pi/vev**6*mass(23)**2*mass(24)**2/12*_s0stu(s,m(4))";
printf "!!!!*_(3*(1+2*s/m(4)**2+2*s**2/m(4)**4)+kappat_)*_3*(s/m(4)**2-s**2/";
printf "!!!!_Mixed"; nl ();
printf "!!!!_Tensor_isosinglet"; nl ();
printf "!!!!a20(7)=-cc(11)*cc(9)*cc(4)/Pi/vev**4*(mass(23)**2+mass(24)**2)/12*_s";
printf "!!!!*_(12*s/m(4)**2+12*s**2/m(4)**4+2*kappam_)*_6*(s/m(4)**2-s**2/";
printf "!!!!_Fudge-Higgs"; nl ();
printf "!!!!a20_f=-_fudge_higgs*s/vev**2"; nl ();
printf "!!!!a20_f=_a20_f*_0*2*(1-ghvva)**2/vev**2*mass(25)**2"; nl ();
printf "!!!!_Low_energy_theory_alphas"; nl ();
printf "!!!!a20_0=_16*(2*a4+_a5)/3*s**2/vev**4"; nl ();
printf "!!!!a20_1=_10*log(lam_reg**2/s)/9+_25/108.0_default)*_s**2/vev**4"; nl ();
printf "!!!!a20_a=_a20_0!!!!+_a20_1/16/Pi**2"; nl ();
printf "!!!!_Unitarize"; nl ();
printf "!!!!if_(fudge_km/=0)_then"; nl ();
printf "!!!!amp_20=_sum(a20)+a20_f+a20_a"; nl ();
printf "!!!!if_(amp_20/=0)_then"; nl ();
printf "!!!!amp_20=_a20_a-_a20_f*_part_r*_sum(a20)-_a20(3))*_1/(real(1/";
printf "!!!!end_if"; nl ();
printf "!!!!else"; nl ();
printf "!!!!amp_20=_1-part_r)*_sum(a20)+_part_r*_a20(3)"; nl ();
printf "!!!!end_if"; nl ();
printf "!!!!amp_20=_vev**4/s**2*_amp_20"; nl ();
printf "!!!!end_function_da20"; nl ();
nl ();
printf "!!!!%sfunction_da22(cc,s,m)result(amp_22)" pure; nl ();
printf "!!!!real(kind=default),intent(in):_s"; nl ();
printf "!!!!real(kind=default),dimension(1:12),intent(in):_cc"; nl ();
printf "!!!!real(kind=default),dimension(1:5),intent(in):_m"; nl ();
printf "!!!!complex(kind=default):_a22_0,a22_1,a22_a,a22_r"; nl ();
printf "!!!!complex(kind=default),dimension(1:7):_a22"; nl ();
printf "!!!!complex(kind=default):_ii,jj,amp_22"; nl ();
printf "!!!!real(kind=default):_kappal,kappam,kappat"; nl ();
printf "!!!!ii=_cmplx(0.0,1.0/32.0/Pi,default)"; nl ();
printf "!!!!jj=_s**2/vev**4*ii"; nl ();
printf "!!!!kappal=_cc(12)*((mass(23)**2+mass(24)**2)/m(4)**2-2*mass(23)**2*mass(24)";
printf "!!!!kappam=_cc(12)*((mass(23)**4+mass(24)**4)/m(4)**2/(mass(23)**2+mass(24)";
printf "!!!!*2*mass(23)**2*mass(24)**2/m(4)**4)"; nl ();
printf "!!!!kappat=_cc(12)*mass(23)**2*mass(24)**2/m(4)**4"; nl ();
printf "!!!!_Longitudinal"; nl ();
printf "!!!!_Scalar_isosinglet"; nl ();
printf "!!!!a22(1)=-_2.0*cc(1)**2/vev**2*_s2stu(s,m(1))"; nl ();
printf "!!!!_Scalar_isoquintet"; nl ();
printf "!!!!a22(2)=-_cc(2)**2/vev**2*_s2stu(s,m(2))*_6.0"; nl ();
printf "!!!!_Vector_triplet"; nl ();
printf "!!!!a22(3)=-_2.0*cc(3)**2*(2*s+m(3)**2)*s2stu(s,m(3))/m(3)**4"; nl ();
printf "!!!!_Tensor_isosinglet"; nl ();
printf "!!!!a22(4)=-_cc(4)**2/vev**2*((1.0+_6.0*s/m(4)**2)&"; nl ();

```

```

printf "++++++6.0*s**2/m(4)**4-2*kappal)*s2stu(s,m(4))/3.0"; nl ();
printf "++++++!!!Tensor_isoquintet"; nl ();
printf "++++++a22(5)=_cc(5)**2/vev**2/36._*_*"; nl ();
printf "++++++((1.+6.*s/m(5)**2+6.*s**2/m(5)**4)_&"; nl ();
printf "++++++*s2stu(s,m(5))"; nl ();
printf "++++++if_(cc(5)/=0)_then"; nl ();
printf "++++++a22(5)=_a22(5)-_cc(5)**2/vev**2/60._*_*"; nl ();
printf "++++++s**2/cmplx(s-m(5)**2,m(5)*wkm(5),default)"; nl ();
printf "++++++end_if"; nl ();
printf "++++++!!!Tensor_isosinglet"; nl ();
printf "++++++a22(6)=_cc(9)**2/Pi/vev**6*mass(23)**2*mass(24)**2/12._*(s2stu(s,m(4))";
printf "++++++*(3*(1+2*s/m(4)**2+2*s**2/m(4)**4)+kappat_)"; nl ();
printf "++++++!!!Mixed"; nl ();
printf "++++++!!!Tensor_isosinglet"; nl ();
printf "++++++a22(7)=_cc(11)*cc(9)*cc(4)/Pi/vev**4*(mass(23)**2+mass(24)**2)/12._*(s";
printf "++++++*(12*s/m(4)**2+12*s**2/m(4)**4+2*kappam_)"; nl ();
printf "++++++!!!Low_energy_theory_alphas"; nl ();
printf "++++++a22_0=_4*(a4+_2*a5)/15*s**2/vev**4"; nl ();
printf "++++++a22_1=_*(2*log(lam_reg**2/s)/45._-247/5400.0_default)*s**2/vev**4"; nl ();
printf "++++++a22_a=_a22_0!!!+_a22_1/16/Pi**2"; nl ();
printf "++++++!!!Unitarize"; nl ();
printf "++++++if_(fudge_km/=0)_then"; nl ();
printf "++++++amp_22=_sum(a22)+a22_a"; nl ();
printf "++++++if_(amp_22/=0)_then"; nl ();
printf "++++++amp_22=_a22_a-_part_r*_*(sum(a22)-_a22(3))+_1/(real(1/amp_22,d";
printf "++++++end_if"; nl ();
printf "++++++else"; nl ();
printf "++++++amp_22=_*(1-part_r)*_sum(a22)+_part_r*_a22(3)"; nl ();
printf "++++++end_if"; nl ();
printf "++++++amp_22=_vev**4/s**2*_amp_22"; nl ();
printf "++end_function_da22"; nl ();
nl ();
printf "++%sfunction_dalzz0_s_(cc,m,k)_result_(alzz0_s)" pure; nl ();
printf "++++++type(momentum),_intent(in):_k"; nl ();
printf "++++++real(kind=default),_dimension(1:12),_intent(in):_cc"; nl ();
printf "++++++real(kind=default),_dimension(1:5),_intent(in):_m"; nl ();
printf "++++++complex(kind=default):_alzz0_s"; nl ();
printf "++++++real(kind=default):_s"; nl ();
printf "++++++s=_k*k"; nl ();
printf "++++++alzz0_s=_2*g**4/costhw**2*((da00(cc,s,m)_&"; nl ();
printf "++++++da20(cc,s,m))/24_&"; nl ();
printf "++++++(5.)*(da02(cc,s,m)-_da22(cc,s,m))/12)"; nl ();
printf "++end_function_dalzz0_s"; nl ();
nl ();
printf "++%sfunction_dalzz0_t_(cc,m,k)_result_(alzz0_t)" pure; nl ();
printf "++++++type(momentum),_intent(in):_k"; nl ();
printf "++++++real(kind=default),_dimension(1:12),_intent(in):_cc"; nl ();
printf "++++++real(kind=default),_dimension(1:5),_intent(in):_m"; nl ();
printf "++++++complex(kind=default):_alzz0_t"; nl ();

```

```

printf "UUUUUUreal(kind=default)_:s"; nl ();
printf "UUUUUUs=k*k"; nl ();
printf "UUUUUUalzz0_t=(5.)*g**4/costhw**2*(da02(cc,s,m)_-&"; nl ();
printf "UUUUUUUUUUUUUUUUUUUUda22(cc,s,m))/4"; nl ();
printf "UUend_function_dalzz0_t"; nl ();
nl ();
printf "UU%sfunction_dalzz1_s(cc,m,k)_result_(alzz1_s)" pure; nl ();
printf "UUUUUUtype(momentum),_intent(in)_:k"; nl ();
printf "UUUUUUreal(kind=default),_dimension(1:12),_intent(in)_:cc"; nl ();
printf "UUUUUUreal(kind=default),_dimension(1:5),_intent(in)_:m"; nl ();
printf "UUUUUUcomplex(kind=default)_:alzz1_s"; nl ();
printf "UUUUUUreal(kind=default)_:s"; nl ();
printf "UUUUUUs=k*k"; nl ();
printf "UUUUUUalzz1_s=g**4/costhw**2*(da20(cc,s,m)/8_&"; nl ();
printf "UUUUUUUUUUUUUUUUUUUU-(5.)*da22(cc,s,m)/4"; nl ();
printf "UUend_function_dalzz1_s"; nl ();
nl ();
printf "UU%sfunction_dalzz1_t(cc,m,k)_result_(alzz1_t)" pure; nl ();
printf "UUUUUUtype(momentum),_intent(in)_:k"; nl ();
printf "UUUUUUreal(kind=default),_dimension(1:12),_intent(in)_:cc"; nl ();
printf "UUUUUUreal(kind=default),_dimension(1:5),_intent(in)_:m"; nl ();
printf "UUUUUUcomplex(kind=default)_:alzz1_t"; nl ();
printf "UUUUUUreal(kind=default)_:s"; nl ();
printf "UUUUUUs=k*k"; nl ();
printf "UUUUUUalzz1_t=g**4/costhw**2*(-(3.)*da11(cc,s,m)/8_&"; nl ();
printf "UUUUUUUUUUUUUUUUUUUU+3*(5.)*da22(cc,s,m)/8"; nl ();
printf "UUend_function_dalzz1_t"; nl ();
nl ();
printf "UU%sfunction_dalzz1_u(cc,m,k)_result_(alzz1_u)" pure; nl ();
printf "UUUUUUtype(momentum),_intent(in)_:k"; nl ();
printf "UUUUUUreal(kind=default),_dimension(1:12),_intent(in)_:cc"; nl ();
printf "UUUUUUreal(kind=default),_dimension(1:5),_intent(in)_:m"; nl ();
printf "UUUUUUcomplex(kind=default)_:alzz1_u"; nl ();
printf "UUUUUUreal(kind=default)_:s"; nl ();
printf "UUUUUUs=k*k"; nl ();
printf "UUUUUUalzz1_u=g**4/costhw**2*((3.)*da11(cc,s,m)/8_&"; nl ();
printf "UUUUUUUUUUUUUUUUUUUU+3*(5.)*da22(cc,s,m)/8"; nl ();
printf "UUend_function_dalzz1_u"; nl ();
nl ();
printf "UU%sfunction_dalww0_s(cc,m,k)_result_(alww0_s)" pure; nl ();
printf "UUUUUUtype(momentum),_intent(in)_:k"; nl ();
printf "UUUUUUreal(kind=default),_dimension(1:12),_intent(in)_:cc"; nl ();
printf "UUUUUUreal(kind=default),_dimension(1:5),_intent(in)_:m"; nl ();
printf "UUUUUUcomplex(kind=default)_:alww0_s"; nl ();
printf "UUUUUUreal(kind=default)_:s"; nl ();
printf "UUUUUUs=k*k"; nl ();
printf "UUUUUUalww0_s=g**4*((2*da00(cc,s,m)_+da20(cc,s,m))/24_&"; nl ();
printf "UUUUUUUUUUUUUUUUUUUU-(5.)*(2*da02(cc,s,m)_+da22(cc,s,m))/12"; nl ();
printf "UUend_function_dalww0_s"; nl ();
nl ();

```

```

printf "%sfunction_dalww0_t(cc,m,k)_result_(alww0_t)" pure; nl ();
printf "type(momentum),intent(in):_k"; nl ();
printf "real(kind=default),dimension(1:12),intent(in):_cc"; nl ();
printf "real(kind=default),dimension(1:5),intent(in):_m"; nl ();
printf "complex(kind=default):_alww0_t"; nl ();
printf "real(kind=default):_s"; nl ();
printf "s=_k*k"; nl ();
printf "alww0_t=_g**4*(2*(5.)*da02(cc,s,m)_-(3.)*da11(cc,s,m)_&"; nl ();
printf "+++++(5.)*da22(cc,s,m))/8"; nl ();
printf "end_function_dalww0_t"; nl ();
nl ();
printf "%sfunction_dalww0_u(cc,m,k)_result_(alww0_u)" pure; nl ();
printf "type(momentum),intent(in):_k"; nl ();
printf "real(kind=default),dimension(1:12),intent(in):_cc"; nl ();
printf "real(kind=default),dimension(1:5),intent(in):_m"; nl ();
printf "complex(kind=default):_alww0_u"; nl ();
printf "real(kind=default):_s"; nl ();
printf "s=_k*k"; nl ();
printf "alww0_u=_g**4*(2*(5.)*da02(cc,s,m)_+(3.)*da11(cc,s,m)_&"; nl ();
printf "+++++(5.)*da22(cc,s,m))/8"; nl ();
printf "end_function_dalww0_u"; nl ();
nl ();
printf "%sfunction_dalww2_s(cc,m,k)_result_(alww2_s)" pure; nl ();
printf "type(momentum),intent(in):_k"; nl ();
printf "real(kind=default),dimension(1:12),intent(in):_cc"; nl ();
printf "real(kind=default),dimension(1:5),intent(in):_m"; nl ();
printf "complex(kind=default):_alww2_s"; nl ();
printf "real(kind=default):_s"; nl ();
printf "s=_k*k"; nl ();
printf "alww2_s=_g**4*(da20(cc,s,m)_-2*(5.)*da22(cc,s,m))/4"; nl ();
printf "end_function_dalww2_s"; nl ();
nl ();
printf "%sfunction_dalww2_t(cc,m,k)_result_(alww2_t)" pure; nl ();
printf "type(momentum),intent(in):_k"; nl ();
printf "real(kind=default),dimension(1:12),intent(in):_cc"; nl ();
printf "real(kind=default),dimension(1:5),intent(in):_m"; nl ();
printf "complex(kind=default):_alww2_t"; nl ();
printf "real(kind=default):_s"; nl ();
printf "s=_k*k"; nl ();
printf "alww2_t=_3*(5.)*g**4*da22(cc,s,m)/4"; nl ();
printf "end_function_dalww2_t"; nl ();
nl ();
printf "%sfunction_dalz4_s(cc,m,k)_result_(alz4_s)" pure; nl ();
printf "type(momentum),intent(in):_k"; nl ();
printf "real(kind=default),dimension(1:12),intent(in):_cc"; nl ();
printf "real(kind=default),dimension(1:5),intent(in):_m"; nl ();
printf "complex(kind=default):_alz4_s"; nl ();
printf "real(kind=default):_s"; nl ();
printf "s=_k*k"; nl ();
printf "alz4_s=_g**4/costhw**4*((da00(cc,s,m)_&"; nl ();

```

```

printf "+++++2*da20(cc,s,m))/12_&"; nl ();
printf "+++++(5.)*(da02(cc,s,m)+2*da22(cc,s,m))/6"; nl ();
printf "++end_function_dalz4_s"; nl ();
nl ();
printf "++@[<5>";
printf "++%sfunction_dalz4_t_(cc,m,k)_result_(alz4_t)" pure; nl ();
printf "++++type(momentum),_intent(in)_:_k"; nl ();
printf "++++real(kind=default),_dimension(1:12),_intent(in)_:_cc"; nl ();
printf "++++real(kind=default),_dimension(1:5),_intent(in)_:_m"; nl ();
printf "++++complex(kind=default)_:_alz4_t"; nl ();
printf "++++real(kind=default)_:_s"; nl ();
printf "++++s=_k*k"; nl ();
printf "++++alz4_t=_g**4/costhw**4*(5.)*(da02(cc,s,m)_&"; nl ();
printf "++++2*da22(cc,s,m))/4"; nl ();
printf "++end_function_dalz4_t"; nl ();
nl ();
end

```

---

# —16—

## PHASE SPACE

### 16.1 Interface of Phasespace

```

module type T =
  sig
    type momentum

    type  $\alpha$  t
    type  $\alpha$  decay
  end

```

Sort individual decays and complete phasespaces in a canonical order to determine topological equivalence classes.

```

val sort : ( $\alpha \rightarrow \alpha \rightarrow \text{int}$ )  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\alpha$  t
val sort_decay : ( $\alpha \rightarrow \alpha \rightarrow \text{int}$ )  $\rightarrow$   $\alpha$  decay  $\rightarrow$   $\alpha$  decay

```

Functionals:

```

val map : ( $\alpha \rightarrow \beta$ )  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\beta$  t
val map_decay : ( $\alpha \rightarrow \beta$ )  $\rightarrow$   $\alpha$  decay  $\rightarrow$   $\beta$  decay

val eval : ( $\alpha \rightarrow \beta$ )  $\rightarrow$  ( $\alpha \rightarrow \beta$ )  $\rightarrow$  ( $\alpha \rightarrow \beta \rightarrow \beta \rightarrow \beta$ )  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\beta$  t
val eval_decay : ( $\alpha \rightarrow \beta$ )  $\rightarrow$  ( $\alpha \rightarrow \beta \rightarrow \beta \rightarrow \beta$ )  $\rightarrow$   $\alpha$  decay  $\rightarrow$ 
 $\beta$  decay

```

*of\_momenta* *f1* *f2* *plist* constructs the phasespace parameterization for a process  $f_1 f_2 \rightarrow X$  with flavor decoration from pairs of outgoing momenta and flavors *plist* and initial flavors *f1* and *f2*

```

val of_momenta :  $\alpha \rightarrow \alpha \rightarrow (\text{momentum} \times \alpha) \text{ list} \rightarrow (\text{momentum} \times \alpha) t$ 
val decay_of_momenta : ( $\text{momentum} \times \alpha$ ) list  $\rightarrow$  ( $\text{momentum} \times \alpha$ ) decay

exception Duplicate of momentum
exception Unordered of momentum
exception Incomplete of momentum

```

end

```

module Make (M : Momentum.T) : T with type momentum = M.t

```

## 16.2 Implementation of *Phasespace*

### 16.2.1 Tools

These are candidates for *ThoList* and not specific to phase space.

```
let rec first_match' mismatch f = function
| [] → None
| x :: rest →
  if f x then
    Some (x, List.rev_append mismatch rest)
  else
    first_match' (x :: mismatch) f rest
```

Returns  $(x, X \setminus \{x\})$  if  $\exists x \in X : f(x)$ .

```
let first_match f l = first_match' [] f l
```

```
let rec first_pair' mismatch1 f l1 l2 =
  match l1 with
  | [] → None
  | x1 :: rest1 →
    begin match first_match (f x1) l2 with
    | None → first_pair' (x1 :: mismatch1) f rest1 l2
    | Some (x2, rest2) →
      Some ((x1, x2), (List.rev_append mismatch1 rest1, rest2))
    end
```

Returns  $((x, y), (X \setminus \{x\}, Y \setminus \{y\}))$  if  $\exists x \in X : \exists y \in Y : f(x, y)$ .

```
let first_pair f l1 l2 = first_pair' [] f l1 l2
```

### 16.2.2 Phase Space Parameterization Trees

```
module type T =
sig
  type momentum
  type  $\alpha$  t
  type  $\alpha$  decay
  val sort : ( $\alpha \rightarrow \alpha \rightarrow \text{int}$ )  $\rightarrow \alpha$  t  $\rightarrow \alpha$  t
  val sort_decay : ( $\alpha \rightarrow \alpha \rightarrow \text{int}$ )  $\rightarrow \alpha$  decay  $\rightarrow \alpha$  decay
  val map : ( $\alpha \rightarrow \beta$ )  $\rightarrow \alpha$  t  $\rightarrow \beta$  t
  val map_decay : ( $\alpha \rightarrow \beta$ )  $\rightarrow \alpha$  decay  $\rightarrow \beta$  decay
  val eval : ( $\alpha \rightarrow \beta$ )  $\rightarrow (\alpha \rightarrow \beta) \rightarrow (\alpha \rightarrow \beta \rightarrow \beta \rightarrow \beta) \rightarrow \alpha$  t  $\rightarrow \beta$  t
  val eval_decay : ( $\alpha \rightarrow \beta$ )  $\rightarrow (\alpha \rightarrow \beta \rightarrow \beta \rightarrow \beta) \rightarrow \alpha$  decay  $\rightarrow \beta$  decay
  val of_momenta :  $\alpha \rightarrow \alpha \rightarrow (\text{momentum} \times \alpha)$  list  $\rightarrow (\text{momentum} \times \alpha)$  t
  val decay_of_momenta : ( $\text{momentum} \times \alpha$ ) list  $\rightarrow (\text{momentum} \times \alpha)$  decay
  exception Duplicate of momentum
  exception Unordered of momentum
  exception Incomplete of momentum
end
```

```

module Make (M : Momentum.T) =
  struct
    type momentum = M.t
  end

```



Finally, we came back to binary trees ...

### *Cascade Decays*

```

type  $\alpha$  decay =
  | Leaf of  $\alpha$ 
  | Branch of  $\alpha \times \alpha$  decay  $\times \alpha$  decay

```



Trees of type  $(\text{momentum} \times \alpha \text{ option}) \text{ decay}$  can be build easily and mapped to  $(\text{momentum} \times \alpha) \text{ decay}$  later, once all the  $\alpha$  slots are filled. A more elegant functor operating on  $\beta \text{ decay}$  directly (with *Momentum* style functions defined for  $\beta$ ) would not allow holes in the  $\beta \text{ decay}$  during the construction.

```

let label = function
  | Leaf p → p
  | Branch (p, -, -) → p

let rec sort_decay cmp = function
  | Leaf _ as l → l
  | Branch (p, d1, d2) →
    let d1' = sort_decay cmp d1
    and d2' = sort_decay cmp d2 in
    if cmp (label d1') (label d2') ≤ 0 then
      Branch (p, d1', d2')
    else
      Branch (p, d2', d1')

let rec map_decay f = function
  | Leaf p → Leaf (f p)
  | Branch (p, d1, d2) → Branch (f p, map_decay f d1, map_decay f d2)

let rec eval_decay fl fb = function
  | Leaf p → Leaf (fl p)
  | Branch (p, d1, d2) →
    let d1' = eval_decay fl fb d1
    and d2' = eval_decay fl fb d2 in
    Branch (fb p (label d1') (label d2'), d1', d2')

```

Assuming that  $p > p_D \vee p = p_D \vee p < p_D$ , where  $p_D$  is the overall momentum of a decay tree  $D$ , we can add  $p$  to  $D$  at the top or somewhere in the middle. Note that ' $<$ ' is not a total ordering and the operation can fail (raise exceptions) if the set of momenta does not correspond to a tree. Also note that a momentum can already be present without flavor as a complement in a branching entered earlier.

```

exception Duplicate of momentum
exception Unordered of momentum

```



```

let rec embed_in_decay (p, f as pf) = function
| Leaf (p', f' as pf') as d' →
  if M.less p' p then
    Branch ((p, Some f), d', Leaf (M.sub p p', None))
  else if M.less p p' then
    Branch (pf', Leaf (p, Some f), Leaf (M.sub p' p, None))
  else if p = p' then
    begin match f' with
    | None → Leaf (p, Some f)
    | Some _ → raise (Duplicate p)
    end
  else
    raise (Unordered p)
| Branch ((p', f' as pf'), d1, d2) as d' →
  let p1, _ = label d1
  and p2, _ = label d2 in
  if M.less p' p then
    Branch ((p, Some f), d', Leaf (M.sub p p', None))
  else if M.lesseq p p1 then
    Branch (pf', embed_in_decay pf d1, d2)
  else if M.lesseq p p2 then
    Branch (pf', d1, embed_in_decay pf d2)
  else if p = p' then
    begin match f' with
    | None → Branch ((p, Some f), d1, d2)
    | Some _ → raise (Duplicate p)
    end
  else
    raise (Unordered p)

```



Note that both *embed\_in\_decay* and *embed\_in\_decays* below do *not* commute, and should process ‘bigger’ momenta first, because disjoint sub-momenta will create disjoint subtrees in the latter and raise exceptions in the former.

exception *Incomplete of momentum*

```

let finalize1 = function
| p, Some f → (p, f)
| p, None → raise (Incomplete p)

let finalize_decay t = map_decay finalize1 t

```

Process the momenta starting in with the highest *M.rank*:

```

let sort_momenta plist =
  List.sort (fun (p1, _) (p2, _) → M.compare p1 p2) plist

let decay_of_momenta plist =
  match sort_momenta plist with
  | (p, f) :: rest →
    finalize_decay (List.fold_right embed_in_decay rest (Leaf (p, Some f)))
  | [] → invalid_arg "Phasespace.decay_of_momenta:␣empty"

```

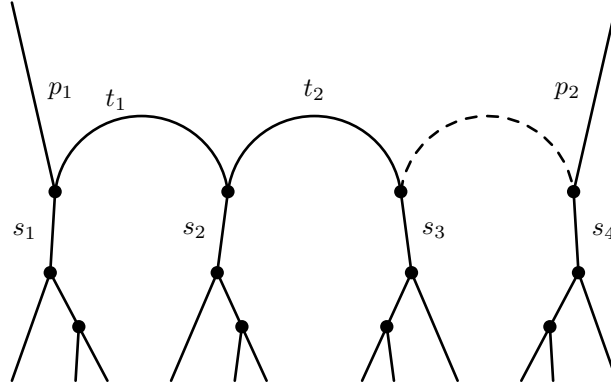


Figure 16.1: Phasespace parameterization for  $2 \rightarrow n$  scattering by a sequence of cascade decays.

### $2 \rightarrow n$ Scattering

A general  $2 \rightarrow n$  scattering process can be parameterized by a sequence of cascade decays. The most symmetric representation is a little bit redundant and enters each  $t$ -channel momentum twice.

```
type α t = (α × α decay × α) list
```



let *topology* = *map snd* has type  $(\text{momentum} \times \alpha) t \rightarrow \alpha t$  and can be used to define topological equivalence classes “up to permutations of momenta,” which are useful for calculating Whizard “groves”<sup>1</sup> [11].

```
let sort cmp = List.map (fun (l, d, r) → (l, sort_decay cmp d, r))
let map f = List.map (fun (l, d, r) → (f l, map_decay f d, f r))
let eval ft fl fb = List.map (fun (l, d, r) → (ft l, eval_decay fl fb d, ft r))
```

Find a tree with a defined ordering relation with respect to  $p$  or create a new one at the end of the list.

```
let rec embed_in_decays (p, f as pf) = function
| [] → [Leaf (p, Some f)]
| d' :: rest →
  let p', _ = label d' in
  if M.lesseq p' p ∨ M.less p p' then
    embed_in_decay pf d' :: rest
  else
    d' :: embed_in_decays pf rest
```

### Collecting Ingredients

```
type α unfinished_decays =
```

<sup>1</sup>Not to be confused with gauge invariant classes of Feynman diagrams [12].

```

    { n : int;
      t_channel : (momentum × α option) list;
      decays : (momentum × α option) decay list }

let empty n = { n = n; t_channel = []; decays = [] }

let insert_in_unfinished_decays (p, f as pf) d =
  if M.Scattering.spacelike p then
    { d with t_channel = (p, Some f) :: d.t_channel }
  else
    { d with decays = embed_in_decays pf d.decays }

let flip_incoming plist =
  List.map (fun (p', f') → (M.Scattering.flip_s_channel_in p', f')) plist

let unfinished_decays_of_momenta n f2 p =
  List.fold_right insert_in_unfinished_decays
    (sort_momenta (flip_incoming ((M.of_ints n [2], f2) :: p))) (empty n)

```

### Assembling Ingredients

```

let sort3 compare x y z =
  let a = [| x; y; z |] in
  Array.sort compare a;
  (a.(0), a.(1), a.(2))

```

Take advantage of the fact that sorting with *M.compare* sorts with *rising* values of *M.rank*:

```

let allows_momentum_fusion (p, -) (p1, -) (p2, -) =
  let p2', p1', p' = sort3 M.compare p p1 p2 in
  match M.try_fusion p' p1' p2' with
  | Some _ → true
  | None → false

let allows_fusion p1 p2 d = allows_momentum_fusion (label d) p1 p2

let rec thread_unfinished_decays' p acc tlist dlist =
  match first_pair (allows_fusion p) tlist dlist with
  | None → (p, acc, tlist, dlist)
  | Some ((t, _ as td), (tlist', dlist')) →
    thread_unfinished_decays' t (td :: acc) tlist' dlist'

let thread_unfinished_decays p c =
  match thread_unfinished_decays' p [] c.t_channel c.decays with
  | -, pairs, [], [] → pairs
  | - → failwith "thread_unfinished_decays"

let rec combine_decays = function
| [] → []
| ((t, f as tf), d) :: rest →
  let p, _ = label d in
  begin match M.try_sub t p with
  | Some p' → (tf, d, (p', f)) :: combine_decays rest

```

```

      | None → (tf, d, (M.sub (M.neg t) p, f)) :: combine_decays rest
    end

let finalize t = map finalize1 t

let of_momenta f1 f2 = function
| (p, _) :: _ as l →
  let n = M.dim p in
  finalize (combine_decays
            (thread_unfinished_decays (M.of_ints n [1], Some f1)
            (unfinished_decays_of_momenta n f2 l)))
| [] → []

```

*Diagnostics*

```

let p_to_string p =
  String.concat "" (List.map string_of_int (M.to_ints (M.abs p)))

let rec to_string1 = function
| Leaf p → "(" ^ p_to_string p ^ ")"
| Branch (_, d1, d2) → "(" ^ to_string1 d1 ^ to_string1 d2 ^ ")"

let to_string ps =
  String.concat "/"
  (List.map (fun (p1, d, p2) →
    p_to_string p1 ^ to_string1 d ^ p_to_string p2) ps)

```

*Examples*

```

let try_thread_unfinished_decays p c =
  thread_unfinished_decays' p [] c.t_channel c.decays

let try_of_momenta f = function
| (p, _) :: _ as l →
  let n = M.dim p in
  try_thread_unfinished_decays
    (M.of_ints n [1], None) (unfinished_decays_of_momenta n f l)
| [] → invalid_arg "try_of_momenta"

end

```

---

# —17—

## WHIZARD

Talk to [11].

### 17.1 Interface of Whizard

```

module type T =
  sig
    type t
    type amplitude
    val trees : amplitude → t
    val merge : t → t
    val write : out_channel → string → t → unit
  end

module Make (FM : Fusion.Maker) (P : Momentum.T)
  (PW : Momentum.Whizard with type t = P.t) (M : Model.T) :
  T with type amplitude = FM(P)(M).amplitude

val write_interface : out_channel → string list → unit
val write_makefile : out_channel → α → unit
val write_makefile_processes : out_channel → string list → unit

```

### 17.2 Implementation of Whizard

```

let rcs = RCS.parse "Whizard" ["Whizard_Interface"]
{ RCS.revision = "$Revision: 4926$";
  RCS.date = "$Date: 2013-12-04 13:35:06 +0100 (Wed, 04 Dec 2013)$";
  RCS.author = "$Author: jr-reuter$";
  RCS.source
    = "$URL: svn+ssh://jr-reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/s";
open Printf

module type T =
  sig
    type t
    type amplitude

```

```

    val trees : amplitude → t
    val merge : t → t
    val write : out_channel → string → t → unit
end

module Make (FM : Fusion.Maker) (P : Momentum.T)
  (PW : Momentum.Whizard with type t = P.t) (M : Model.T) =
struct
  module F = FM(P)(M)
  type tree = (P.t × F.flavor list) list
  module Poles = Map.Make
    (struct
      type t = int × int
      let compare (s1, t1) (s2, t2) =
        let c = compare s2 s1 in
        if c ≠ 0 then
          c
        else
          compare t1 t2
    end)
  let add_tree maps tree trees =
    Poles.add maps
      (try tree :: (Poles.find maps trees) with Not_found → [tree]) trees
  type t =
    { in1 : F.flavor;
      in2 : F.flavor;
      out : F.flavor list;
      trees : tree list Poles.t }
  type amplitude = F.amplitude

```

### 17.2.1 Building Trees

A singularity is to be mapped if it is timelike and not the overall *s*-channel.

```

let timelike_map c = P.Scattering.timelike c ∧ ¬(P.Scattering.s_channel c)

let count_maps n clist =
  List.fold_left (fun (s, t as cnt) (c, _) →
    if timelike_map c then
      (succ s, t)
    else if P.Scattering.spacelike c then
      (s, succ t)
    else
      cnt) (0, 0) clist

let poles_to_whizard n trees poles =
  let tree = List.map (fun wf →
    (P.Scattering.flip_s_channel_in (F.momentum wf), [F.flavor wf])) poles in
  add_tree (count_maps n tree) tree trees

```



I must reinstate the *conjugate* eventually!

```

let trees a =
  match F.externals a with
  | in1 :: in2 :: out →
    let n = List.length out + 2 in
    { in1 = F.flavor in1;
      in2 = F.flavor in2;
      out = List.map (fun f → (* M.conjugate *) (F.flavor f)) out;
      trees = List.fold_left
        (poles_to_whizard n) Poles.empty (F.poles a) }
  | _ → invalid_arg "Whizard().trees"

```

### 17.2.2 Merging Homomorphic Trees

```

module Pole_Map =
  Map.Make (struct type t = P.t list let compare = compare end)
module Flavor_Set =
  Set.Make (struct type t = F.flavor let compare = compare end)

let add_flavors flist fset =
  List.fold_right Flavor_Set.add flist fset

let set_of_flavors flist =
  List.fold_right Flavor_Set.add flist Flavor_Set.empty

let pack_tree map t =
  let c, f =
    List.split (List.sort (fun (c1, _) (c2, _) →
      compare (PW.of_momentum c2) (PW.of_momentum c1))) t) in
  let f' =
    try
      List.map2 add_flavors f (Pole_Map.find c map)
    with
    | Not_found → List.map set_of_flavors f in
  Pole_Map.add c f' map

let pack_map trees = List.fold_left pack_tree Pole_Map.empty trees

let merge_sets clist flist =
  List.map2 (fun c f → (c, Flavor_Set.elements f)) clist flist

let unpack_map map =
  Pole_Map.fold (fun c f l → (merge_sets c f) :: l) map []

```

If a singularity is to be mapped (i.e. if it is timelike and not the overall *s*-channel), expand merged particles again:

```

let unfold1 (c, f) =
  if timelike_map c then
    List.map (fun f' → (c, [f'])) f
  else
    [(c, f)]

```

```

let unfold_tree tree = Product.list (fun x → x) (List.map unfold1 tree)
let unfold trees = ThoList.flatmap unfold_tree trees
let merge t =
  { t with trees = Poles.map
    (fun t' → unfold (unpack_map (pack_map t')) t.trees }

```

### 17.2.3 Printing Trees

```

let flavors_to_string f =
  String.concat "/" (List.map M.flavor_to_string f)
let whizard_tree t =
  "tree" ^
  (String.concat " " (List.rev_map (fun (c, _) →
    (string_of_int (PW.of_momentum c))) t)) ^
  "!" ^
  (String.concat ", " (List.rev_map (fun (_, f) → flavors_to_string f) t))
let whizard_tree_debug t =
  "tree" ^
  (String.concat " " (List.rev_map (fun (c, _) →
    ("[" ^ (String.concat "+" (List.map string_of_int (P.to_ints c))) ^ "]")
    (List.sort (fun (t1, _) (t2, _) →
      let c =
        compare
          (List.length (P.to_ints t2))
          (List.length (P.to_ints t1)) in
      if c ≠ 0 then
        c
      else
        compare t1 t2) t))) ^
    "!" ^
  (String.concat ", " (List.rev_map (fun (_, f) → flavors_to_string f) t))
let format_maps = function
| (0, 0) → "neither_mapped_timelike_nor_spacelike_poles"
| (0, 1) → "no_mapped_timelike_poles_one_spacelike_pole"
| (0, n) → "no_mapped_timelike_poles" ^
  string_of_int n ^ "spacelike_poles"
| (1, 0) → "one_mapped_timelike_pole_no_spacelike_pole"
| (1, 1) → "one_mapped_timelike_and_spacelike_pole_each"
| (1, n) → "one_mapped_timelike_and" ^
  string_of_int n ^ "spacelike_poles"
| (n, 0) → string_of_int n ^
  "mapped_timelike_poles_and_no_spacelike_pole"
| (n, 1) → string_of_int n ^
  "mapped_timelike_poles_and_one_spacelike_pole"
| (n, n') → string_of_int n ^ "mapped_timelike_and" ^
  string_of_int n' ^ "spacelike_poles"

```



```

let format_flavor f =
  match flavors_to_string f with
  | "d" → "d" | "d̄" → "D"
  | "u" → "u" | "ū" → "U"
  | "s" → "s" | "s̄" → "S"
  | "c" → "c" | "c̄" → "C"
  | "b" → "b" | "b̄" → "B"
  | "t" → "t" | "t̄" → "T"
  | "e-" → "e1" | "e+" → "E1"
  | "nue" → "n1" | "nuebar" → "N1"
  | "mu-" → "e2" | "mu+" → "E2"
  | "numu" → "n2" | "numubar" → "N2"
  | "tau-" → "e3" | "tau+" → "E3"
  | "nutau" → "n3" | "nutaubar" → "N3"
  | "g" → "G" | "A" → "A" | "Z" → "Z"
  | "W+" → "W+" | "W-" → "W-"
  | "H" → "H"
  | s → s ^ "_(not_translated)"

module Mappable =
  Set.Make (struct type t = string let compare = compare end)
let mappable =
  List.fold_right Mappable.add
    [ "T"; "Z"; "W+"; "W-"; "H" ] Mappable.empty

let analyze_tree ch t =
  List.iter (fun (c, f) →
    let f' = format_flavor f
    and c' = PW.of_momentum c in
    if P.Scattering.timelike c then begin
      if P.Scattering.s_channel c then
        fprintf ch "!!!!!!_overall_s-channel_%d%s_not_mapped\n" c' f'
      else if Mappable.mem f' mappable then
        fprintf ch "!!!!!!map_%d_s-channel_%s\n" c' f'
      else
        fprintf ch
          "!!!!!!_%d_s-channel_%s_can't_be_mapped_by_whizard\n"
          c' f'
    end else
      fprintf ch "!!!!!!_t-channel_%d%s_not_mapped\n" c' f') t

let write ch pid t =
  failwith "Whizard.Make().write:incomplete"
  fprintf ch "process_%s\n" pid;
  Poles.iter (fun maps ds →
    fprintf ch "\n!!!!!!_d_times_%s:\n"
      (List.length ds) (format_maps maps);
    List.iter (fun d →
      fprintf ch "\n!!!!!!grove\n";
      fprintf ch "!!!!!!s\n" (whizard_tree d);
      analyze_tree ch d) ds) t.trees;
  fprintf ch "\n!_0'Mega_revision_control_information:\n";

```

```

      List.iter (fun s → fprintf ch "!%s\n" s)
        (ThoList.flatmap RCS.summary (rcs :: M.rcs :: F.rcs_list));
      fprintf ch "\n"
    i × )
  end

```

#### 17.2.4 Process Dispatcher

```

let arguments = function
| [] → (" ", "")
| args →
  let arg_list = String.concat ", " (List.map snd args) in
  (arg_list, ", " ^ arg_list)

let import_prefix ch pid name =
  fprintf ch "use%s,only:%s-%s=>%s!NODEP!\n"
    pid pid name name

let declare_argument ch (arg_type, arg) =
  fprintf ch "%s,intent(in):%s\n" arg_type arg

let call_function ch pid result name args =
  fprintf ch "case(pr-%s)\n" pid;
  fprintf ch "%s=%s-%s(%s)\n" result pid name args

let default_function ch result default =
  fprintf ch "case default\n";
  fprintf ch "call_invalid_process(pid)\n";
  fprintf ch "%s=%s\n" result default

let call_subroutine ch pid name args =
  fprintf ch "case(pr-%s)\n" pid;
  fprintf ch "%s-%s(%s)\n" pid name args

let default_subroutine ch =
  fprintf ch "case default\n";
  fprintf ch "call_invalid_process(pid)\n"

let write_interface_subroutine ch wrapper name args processes =
  let arg_list, arg_list' = arguments args in
  fprintf ch "subroutine%s(pid%s)\n" wrapper arg_list';
  List.iter (fun p → import_prefix ch p name) processes;
  List.iter (declare_argument ch) (("character(len=*)", "pid") :: args);
  fprintf ch "select case(pid)\n";
  List.iter (fun p → call_subroutine ch p name arg_list) processes;
  default_subroutine ch;
  fprintf ch "end select\n";
  fprintf ch "end subroutine%s\n" wrapper

let write_interface_function ch wrapper name
  (result_type, result, default) args processes =
  let arg_list, arg_list' = arguments args in
  fprintf ch "function%s(pid%s)%s(%s)\n" wrapper arg_list' result;

```

```

List.iter (fun p → import_prefixed ch p name) processes;
List.iter (declare_argument ch) (("character(len=*)", "pid") :: args);
fprintf ch "%%s:::%s\n" result_type result;
fprintf ch "%%select_case(pid)\n";
List.iter (fun p → call_function ch p result name arg_list) processes;
default_function ch result default;
fprintf ch "%%end_select\n";
fprintf ch "%%end_function%%s\n" wrapper

let write_other_interface_functions ch =
  fprintf ch "%%subroutine_invalid_process(pid)\n";
  fprintf ch "%%character(len=*),intent(in)::pid\n";
  fprintf ch "%%print*,\"PANIC:\"";
  fprintf ch "process '\"//trim(pid)//\"'\",not_available!\n";
  fprintf ch "%%end_subroutine_invalid_process\n";
  fprintf ch "%%function_n_tot(pid),result(n)\n";
  fprintf ch "%%character(len=*),intent(in)::pid\n";
  fprintf ch "%%integer::n\n";
  fprintf ch "%%n=n_in(pid)+n_out(pid)\n";
  fprintf ch "%%end_function_n_tot\n"

let write_other_declarations ch =
  fprintf ch "%%public::n_in,n_out,n_tot,pg_code\n";
  fprintf ch "%%public::allow_helicities\n";
  fprintf ch "%%public::create,destroy\n";
  fprintf ch "%%public::set_const,sqme\n";
  fprintf ch "%%interface_create\n";
  fprintf ch "%%module_procedure_process_create\n";
  fprintf ch "%%end_interface\n";
  fprintf ch "%%interface_destroy\n";
  fprintf ch "%%module_procedure_process_destroy\n";
  fprintf ch "%%end_interface\n";
  fprintf ch "%%interface_set_const\n";
  fprintf ch "%%module_procedure_process_set_const\n";
  fprintf ch "%%end_interface\n";
  fprintf ch "%%interface_sqme\n";
  fprintf ch "%%module_procedure_process_sqme\n";
  fprintf ch "%%end_interface\n"

let write_interface ch names =
  fprintf ch "module_process_interface\n";
  fprintf ch "use kinds,only:default,NODEP!\n";
  fprintf ch "use parameters,only:parameter_set\n";
  fprintf ch "implicit none\n";
  fprintf ch "private\n";
  List.iter (fun p →
    fprintf ch
      "character(len=*),parameter,public::pr_%%s= \"%%s\" \"n\" p p)
    names;
  write_other_declarations ch;
  fprintf ch "contains\n";
  write_interface_function ch "n_in" "n_in" ("integer", "n", "0") [] names;

```

```

write_interface_function ch "n_out" "n_out" ("integer", "n", "0") [] names;
write_interface_function ch "pdg_code" "pdg_code"
    ("integer", "n", "0") [ "integer", "i" ] names;
write_interface_function ch "allow_helicities" "allow_helicities"
    ("logical", "yorn", ".false.") [] names;
write_interface_subroutine ch "process_create" "create" [] names;
write_interface_subroutine ch "process_destroy" "destroy" [] names;
write_interface_subroutine ch "process_set_const" "set_const"
    [ "type(parameter_set)", "par" ] names;
write_interface_function ch "process_sqme" "sqme"
    ("real(kind=default)", "sqme", "0")
    [ "real(kind=default), dimension(0:,:)", "p";
      "integer, dimension(:), optional", "h" ] names;
write_other_interface_functions ch;
fprintf ch "end_module_process_interface\n"

```

### 17.2.5 Makefile

```
let write_makefile_ch_names =
  fprintf ch "KINDS_=@@KINDS@\n";
  fprintf ch "HELAS_=@@HELAS@\n";
  fprintf ch "F90_=@F90@\n";
  fprintf ch "F90FLAGS_=@F90FLAGS@\n";
  fprintf ch "F90INCL_=-I$(KINDS)_-I$(HELAS)\n";
  fprintf ch "F90COMMON_=@omega_bundle_whizard.f90";
  fprintf ch "_file_utils.f90_process_interface.f90\n";
  fprintf ch "include_Makefile.processes\n";
  fprintf ch "F90SRC_=$(F90COMMON)_$(F90PROCESSES)\n";
  fprintf ch "OBJ_=$(F90SRC:.f90=.o)\n";
  fprintf ch "MOD_=$(F90SRC:.f90=.mod)\n";
  fprintf ch "archive:@processes.a\n";
  fprintf ch "processes.a:@(OBJ)\n";
  fprintf ch "\t$(AR) r _$@(OBJ)\n";
  fprintf ch "\t@RANLIB@$@\n";
  fprintf ch "clean:\n";
  fprintf ch "\trm -f $(OBJ)\n";
  fprintf ch "realclean:\n";
  fprintf ch "\trm -f processes.a\n";
  fprintf ch "parameters.o:_file_utils.o\n";
  fprintf ch "omega_bundle_whizard.o:_parameters.o\n";
  fprintf ch "process_interface.o:_parameters.o\n";
  fprintf ch "%.@.%f90_$(KINDS)/kinds.f90\n";
  fprintf ch "\t$(F90)_$(F90FLAGS)_$(F90INCL)-c_<\n"

let write_makefile_processes_ch_names =
  fprintf ch "F90PROCESSES_=";
  List.iter (fun f → fprintf ch "_\\n%s.f90" f) names;
  fprintf ch "\n";
  List.iter (fun f →
    fprintf ch "%s.o:_omega_bundle_whizard.o_parameters
```

```
fprintf ch "process_interface.o:␣%s.o␣n" f) names
```

---

# —18—

## APPLICATIONS

### 18.1 *Sample*

### 18.2 *Interface of Omega*

```
module type T =  
  sig  
    val main : unit → unit
```



This used to be only intended for debugging O’Giga, but might live longer  
...

```
  type flavor  
  val diagrams : flavor → flavor → flavor list →  
    ((flavor × Momentum.Default.t) ×  
     (flavor × Momentum.Default.t,  
      flavor × Momentum.Default.t) Tree.t) list  
end  
  
module Make (FM : Fusion.Maker) (TM : Target.Maker) (M : Model.T) :  
  T with type flavor = M.flavor
```

### 18.3 *Implementation of Omega*

```
let (<<) f g x = f (g x)  
let (>>) f g x = g (f x)  
  
module P = Momentum.Default  
module P_Whizard = Momentum.DefaultW  
  
module type T =  
  sig  
    val main : unit → unit  
    type flavor  
    val diagrams : flavor → flavor → flavor list →  
      ((flavor × Momentum.Default.t) ×  
       (flavor × Momentum.Default.t,
```

```

      flavor × Momentum.Default.t) Tree.t) list
end

module Make (Fusion_Maker : Fusion.Maker) (Target_Maker : Target.Maker) (M : Model.T) =
struct
  module CM = Colorize.It(M)
  type flavor = M.flavor
  module Proc = Process.Make(M)

```



NB: this causes the constant initializers in *Fusion\_Maker* more than once. Such side effects must be avoided if the initializers involve expensive computations. *Relying on the fact that the functor will be called only once is not a good idea!*

```

module F = Fusion_Maker(P)(M)
module CF = Fusion.Multi(Fusion_Maker)(P)(M)
module T = Target_Maker(Fusion_Maker)(P)(M)
module W = Whizard.Make(Fusion_Maker)(P)(P_Whizard)(M)
module C = Cascade.Make(M)(P)

```

Form a  $\alpha$  list from a  $\alpha$  option array, containing the elements that are not *None* in order.

```

let opt_array_to_list a =
  let rec opt_array_to_list' acc i a =
    if i < 0 then
      acc
    else
      begin match a.(i) with
      | None → opt_array_to_list' acc (pred i) a
      | Some x → opt_array_to_list' (x :: acc) (pred i) a
      end in
    opt_array_to_list' [] (Array.length a - 1) a

```

Return a list of *CF.amplitude lists*, corresponing to the diagrams for a specific color flow for each flavor combination.

```

let amplitudes_by_flavor amplitudes =
  List.map opt_array_to_list (Array.to_list (CF.process_table amplitudes))

```



If we plan to distiguish different couplings later on, we can no long map all instances of *coupling option* in the tree to *None*. In this case, we will need to normalize different fusion orders *Coupling.fuse2*, *Coupling.fuse3* or *Coupling.fusen*, because they would otherwise lead to inequivalent diagrams. Unfortunately, this stuff packaged deep in *Fusion.Tagged\_Coupling*.



The *Tree.canonicalize* below should be necessary to remove topologically equivalent duplicates.

Take a *CF.amplitude list* assumed to correspond to the same external states after stripping the color and return a pair of the list of external particles and the corresponding Feynman diagrams without color.

```

let wf1 amplitude =
  match F.externals amplitude with
  | wf :: _ → wf
  | [] → failwith "Omega.forest_sans_color:_no_external_particles"

let uniq l =
  ThoList.uniq (List.sort compare l)

let forest_sans_color = function
| amplitude :: _ as amplitudes →
  let externals = F.externals amplitude in
  let prune_color wf =
    (F.flavor_sans_color wf, F.momentum_list wf) in
  let prune_color_and_couplings (wf, c) =
    (prune_color wf, None) in
  (List.map prune_color externals,
   uniq
    (List.map
      (fun t →
        Tree.canonicalize
          (Tree.map prune_color_and_couplings prune_color t))
      (ThoList.flatmap (fun a → F.forest (wf1 a) a) amplitudes)))
| [] → ([], [])

let p2s p =
  if p ≥ 0 ∧ p ≤ 9 then
    string_of_int p
  else if p ≤ 36 then
    String.make 1 (Char.chr (Char.code 'A' + p - 10))
  else
    "_"

let format_p wf =
  String.concat "" (List.map p2s (F.momentum_list wf))

let variable wf =
  M.flavor_to_string (F.flavor_sans_color wf) ^ "[" ^ format_p wf ^ "]"

let variable' wf =
  CM.flavor_to_TeX (F.flavor wf) ^ "(" ^ format_p wf ^ ")"

let feynmf_style propagator color =
{ Tree.style =
  begin match propagator with
  | Coupling.Prop_Feynman
  | Coupling.Prop_Gauge _ →
  begin match color with
  | Color.AdjSUN _ → Some ("gluon", "")
  | _ → Some ("boson", "")
  end
end

```



```

| Coupling.Prop_Col_Feynman → Some ("gluon", "")
| Coupling.Prop_Unitarity
| Coupling.Prop_Rxi _ → Some ("dbl_wiggly", "")
| Coupling.Prop_Spinor
| Coupling.Prop_ConjSpinor → Some ("fermion", "")
| _ → None
end;
Tree.rev =
begin match propagator with
| Coupling.Prop_Spinor → true
| Coupling.Prop_ConjSpinor → false
| _ → false
end;
Tree.label = None;
Tree.tension = None }

let header incoming outgoing =
"$\square" ^
String.concat "\square"
(List.map (CM.flavor_to_TeX << F.flavor) incoming) ^
"\square\to\square" ^
String.concat "\square"
(List.map (CM.flavor_to_TeX << CM.conjugate << F.flavor) outgoing) ^
"\square$"

let header_sans_color incoming outgoing =
"$\square" ^
String.concat "\square"
(List.map (M.flavor_to_TeX << fst) incoming) ^
"\square\to\square" ^
String.concat "\square"
(List.map (M.flavor_to_TeX << M.conjugate << fst) outgoing) ^
"\square$"

let diagram incoming tree =
let fmf wf =
let f = F.flavor wf in
feynmf_style (CM.propagator f) (CM.color f) in
Tree.map
(fun (n, _) →
let n' = fmf n in
if List.mem n incoming then
{ n' with Tree.rev = ¬ n'.Tree.rev }
else
n')
(fun l →
if List.mem l incoming then
l
else
F.conjugate l)
tree

```

```

let diagram_sans_color incoming (tree) =
  let fmf (f, p) =
    feynmf_style (M.propagator f) (M.color f) in
  Tree.map
    (fun (n, c) →
      let n' = fmf n in
      if List.mem n incoming then
        { n' with Tree.rev = ¬ n'.Tree.rev }
      else
        n')
    (fun (f, p) →
      if List.mem (f, p) incoming then
        (f, p)
      else
        (M.conjugate f, p))
  tree

let feynmf_set_amplitude =
  match F.externals amplitude with
  | wf1 :: wf2 :: wfs →
    let incoming = [wf1; wf2] in
    { Tree.header = header incoming wfs;
      Tree.incoming = incoming;
      Tree.diagrams =
        List.map (diagram incoming) (F.forest wf1 amplitude) }
  | _ → failwith "less_than_two_external_particles"

let feynmf_set_sans_color (externals, trees) =
  match externals with
  | wf1 :: wf2 :: wfs →
    let incoming = [wf1; wf2] in
    { Tree.header = header_sans_color incoming wfs;
      Tree.incoming = incoming;
      Tree.diagrams =
        List.map (diagram_sans_color incoming) trees }
  | _ → failwith "less_than_two_external_particles"

let feynmf_set_sans_color_empty (externals, trees) =
  match externals with
  | wf1 :: wf2 :: wfs →
    let incoming = [wf1; wf2] in
    { Tree.header = header_sans_color incoming wfs;
      Tree.incoming = incoming;
      Tree.diagrams = [] }
  | _ → failwith "less_than_two_external_particles"

let uncolored_colored_amplitudes =
  { Tree.outer = feynmf_set_sans_color (forest_sans_color amplitudes);
    Tree.inner = List.map feynmf_set amplitudes }

let uncolored_only_amplitudes =
  { Tree.outer = feynmf_set_sans_color (forest_sans_color amplitudes);
    Tree.inner = [] }

```



```

type cache_mode =
  | Cache_Default
  | Cache_Initialize of string

let cache_option =
  ref Cache_Default

let unphysical_polarization = ref None

```

### 18.3.1 Main Program

```

let main () =
  let usage =
    "usage: " ^ Sys.argv.(0) ^
    "[options] [" ^
      String.concat "|" (List.map M.flavor_to_string
        (ThoList.flatmap snd
          (M.external_flavors ()))) ^ "]"
  and rev_scatterings = ref []
  and rev_decays = ref []
  and cascades = ref []
  and checks = ref []
  and output_file = ref None
  and print_forest = ref false
  and template = ref false
  and diagrams_all = ref None
  and diagrams_sans_color = ref None
  and diagrams_color_only = ref None
  and diagrams_LaTeX = ref false
  and quiet = ref false
  and write = ref true
  and params = ref false
  and poles = ref false
  and dag_out = ref None
  and dag0_out = ref None in
  Arg.parse
    (Options.cmdline "-target:" T.options @
     Options.cmdline "-model:" M.options @
     Options.cmdline "-fusion:" CF.options @
     ThoList.flatmap debug
       ["a", "arguments", T.All, checks;
        "n", "#_of_input_arguments", T.Arguments, checks;
        "m", "input_momenta", T.Momenta, checks;
        "g", "internal_Ward_identities", T.Gauge, checks] @
     [("-o", Arg.String (fun s → output_file := Some s),
       "file_ write_to_given_file_instead_of_/dev/stdout");
      ("-scatter",
       Arg.String (fun s → rev_scatterings := s :: !rev_scatterings),
       "expr_in1_in2->out1_out2...");
      ("-scatter_file",

```

```

    Arg.String (fun s → rev_scatterings := read_lines_rev s @ !rev_scatterings),
    "name_{}_each_line:{}_in1{}_in2->{}_out1{}_out2...");
  ("-decay", Arg.String (fun s → rev_decays := s :: !rev_decays),
    "expr_{}{}_in->{}_out1{}_out2...");
  ("-decay_file",
    Arg.String (fun s → rev_decays := read_lines_rev s @ !rev_decays),
    "name_{}_each_line:{}_in->{}_out1{}_out2...");
  ("-cascade", Arg.String (fun s → cascades := s :: !cascades),
    "expr_{}{}_select_diagrams");
  ("-initialize",
    Arg.String (fun s → cache_option := Cache_Initialize s),
    "dir_{}{}_precompute_lookup_tables_and_store_them_in_directory");
  ("-unphysical", Arg.Int (fun i → unphysical_polarization := Some i),
    "n_{}{}_use_unphysical_polarization_for_n-th_particle_/_test_WIs");
  ("-template", Arg.Set template,
    "write_a_template_for_handwritten_amplitudes");
  ("-forest", Arg.Set print_forest,
    "Diagrammatic_expansion");
  ("-diagrams", Arg.String (fun s → diagrams_sans_color := Some s),
    "file_{}{}_produce_FeynMP_output_for_Feynman_diagrams");
  ("-diagrams:c", Arg.String (fun s → diagrams_color_only := Some s),
    "file_{}{}_produce_FeynMP_output_for_color_flow_diagrams");
  ("-diagrams:C", Arg.String (fun s → diagrams_all := Some s),
    "file_{}{}_produce_FeynMP_output_for_Feynman_and_color_flow_diagrams");
  ("-diagrams_LaTeX", Arg.Set diagrams_LaTeX,
    "enclose_FeynMP_output_in_LaTeX_wrapper");
  ("-revision", Arg.Unit version,
    "print_revision_control_information");
  ("-quiet", Arg.Set quiet,
    "don't_print_a_summary");
  ("-summary", Arg.Clear write,
    "print_only_a_summary");
  ("-params", Arg.Set params,
    "print_the_model_parameters");
  ("-poles", Arg.Set poles,
    "print_the_Monte_Carlo_poles");
  ("-dag", Arg.String (fun s → dag_out := Some s),
    "print_minimal_DAG");
  ("-full_dag", Arg.String (fun s → dag0_out := Some s),
    "print_complete_DAG"))
  (fun _ → prerr_endline usage; exit 1)
  usage;

let cmdline =
  String.concat " " (List.map ThoString.quote (Array.to_list Sys.argv)) in

let output_channel =
  match !output_file with
  | None → stdout
  | Some name → open_out name in

```

```

let processes =
  try
    ThoList.uniq
      (List.sort compare
        (match List.rev !rev_scatterings, List.rev !rev_decays with
         | [], [] → []
         | scatterings, [] →
             Proc.expand_scatterings (List.map Proc.parse_scattering scatterings)
         | [], decays →
             Proc.expand_decays (List.map Proc.parse_decay decays)
         | scatterings, decays →
             invalid_arg "mixed_scattering_and_decay!"))
  with
  | Invalid_argument s →
      begin
        Printf.eprintf "0'Mega: invalid_process_specification: %s!\n" s;
        flush stderr;
        []
      end in

```



This is still crude. Eventually, we want to catch *all* exceptions and write an empty (but compilable) amplitude unless one of the special options is selected.

```

begin match processes, !cache_option, !params with
| [], Cache_Initialize dir, false →
    F.initialize_cache dir;
    exit 0
| -, -, true →
    T.parameters_to_channel output_channel;
    exit 0
| [], -, false →
    T.amplitudes_to_channel cmdline output_channel !checks CF.empty;
    exit 0
| -, -, false →
    let selectors =
      let fin, fout = List.hd processes in
      C.to_selectors (C.of_string_list (List.length fin + List.length fout) !cascades) in
    let amplitudes =
      try
        begin match F.check_charges () with
        | [] → ()
        | violators →
            let violator_strings =
              String.concat ", "
                (List.map
                 (fun flist →
                  "(" ^ String.concat ", " (List.map M.flavor_to_string flist) ^ ")")
                 violators) in

```

```

        failwith ("charge_violating_vertices:_" ^ violator_strings)
    end;
    CF.amplitudes (include_goldstones !checks) !unphysical_polarization selectors processes
with
| exc →
    begin
        Printf.eprintf
            "O'Mega: _exception_%s_in_amplitude_construction!\n"
            (Printexc.to_string exc);
        flush stderr;
        CF.empty;
    end in
if !write then
    T.amplitudes_to_channel cmdline output_channel !checks amplitudes;
if ¬ !quiet then begin
    List.iter
        (fun amplitude →
            Printf.eprintf "SUMMARY:_%d_fusions,_%d_propagators"
                (F.count_fusions amplitude) (F.count_propagators amplitude);
            flush stderr;
            Printf.eprintf ",_%d_diagrams" (F.count_diagrams amplitude);
            Printf.eprintf "\n")
            (CF.processes amplitudes);
end;
if !poles then begin
    List.iter
        (fun amplitude →
            W.write output_channel "omega" (W.merge (W.trees amplitude)))
            (CF.processes amplitudes)
end;
begin match !dag0_out with
| Some name →
    let ch = open_out name in
    List.iter (F.tower_to_dot ch) (CF.processes amplitudes);
    close_out ch
| None → ()
end;
begin match !dag_out with
| Some name →
    let ch = open_out name in
    List.iter (F.amplitude_to_dot ch) (CF.processes amplitudes);
    close_out ch
| None → ()
end;
if !print_forest then
    List.iter
        (fun amplitude →

```

```

        List.iter (fun t → Printf.eprintf "%s\n"
            (Tree.to_string
                (Tree.map (fun (wf, _) → variable wf) (fun _ →
                    "")) t)))
            (F.forest (List.hd (F.externals amplitude)) amplitude))
        (CF.processes amplitudes);
begin match !diagrams_all with
| Some name →
    amplitudes_to_feynmf !diagrams_LaTeX name amplitudes
| None → ()
end;
begin match !diagrams_sans_color with
| Some name →
    amplitudes_to_feynmf_sans_color !diagrams_LaTeX name amplitudes
| None → ()
end;
begin match !diagrams_color_only with
| Some name →
    amplitudes_to_feynmf_color_only !diagrams_LaTeX name amplitudes
| None → ()
end;
begin match !output_file with
| None → ()
| Some name → close_out output_channel
end;
exit 0
end

```



This was only intended for debugging O’Giga ...

```

let decode wf =
    (F.flavor wf, (F.momentum wf : Momentum.Default.t))
let diagrams in1 in2 out =
    match F.amplitudes false C.no_cascades [in1; in2] out with
    | a :: _ →
        let wf1 = List.hd (F.externals a)
        and wf2 = List.hd (List.tl (F.externals a)) in
        let wf2 = decode wf2 in
        List.map (fun t →
            (wf2,
                Tree.map (fun (wf, _) → decode wf) decode t))
            (F.forest wf1 a)
    | [] → []
let diagrams in1 in2 out =
    failwith "Omega().diagrams: disabled"
end

```



## 18.4 Implementation of *Omega-QED*

```
module O = Omega.Make(Fusion.Binary)(Targets.Fortran)(Modellib.SM.QED)
let _ = O.main ()
```

## 18.5 Implementation of *Omega-SM*

```
module O = Omega.Make(Fusion.Mixed23)(Targets.Fortran)
                                   (Modellib.SM.SM (Modellib.SM.SM_no_anomalous))
let _ = O.main ()
```

## 18.6 Implementation of *Omega-SYM*

```
let rcs_file = RCS.parse "omega-SYM"
  ["SuperYang-Mills (incomplete, just for stress-testing Colorize.It())"]
  { RCS.revision = "$Revision: 6004$";
    RCS.date = "$Date: 2014-07-09 17:46:54 +0200 (Wed, 09 Jul 2014)$";
    RCS.author = "$Author: cweiss$";
    RCS.source = "$URL: svn+ssh://jr-reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/sym";
  }

module SYM =
struct
  let rcs = rcs_file

  open Coupling

  let options = Options.empty

  let nc = 3

  type flavor =
    | Q of int | SQ of int
    | G of int | SG of int
    | Phi

  let generations = ThoList.range 1 1

  let generations_pairs =
    List.map
      (function [a; b] → (a, b)
        | _ → failwith "omega-SYM.generations_pairs")
      (Product.power 2 generations)

  let generations_triples =
    List.map
      (function [a; b; c] → (a, b, c)
        | _ → failwith "omega-SYM.generations_triples")
      (Product.power 3 generations)

  let generations_quadruples =
```

```

List.map
  (function [a; b; c; d] → (a, b, c, d)
   | _ → failwith "omega-SYM.generations_quadruples")
  (Product.power 4 generations)

let external_flavors () =
  [ "Quarks", List.map (fun i → Q i) generations;
    "Anti-Quarks", List.map (fun i → Q (-i)) generations;
    "SQuarks", List.map (fun i → SQ i) generations;
    "Anti-SQuarks", List.map (fun i → SQ (-i)) generations;
    "Gluons", List.map (fun i → G i) generations;
    "SGluons", List.map (fun i → SG i) generations;
    "Other", [Phi]]

let flavors () =
  ThoList.flatmap snd (external_flavors ())

type gauge = unit
type constant =
  | G_saa of int × int
  | G_saaa of int × int × int
  | G3 of int × int × int
  | I_G3 of int × int × int
  | G4 of int × int × int × int

type orders = unit
let orders = function
  | _ → ()

let lorentz = function
  | Q i →
    if i > 0 then
      Spinor
    else if i < 0 then
      ConjSpinor
    else
      invalid_arg "SYM.lorentz_⊔(Q_0)"
  | SQ _ | Phi → Scalar
  | G _ → Vector
  | SG _ → Majorana

let color = function
  | Q i | SQ i →
    Color.SUN (if i > 0 then nc else if i < 0 then -nc else invalid_arg "SYM.color_⊔(Q_0)")
  | G _ | SG _ → Color.AdjSUN nc
  | Phi → Color.Singlet

let propagator = function
  | Q i →
    if i > 0 then
      Prop_Spinor
    else if i < 0 then
      Prop_ConjSpinor
    else

```

```

      invalid_arg "SYM.lorentz_⊔(Q_0)"
    | SQ _ | Phi → Prop_Scalar
    | G _ → Prop_Feynman
    | SG _ → Prop_Majorana
let width _ = Timelike
let goldstone _ = None
let conjugate = function
| Q i → Q (-i)
| SQ i → SQ (-i)
| (G _ | SG _ | Phi) as p → p
let fermion = function
| Q i →
  if i > 0 then
    1
  else if i < 0 then
    -1
  else
    invalid_arg "SYM.fermion_⊔(Q_0)"
| SQ _ | G _ | Phi → 0
| SG _ → 2
module Ch = Charges.Null
let charges _ = ()
module F = Modeltools.Fusions (struct
  type f = flavor
  type c = constant
  let compare = compare
  let conjugate = conjugate
end)
let quark_current =
  List.map
    (fun (i, j, k) →
      ((Q (-i), G j, Q k), FBF (-1, Psibar, V, Psi), G3 (i, j, k)))
    generations_triples
let squark_current =
  List.map
    (fun (i, j, k) →
      ((G j, SQ i, SQ (-k)), Vector_Scalar_Scalar 1, G3 (i, j, k)))
    generations_triples
let three_gluon =
  List.map
    (fun (i, j, k) →
      ((G i, G j, G k), Gauge_Gauge_Gauge 1, I_G3 (i, j, k)))
    generations_triples
let gluon2_phi =
  List.map
    (fun (i, j) →

```

```

      ((Phi, G i, G j), Dim5_Scalar_Gauge2 1, G_saa (i, j)))
    generations_pairs

let vertices3 =
  quark_current @ squark_current @ three_gluon @ gluon2_phi
let gauge4 = Vector4 [(2, C_13_42); (-1, C_12_34); (-1, C_14_23)]
let squark_seagull =
  List.map
    (fun (i, j, k, l) →
      ((SQ i, SQ (-j), G k, G l), Scalar2_Vector2 1, G4 (i, j, k, l)))
    generations_quadruples
let four_gluon =
  List.map
    (fun (i, j, k, l) →
      ((G i, G j, G k, G l), gauge4, G4 (i, j, k, l)))
    generations_quadruples

```



We need at least a *Dim6\_Scalar\_Gauge3* vertex to support this.

```

let gluon3_phi =
  []
let vertices4 =
  squark_seagull @ four_gluon @ gluon3_phi
let vertices () =
  (vertices3, vertices4, [])
let table = F.of_vertices (vertices ())
let fuse2 = F.fuse2 table
let fuse3 = F.fuse3 table
let fuse = F.fuse table
let max_degree () = 4
let parameters () = { input = []; derived = []; derived_arrays = [] }
let invalid_flavor s =
  invalid_arg ("omega-SYM.flavor_of_string:␣" ^ s)
let flavor_of_string s =
  let l = String.length s in
  if l < 2 then
    invalid_flavor s
  else if l = 2 then
    if String.sub s 0 1 = "q" then
      Q (int_of_string (String.sub s 1 1))
    else if String.sub s 0 1 = "Q" then
      Q (- (int_of_string (String.sub s 1 1)))
    else if String.sub s 0 1 = "g" then
      G (int_of_string (String.sub s 1 1))
    else
      invalid_flavor s

```

```

else if  $l = 3$  then
  if  $s = \text{"phi"}$  then
     $\Phi$ 
  else if  $\text{String.sub } s \ 0 \ 2 = \text{"sq"}$  then
     $SQ \ (\text{int\_of\_string } (\text{String.sub } s \ 2 \ 1))$ 
  else if  $\text{String.sub } s \ 0 \ 2 = \text{"sQ"}$  then
     $SQ \ (- \ (\text{int\_of\_string } (\text{String.sub } s \ 2 \ 1)))$ 
  else if  $\text{String.sub } s \ 0 \ 2 = \text{"sg"}$  then
     $SG \ (\text{int\_of\_string } (\text{String.sub } s \ 2 \ 1))$ 
  else
     $\text{invalid\_flavor } s$ 
else
   $\text{invalid\_flavor } s$ 

let  $\text{flavor\_to\_string} = \text{function}$ 
|  $Q \ i \rightarrow$ 
  if  $i > 0$  then
     $\text{"q"} \wedge \text{string\_of\_int } i$ 
  else if  $i < 0$  then
     $\text{"Q"} \wedge \text{string\_of\_int } (-i)$ 
  else
     $\text{invalid\_arg "SYM.flavor\_to\_string\_}(Q_0)\text{"}$ 
|  $SQ \ i \rightarrow$ 
  if  $i > 0$  then
     $\text{"sq"} \wedge \text{string\_of\_int } i$ 
  else if  $i < 0$  then
     $\text{"sQ"} \wedge \text{string\_of\_int } (-i)$ 
  else
     $\text{invalid\_arg "SYM.flavor\_to\_string\_}(SQ_0)\text{"}$ 
|  $G \ i \rightarrow \text{"g"} \wedge \text{string\_of\_int } i$ 
|  $SG \ i \rightarrow \text{"sg"} \wedge \text{string\_of\_int } i$ 
|  $\Phi \rightarrow \text{"phi"}$ 

let  $\text{flavor\_to\_TeX} = \text{function}$ 
|  $Q \ i \rightarrow$ 
  if  $i > 0$  then
     $\text{"q-"} \wedge \text{string\_of\_int } i \wedge \text{"}"$ 
  else if  $i < 0$  then
     $\text{"{\bar{q}}-"} \wedge \text{string\_of\_int } (-i) \wedge \text{"}"$ 
  else
     $\text{invalid\_arg "SYM.flavor\_to\_string\_}(Q_0)\text{"}$ 
|  $SQ \ i \rightarrow$ 
  if  $i > 0$  then
     $\text{"{\tilde{q}}-"} \wedge \text{string\_of\_int } i \wedge \text{"}"$ 
  else if  $i < 0$  then
     $\text{"{\bar{\tilde{q}}}}-"} \wedge \text{string\_of\_int } (-i) \wedge \text{"}"$ 
  else
     $\text{invalid\_arg "SYM.flavor\_to\_string\_}(SQ_0)\text{"}$ 
|  $G \ i \rightarrow \text{"g-"} \wedge \text{string\_of\_int } i \wedge \text{"}"$ 
|  $SG \ i \rightarrow \text{"{\tilde{g}}-"} \wedge \text{string\_of\_int } i \wedge \text{"}"$ 
|  $\Phi \rightarrow \text{"phi"}$ 

```

```

let flavor_symbol = function
| Q i →
  if i > 0 then
    "q" ^ string_of_int i
  else if i < 0 then
    "qbar" ^ string_of_int (-i)
  else
    invalid_arg "SYM.flavor_to_string_␣(Q_␣0)"
| SQ i →
  if i > 0 then
    "sq" ^ string_of_int i
  else if i < 0 then
    "sqbar" ^ string_of_int (-i)
  else
    invalid_arg "SYM.flavor_to_string_␣(SQ_␣0)"
| G i → "g" ^ string_of_int i
| SG i → "sg" ^ string_of_int i
| Phi → "phi"

let gauge_symbol () =
  failwith "omega-SYM.gauge_symbol:␣internal␣error"

let pdg _ = 0
let mass_symbol _ = "0.0_default"
let width_symbol _ = "0.0_default"

let string_of_int_list int_list =
  "(" ^ String.concat "," (List.map string_of_int int_list) ^ ")"

let constant_symbol = function
| G_saa (i, j) → "g_saa" ^ string_of_int_list [i; j]
| G_saaa (i, j, k) → "g_saaa" ^ string_of_int_list [i; j; k]
| G3 (i, j, k) → "g3" ^ string_of_int_list [i; j; k]
| I_G3 (i, j, k) → "ig3" ^ string_of_int_list [i; j; k]
| G4 (i, j, k, l) → "g4" ^ string_of_int_list [i; j; k; l]

end

module O = Omega.Make(Fusion.Mixed23)(Targets.Fortran_Majorana)(SYM)
let _ = O.main ()

```

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---

# —A—

## REVISION CONTROL

### A.1 Interface of *RCS*

This is a very simple library for exporting and accessing *RCS* and *CVS* revision control information. In addition, module names and short descriptions are supported as well.

If multiple applications are constructed by functors, the functions in this module can be used to identify the concrete implementations. In the context of O’Mega, this is particularly important for physics models and target languages. One structure of type *raw* has to be initialized in each file by the raw *RCS* keyword strings. It can remain private to the module, because it is only used as argument to the function *parse*.

`type raw = { revision : string; date : string; author : string; source : string }`

Parsed revision control info:

`type t`

*parse name description keywords* initializes revision control info:

`val parse : string → string list → raw → t`

*rename rcs name description* changes the name and description. This is useful if more than one module is defined in a file.

`val rename : t → string → string list → t`

Access individual parts of the revision control information:

`val name : t → string`

`val description : t → string list`

`val revision : t → string`

`val date : t → string`

`val author : t → string`

This one tries *URL* (*svn*), *Source* (*CVS*) and *Id*, in that order, for the filename.

`val source : t → string`

Return the formatted revision control info as a list of strings suitable for printing to the terminal or embedding in the output:

`val summary : t → string list`

## A.2 Implementation of RCS

```

type raw = { revision : string; date : string; author : string; source : string }

type t =
  { name : string;
    description : string list;
    rcs_revision : string;
    rcs_date : string;
    rcs_author : string;
    rcs_source : string }

let name r = r.name
let description r = r.description
let revision r = r.rcs_revision
let date r = r.rcs_date
let author r = r.rcs_author
let source r = r.rcs_source

module TS = ThoString

let strip_dollars s =
  TS.strip_from_last '$' (TS.strip_prefix "$" s)

let strip_keyword k s =
  TS.strip_prefix_star ' ' (TS.strip_prefix ":" (TS.strip_required_prefix k s))

let parse1 k s =
  strip_keyword k (strip_dollars s)

let strip_before_keyword k s =
  try
    let i = TS.index_string k s in
    String.sub s i (String.length s - i)
  with
  | Not_found → s

let strip_before_a_keyword k_list s =
  let rec strip_before_a_keyword' = function
    | k :: k_rest →
        begin try
          let i = TS.index_string k s in
          String.sub s i (String.length s - i)
        with
        | Not_found → strip_before_a_keyword' k_rest
        end
    | [] → s in
  strip_before_a_keyword' k_list

let parse_source s =
  let s = strip_dollars s in

```

Required for the transition from CVS to Subversion, because the latter doesn't support the `Source` keyword. `URL` is probably the way to go, but we leave in `Id` as a fallback option.

```

try strip_keyword "URL" s with Invalid_argument _ →
  try strip_keyword "Source" s with Invalid_argument _ →
    TS.strip_from_first ' ' (strip_keyword "Id" s)

```

Assume that the SVN repository follows the recommended layout and that all files can be found beneath `/trunk/`, `/branches/` or `/tags/`. Strip everything before that.

```

let strip_svn_repos s =
  strip_before_a_keyword ["/trunk/"; "/branches/"; "/tags/"] s

let parse_name_description r =
  { name = name;
    description = description;
    rcs_revision = parse1 "Revision" r.revision;
    rcs_date = parse1 "Date" r.date;
    rcs_author = parse1 "Author" r.author;
    rcs_source = strip_svn_repos (parse_source r.source) }

let rename_rcs name description =
  { rcs with name = name; description = description }

let summary rcs =
  [ name rcs ^ ":" ] @
  List.map (fun s → "  " ^ s) (description rcs) @
  [ "  Source:" ^ source rcs;
    "  revision:" ^ revision rcs ^ "checked_in_by" ^
    author rcs ^ "at" ^ date rcs ]

```

---

# —B—

## AUTOTOOLS

### *B.1 Interface of Config*

Cache writing is attempted in the order `[system_cache_dir]`, `[user_cache_dir]`, `["."]` and cache reading in the opposite order.

```
val system_cache_dir : string
val user_cache_dir   : string

val cache_prefix : string
val cache_suffix : string

val openmp : bool
```

### *B.2 Implementation of Config*

```
let system_cache_dir = "/Users/reuter/local/packages/whizard/omega/inst/var/cache"
let user_cache_dir   = "/Users/reuter/.whizard/var/cache"
```



This relies on the fact that the executable names should be unique.

```
let cache_prefix =
  let basename = Filename.basename Sys.executable_name in
  try Filename.chop_extension basename with | _ → basename

let cache_suffix = "vertices"

let openmp = false
```

---

# —C—

## TEXTUAL OPTIONS

### *C.1 Interface of Options*

```
type t
val empty : t
val merge : t → t → t
val extend : t → (string × Arg.spec × string) list → t
val create : (string × Arg.spec × string) list → t
val parse : t → string × string → unit
val list : t → (string × string) list
val cmdline : string → t → (string × Arg.spec × string) list
exception Invalid of string × string
```

### *C.2 Implementation of Options*

```
module A = Map.Make (struct type t = string let compare = compare end)
type t =
  { actions : Arg.spec A.t;
    raw : (string × Arg.spec × string) list }
let empty = { actions = A.empty; raw = [] }
let extend old options =
  { actions = List.fold_left
    (fun a (s, f, _) → A.add s f a) old.actions options;
    raw = options @ old.raw }
let create = extend empty
let merge o1 o2 =
  extend o1 o2.raw
exception Invalid of string × string
let parse options (name, value) =
  try
    match A.find name options.actions with
    | Arg.Unit f → f ()
```

```
| Arg.Set b → b := true
| Arg.Clear b → b := false
| Arg.String f → f value
| Arg.Int f → f (int_of_string value)
| Arg.Float f → f (float_of_string value)
| _ → invalid_arg "Options.parse"
with
| Not_found → raise (Invalid (name, value))

let list options =
  List.map (fun (o, _, d) → (o, d)) options.raw

let cmdline prefix options =
  List.map (fun (o, f, d) → (prefix ^ o, f, d)) options.raw
```

---

# —D—

## PROGRESS REPORTS

### *D.1 Interface of Progress*

```
type t
val dummy : t
val channel : out_channel → int → t
val file : string → int → t
val open_file : string → int → t
val reset : t → int → string → unit
val begin_step : t → string → unit
val end_step : t → string → unit
val summary : t → string → unit
```

### *D.2 Implementation of Progress*

```
type channel =
| Channel of out_channel
| File of string
| Open_File of string × out_channel

type state =
{ channel : channel;
  mutable steps : int;
  mutable digits : int;
  mutable step : int;
  created : float;
  mutable last_reset : float;
  mutable last_begin : float; }

type t = state option

let digits n =
  if n > 0 then
    succ (truncate (log10 (float n)))
  else
    invalid_arg "Progress.digits: non-positive argument"

let mod_float2 a b =
```

```

let modulus = mod_float a b in
((a - . modulus) /. b, modulus)

let time_to_string seconds =
  let minutes, seconds = mod_float2 seconds 60. in
  if minutes > 0.0 then
    let hours, minutes = mod_float2 minutes 60. in
    if hours > 0.0 then
      let days, hours = mod_float2 hours 24. in
      if days > 0.0 then
        Printf.sprintf "%.0f:%02.0f_days" days hours
      else
        Printf.sprintf "%.0f:%02.0f_hrs" hours minutes
      else
        Printf.sprintf "%.0f:%02.0f_mins" minutes seconds
    else
      Printf.sprintf "%.2f_secs" seconds

let create_channel steps =
  let now = Sys.time () in
  Some { channel = channel;
        steps = steps;
        digits = digits steps;
        step = 0;
        created = now;
        last_reset = now;
        last_begin = now }

let dummy =
  None

let channel oc =
  create (Channel oc)

let file name =
  let oc = open_out name in
  close_out oc;
  create (File name)

let open_file name =
  let oc = open_out name in
  create (Open_File (name, oc))

let close_channel state =
  match state.channel with
  | Channel oc →
    flush oc
  | File _ → ()
  | Open_File (_, oc) →
    flush oc;
    close_out oc

let use_channel state f =
  match state.channel with

```



```

| Channel oc | Open_File (_, oc) →
  f oc;
  flush oc
| File name →
  let oc = open_out_gen [Open_append; Open_creat] 644 name in
  f oc;
  flush oc;
  close_out oc

let reset state steps msg =
  match state with
  | None → ()
  | Some state →
    let now = Sys.time () in
    state.steps ← steps;
    state.digits ← digits steps;
    state.step ← 0;
    state.last_reset ← now;
    state.last_begin ← now

let begin_step state msg =
  match state with
  | None → ()
  | Some state →
    let now = Sys.time () in
    state.step ← succ state.step;
    state.last_begin ← now;
    use_channel state (fun oc →
      Printf.fprintf oc "[%0*d/%0*d] %s. . ." state.digits state.step state.digits state.steps msg)

let end_step state msg =
  match state with
  | None → ()
  | Some state →
    let now = Sys.time () in
    let last = now - . state.last_begin in
    let elapsed = now - . state.last_reset in
    let estimated = float state.steps * . elapsed /. float state.step in
    let remaining = estimated - . elapsed in
    use_channel state (fun oc →
      Printf.fprintf oc "%s. [time: %s, total: %s, remaining: %s]\n" msg
        (time_to_string last) (time_to_string estimated) (time_to_string remaining))

let summary state msg =
  match state with
  | None → ()
  | Some state →
    let now = Sys.time () in
    use_channel state (fun oc →
      Printf.fprintf oc "%s. [total %s, time: %s]\n" msg
        (time_to_string (now - . state.created)));
    close_channel state

```

---

# —E—

## MORE ON FILENAMES

### *E.1 Interface of ThoFilename*

```
val split : string → string list
val join  : string list → string
val expand_home : string → string
```

### *E.2 Implementation of ThoFilename*

```
let rec split' acc path =
  match Filename.dirname path, Filename.basename path with
  | "/", basename → "/" :: basename :: acc
  | ".", basename → basename :: acc
  | dirname, basename → split' (basename :: acc) dirname

let split path =
  split' [] path

let join = function
  | [] → "."
  | [basename] → basename
  | dirname :: rest → List.fold_left Filename.concat dirname rest

let expand_home path =
  match split path with
  | ("~" | "$HOME" | "${HOME}") :: rest →
    join ((try Sys.getenv "HOME" with Not_found → "/tmp") :: rest)
  | _ → path
```

---

# —F—

## CACHE FILES

### *F.1 Interface of Cache*

```
module type T =
  sig
    type key
    type hash = string
    type value

    type  $\alpha$  result =
      | Hit of  $\alpha$ 
      | Miss
      | Stale of string

    exception Mismatch of string  $\times$  string  $\times$  string

    val hash : key  $\rightarrow$  hash
    val exists : hash  $\rightarrow$  string  $\rightarrow$  bool
    val find : hash  $\rightarrow$  string  $\rightarrow$  string option
    val write : hash  $\rightarrow$  string  $\rightarrow$  value  $\rightarrow$  unit
    val write_dir : hash  $\rightarrow$  string  $\rightarrow$  string  $\rightarrow$  value  $\rightarrow$  unit
    val read : hash  $\rightarrow$  string  $\rightarrow$  value
    val maybe_read : hash  $\rightarrow$  string  $\rightarrow$  value result

  end

module type Key =
  sig
    type t
  end

module type Value =
  sig
    type t
  end

module Make (Key : Key) (Value : Value) :
  T with type key = Key.t and type value = Value.t
```

## *F.2 Implementation of Cache*

```

let search_path =
  [ Filename.current_dir_name;
    ThoFilename.expand_home Config.user_cache_dir;
    Config.system_cache_dir ]

module type T =
  sig
    type key
    type hash = string
    type value

    type  $\alpha$  result =
      | Hit of  $\alpha$ 
      | Miss
      | Stale of string

    exception Mismatch of string  $\times$  string  $\times$  string

    val hash : key  $\rightarrow$  hash
    val exists : hash  $\rightarrow$  string  $\rightarrow$  bool
    val find : hash  $\rightarrow$  string  $\rightarrow$  string option
    val write : hash  $\rightarrow$  string  $\rightarrow$  value  $\rightarrow$  unit
    val write_dir : hash  $\rightarrow$  string  $\rightarrow$  string  $\rightarrow$  value  $\rightarrow$  unit
    val read : hash  $\rightarrow$  string  $\rightarrow$  value
    val maybe_read : hash  $\rightarrow$  string  $\rightarrow$  value result
  end

module type Key =
  sig
    type t
  end
end

module type Value =
  sig
    type t
  end
end

module Make (Key : Key) (Value : Value) =
  struct
    type key = Key.t
    type hash = string
    type value = Value.t

    type tagged =
      { tag : hash;
        value : value; }

    let hash value =
      Digest.string (Marshal.to_string value [])

    let find_first path name =

```

```

let rec find_first' = function
| [] → raise Not_found
| dir :: path →
    let f = Filename.concat dir name in
    if Sys.file_exists f then
        f
    else
        find_first' path
in
find_first' path

let find hash name =
    try Some (find_first search_path name) with Not_found → None

let exists hash name =
    match find hash name with
    | None → false
    | Some _ → true

let try_first f path name =
    let rec try_first' = function
    | [] → raise Not_found
    | dir :: path →
        try (f (Filename.concat dir name), dir) with _ → try_first' path
    in
    try_first' path

let open_in_bin_first = try_first open_in_bin
let open_out_bin_last path = try_first open_out_bin (List.rev path)

let write hash name value =
    let oc, _ = open_out_bin_last search_path name in
    Marshal.to_channel oc { tag = hash; value = value } [];
    close_out oc

let write_dir hash dir name value =
    let oc = open_out_bin (Filename.concat dir name) in
    Marshal.to_channel oc { tag = hash; value = value } [];
    close_out oc

type  $\alpha$  result =
| Hit of  $\alpha$ 
| Miss
| Stale of string

exception Mismatch of string  $\times$  string  $\times$  string

let read hash name =
    let ic, dir = open_in_bin_first search_path name in
    let { tag = tag; value = value } = Marshal.from_channel ic in
    close_in ic;
    if tag = hash then
        value
    else
        raise (Mismatch (Filename.concat dir name, hash, tag))

```

```
let maybe_read hash name =  
  try  
    Hit (read hash name)  
  with  
  | Not_found → Miss  
  | Mismatch (file, -, -) → Stale file  
end
```

---

# —G—

## MORE ON LISTS

### *G.1 Interface of ThoList*

*splitn*  $n\ l = (hdn\ l, tln\ l)$ , but more efficient.

**val** *hdn* :  $int \rightarrow \alpha\ list \rightarrow \alpha\ list$

**val** *tln* :  $int \rightarrow \alpha\ list \rightarrow \alpha\ list$

**val** *splitn* :  $int \rightarrow \alpha\ list \rightarrow \alpha\ list \times \alpha\ list$

*chop*  $n\ l$  chops  $l$  into pieces of size  $n$  (except for the last one, which contains the remainder).

**val** *chopn* :  $int \rightarrow \alpha\ list \rightarrow \alpha\ list\ list$

*of\_subarray*  $n\ m\ a$  is  $[a.(n); a.(n+1); \dots; a.(m)]$ . Values of  $n$  and  $m$  out of bounds are silently shifted towards these bounds.

**val** *of\_subarray* :  $int \rightarrow int \rightarrow \alpha\ array \rightarrow \alpha\ list$

*range*  $s\ n\ m$  is  $[n; n+s; n+2s; \dots; m - ((m-n) \bmod s)]$

**val** *range* :  $?stride : int \rightarrow int \rightarrow int \rightarrow int\ list$

*enumerate*  $s\ n\ [a1; a2; \dots]$  is  $[(n, a1); (n+s, a2); \dots]$

**val** *enumerate* :  $?stride : int \rightarrow int \rightarrow \alpha\ list \rightarrow (int \times \alpha)\ list$

Compress identical elements in a sorted list. Identity is determined using the polymorphic equality function *Pervasives*.(=).

**val** *uniq* :  $\alpha\ list \rightarrow \alpha\ list$

Test if all members of a list are structurally identical (actually *homogeneous*  $l$  and  $List.length\ (uniq\ l) \leq 1$  are equivalent, but the former is more efficient if a mismatch comes early).

**val** *homogeneous* :  $\alpha\ list \rightarrow bool$

*compare*  $cmp\ l1\ l2$  compare two lists  $l1$  and  $l2$  according to  $cmp$ .  $cmp$  defaults to the polymorphic *Pervasives*.compare.

**val** *compare* :  $?cmp : (\alpha \rightarrow \alpha \rightarrow int) \rightarrow \alpha\ list \rightarrow \alpha\ list \rightarrow int$

Collect and count identical elements in a list. Identity is determined using the polymorphic equality function *Pervasives*.(=). *classify* does not assume that

the list is sorted. However, it is  $O(n)$  for sorted lists and  $O(n^2)$  in the worst case.

`val classify :  $\alpha$  list  $\rightarrow$  ( $\text{int} \times \alpha$ ) list`

Collect the second factors with a common first factor in lists.

`val factorize : ( $\alpha \times \beta$ ) list  $\rightarrow$  ( $\alpha \times \beta$  list) list`

`flatMap f` is equivalent to `flatten  $\circ$  (map f)`, but more efficient, because no intermediate lists are built. Unfortunately, it is not tail recursive.

`val flatmap : ( $\alpha \rightarrow \beta$  list)  $\rightarrow$   $\alpha$  list  $\rightarrow$   $\beta$  list`

`rev_flatmap f` is equivalent to `flatten  $\circ$  (rev_map (rev  $\circ$  f)) = rev  $\circ$  (flatMap f)`, but more efficient, because no intermediate lists are built. It is tail recursive.

`val rev_flatmap : ( $\alpha \rightarrow \beta$  list)  $\rightarrow$   $\alpha$  list  $\rightarrow$   $\beta$  list`

`val clone : int  $\rightarrow$   $\alpha \rightarrow$   $\alpha$  list`

`val multiply : int  $\rightarrow$   $\alpha$  list  $\rightarrow$   $\alpha$  list`



Invent other names to avoid confusions with `List.fold_left2` and `List.fold_right2`.

`val fold_right2 : ( $\alpha \rightarrow \beta \rightarrow \beta$ )  $\rightarrow$   $\alpha$  list list  $\rightarrow$   $\beta \rightarrow \beta$`

`val fold_left2 : ( $\beta \rightarrow \alpha \rightarrow \beta$ )  $\rightarrow$   $\beta \rightarrow \alpha$  list list  $\rightarrow$   $\beta$`

`iteri f n [a; b; c]` evaluates `f n a`, `f (n + 1) b` and `f (n + 2) c`.

`val iteri : (int  $\rightarrow$   $\alpha \rightarrow$  unit)  $\rightarrow$  int  $\rightarrow$   $\alpha$  list  $\rightarrow$  unit`

`val mapi : (int  $\rightarrow$   $\alpha \rightarrow \beta$ )  $\rightarrow$  int  $\rightarrow$   $\alpha$  list  $\rightarrow$   $\beta$  list`

`iteri2 f n m [[aa; ab]; [ba; bb]]` evaluates `f n m aa`, `f n (m + 1) ab`, `f (n + 1) m ba` and `f (n + 1) (m + 1) bb`. NB: the nested lists need not be rectangular.

`val iteri2 : (int  $\rightarrow$  int  $\rightarrow$   $\alpha \rightarrow$  unit)  $\rightarrow$  int  $\rightarrow$  int  $\rightarrow$   $\alpha$  list list  $\rightarrow$  unit`

Transpose a *rectangular* list of lists like a matrix.

`val transpose :  $\alpha$  list list  $\rightarrow$   $\alpha$  list list`

`interleave f list` walks through `list` and inserts the result of `f` applied to the reversed list of elements before and the list of elements after. The empty lists at the beginning and end are included!

`val interleave : ( $\alpha$  list  $\rightarrow$   $\alpha$  list  $\rightarrow$   $\alpha$  list)  $\rightarrow$   $\alpha$  list  $\rightarrow$   $\alpha$  list`

`interleave_nearest f list` is like `interleave f list`, but `f` looks only at the nearest neighbors.

`val interleave_nearest : ( $\alpha \rightarrow \alpha \rightarrow \alpha$  list)  $\rightarrow$   $\alpha$  list  $\rightarrow$   $\alpha$  list`

`partitioned_sort cmp index_sets list` sorts the sublists of `list` specified by the `index_sets` and the complement of their union. **NB:** the sorting follows to order in the lists in `index_sets`. **NB:** the indices are 0-based.

`val partitioned_sort : ( $\alpha \rightarrow \alpha \rightarrow$  int)  $\rightarrow$  int list list  $\rightarrow$   $\alpha$  list  $\rightarrow$   $\alpha$  list`

exception `Overlapping_indices`

exception `Out_of_bounds`



*ariadne\_sort cmp list* sorts *list* according to *cmp* (default *Pervasives.compare*) keeping track of the original order by a 0-based list of indices.

`val ariadne_sort : ?cmp : ( $\alpha \rightarrow \alpha \rightarrow \text{int}$ )  $\rightarrow \alpha \text{ list} \rightarrow \alpha \text{ list} \times \text{int list}$`

*ariadne\_unsort (ariadne\_sort cmp list)* returns *list*.

`val ariadne_unsort :  $\alpha \text{ list} \times \text{int list} \rightarrow \alpha \text{ list}$`

## G.2 Implementation of *ThoList*

```

let rec hdn n l =
  if n ≤ 0 then
    []
  else
    match l with
    | x :: rest → x :: hdn (pred n) rest
    | [] → invalid_arg "ThoList.hdn"

let rec tln n l =
  if n ≤ 0 then
    l
  else
    match l with
    | _ :: rest → tln (pred n) rest
    | [] → invalid_arg "ThoList.tln"

let rec splitn' n l1_rev l2 =
  if n ≤ 0 then
    (List.rev l1_rev, l2)
  else
    match l2 with
    | x :: l2' → splitn' (pred n) (x :: l1_rev) l2'
    | [] → invalid_arg "ThoList.splitn_n>_len"

let splitn n l =
  if n < 0 then
    invalid_arg "ThoList.splitn_n<_0"
  else
    splitn' n [] l

```

This is *splitn'* all over again, but without the exception.

```

let rec chopn'' n l1_rev l2 =
  if n ≤ 0 then
    (List.rev l1_rev, l2)
  else
    match l2 with
    | x :: l2' → chopn'' (pred n) (x :: l1_rev) l2'
    | [] → (List.rev l1_rev, [])

let rec chopn' n ll_rev = function
  | [] → List.rev ll_rev

```

```

| l →
  begin match chopn'' n [] l with
  | [], [] → List.rev ll_rev
  | l1, [] → List.rev (l1 :: ll_rev)
  | l1, l2 → chopn' n (l1 :: ll_rev) l2
  end

let chopn n l =
  if n ≤ 0 then
    invalid_arg "ThoList.chopn: n ≤ 0"
  else
    chopn' n [] l

let of_subarray n1 n2 a =
  let rec of_subarray' n1 n2 =
    if n1 > n2 then
      []
    else
      a.(n1) :: of_subarray' (succ n1) n2 in
  of_subarray' (max 0 n1) (min n2 (pred (Array.length a)))

let range ?(stride = 1) n1 n2 =
  if stride ≤ 0 then
    invalid_arg "ThoList.range: stride ≤ 0"
  else
    let rec range' n =
      if n > n2 then
        []
      else
        n :: range' (n + stride) in
    range' n1

```

Tail recursive:

```

let enumerate ?(stride = 1) n l =
  let _, l_rev =
    List.fold_left
      (fun (i, acc) a → (i + stride, (i, a) :: acc))
      (n, []) l in
  List.rev l_rev

```

This is *not* tail recursive!

```

let rec flatmap f = function
| [] → []
| x :: rest → f x @ flatmap f rest

```

This is!

```

let rev_flatmap f l =
  let rec rev_flatmap' acc f = function
  | [] → acc
  | x :: rest → rev_flatmap' (List.rev_append (f x) acc) f rest in
  rev_flatmap' [] f l

```

```

let fold_left2 f acc lists =
  List.fold_left (List.fold_left f) acc lists

let fold_right2 f lists acc =
  List.fold_right (List.fold_right f) lists acc

let iteri f start list =
  ignore (List.fold_left (fun i a → f i a; succ i) start list)

let iteri2 f start_outer star_inner lists =
  iteri (fun j → iteri (f j) star_inner) start_outer lists

let mapi f start list =
  let next, list' =
    List.fold_left (fun (i, acc) a → (succ i, f i a :: acc)) (start, []) list in
  List.rev list'

Is there a more efficient implementation?

let transpose lists =
  let rec transpose' rest =
    if List.for_all ((=) []) rest then
      []
    else
      List.map List.hd rest :: transpose' (List.map List.tl rest) in
  try
    transpose' lists
  with
  | Failure "tl" → invalid_arg "ThoList.transpose: not rectangular"

let compare ?(cmp = Pervasives.compare) l1 l2 =
  let rec compare' l1' l2' =
    match l1', l2' with
    | [], [] → 0
    | [], _ → -1
    | _, [] → 1
    | n1 :: r1, n2 :: r2 →
      let c = cmp n1 n2 in
      if c ≠ 0 then
        c
      else
        compare' r1 r2
  in
  compare' l1 l2

let rec uniq' x = function
| [] → []
| x' :: rest →
  if x' = x then
    uniq' x rest
  else
    x' :: uniq' x' rest

let uniq = function
| [] → []

```

```

| x :: rest → x :: uniq' x rest
let rec homogeneous = function
| [] | [-] → true
| a1 :: (a2 :: _ as rest) →
  if a1 ≠ a2 then
    false
  else
    homogeneous rest

```

If we needed it, we could use a polymorphic version of *Set* to speed things up from  $O(n^2)$  to  $O(n \ln n)$ . But not before it matters somewhere ...

```

let classify l =
  let rec add_to_class a = function
  | [] → [1, a]
  | (n, a') :: rest →
    if a = a' then
      (succ n, a) :: rest
    else
      (n, a') :: add_to_class a rest
  in
  let rec classify' cl = function
  | [] → cl
  | a :: rest → classify' (add_to_class a cl) rest
  in
  classify' [] l
let rec factorize l =
  let rec add_to_class x y = function
  | [] → [(x, [y])]
  | (x', ys) :: rest →
    if x = x' then
      (x, y :: ys) :: rest
    else
      (x', ys) :: add_to_class x y rest
  in
  let rec factorize' fl = function
  | [] → fl
  | (x, y) :: rest → factorize' (add_to_class x y fl) rest
  in
  List.map (fun (x, ys) → (x, List.rev ys)) (factorize' [] l)
let rec clone n x =
  if n < 0 then
    invalid_arg "ThoList.clone"
  else if n = 0 then
    []
  else
    x :: clone (pred n) x
let interleave f list =
  let rec interleave' rev_head tail =

```

```

    let rev_head' = List.rev_append (f rev_head tail) rev_head in
    match tail with
    | [] → List.rev rev_head'
    | x :: tail' → interleave' (x :: rev_head') tail'
  in
  interleave' [] list

let interleave_nearest f list =
  interleave
    (fun head tail →
      match head, tail with
      | h :: _, t :: _ → f h t
      | _ → [])
    list

let rec rev_multiply n rl l =
  if n < 0 then
    invalid_arg "ThoList.multiply"
  else if n = 0 then
    []
  else
    List.rev_append rl (rev_multiply (pred n) rl l)

let multiply n l = rev_multiply n (List.rev l) l

module ISet = Set.Make (struct type t = int let compare = Pervasives.compare end)

exception Overlapping_indices
exception Out_of_bounds

let iset_of_list list =
  List.fold_right ISet.add list ISet.empty

let iset_list_union list =
  List.fold_right ISet.union list ISet.empty

let complement_index_sets n index_set_lists =
  let index_sets = List.map iset_of_list index_set_lists in
  let index_set = iset_list_union index_sets in
  let size_index_sets =
    List.fold_left (fun acc s → ISet.cardinal s + acc) 0 index_sets in
  if size_index_sets ≠ ISet.cardinal index_set then
    raise Overlapping_indices
  else if ISet.exists (fun i → i < 0 ∨ i ≥ n) index_set then
    raise Overlapping_indices
  else
    match ISet.elements (ISet.diff (iset_of_list (range 0 (pred n))) index_set) with
    | [] → index_set_lists
    | complement → complement :: index_set_lists

let sort_section cmp array index_set =
  List.iter2
    (Array.set array)
    index_set (List.sort cmp (List.map (Array.get array) index_set))

```

```

let partitioned_sort cmp index_sets list =
  let array = Array.of_list list in
  List.fold_left
    (fun () → sort_section cmp array)
    () (complement_index_sets (List.length list) index_sets);
  Array.to_list array

let ariadne_sort ?(cmp = Pervasives.compare) list =
  let sorted =
    List.sort (fun (n1, a1) (n2, a2) → cmp a1 a2) (enumerate 0 list) in
  (List.map snd sorted, List.map fst sorted)

let ariadne_unsort (sorted, indices) =
  List.map snd
    (List.sort
      (fun (n1, a1) (n2, a2) → Pervasives.compare n1 n2)
      (List.map2 (fun n a → (n, a)) indices sorted))

```

---

# —H—

## MORE ON ARRAYS

### *H.1 Interface of ThoArray*

Compressed arrays, i. e. arrays with only unique elements and an embedding that allows to recover the original array. NB: in the current implementation, compressing saves space, if *and only if* objects of type  $\alpha$  require more storage than integers. The main use of  $\alpha$  *compressed* is *not* for saving space, anyway, but for avoiding the repetition of hard calculations.

```
type  $\alpha$  compressed
val uniq :  $\alpha$  compressed  $\rightarrow$   $\alpha$  array
val embedding :  $\alpha$  compressed  $\rightarrow$  int array
```

These two are inverses of each other:

```
val compress :  $\alpha$  array  $\rightarrow$   $\alpha$  compressed
val uncompress :  $\alpha$  compressed  $\rightarrow$   $\alpha$  array
```

One can play the same game for matrices.

```
type  $\alpha$  compressed2
val uniq2 :  $\alpha$  compressed2  $\rightarrow$   $\alpha$  array array
val embedding1 :  $\alpha$  compressed2  $\rightarrow$  int array
val embedding2 :  $\alpha$  compressed2  $\rightarrow$  int array
```

Again, these two are inverses of each other:

```
val compress2 :  $\alpha$  array array  $\rightarrow$   $\alpha$  compressed2
val uncompress2 :  $\alpha$  compressed2  $\rightarrow$   $\alpha$  array array
```

### *H.2 Implementation of ThoArray*

```
type  $\alpha$  compressed =
  { uniq :  $\alpha$  array;
    embedding : int array }

let uniq a = a.uniq
let embedding a = a.embedding

type  $\alpha$  compressed2 =
  { uniq2 :  $\alpha$  array array;
```

```

    embedding1 : int array;
    embedding2 : int array }

let uniq2 a = a.uniq2
let embedding1 a = a.embedding1
let embedding2 a = a.embedding2

module PMap = Pmap.Tree

let compress a =
  let last = Array.length a - 1 in
  let embedding = Array.make (succ last) (-1) in
  let rec scan num_uniq uniq elements n =
    if n > last then
      { uniq = Array.of_list (List.rev elements);
        embedding = embedding }
    else
      match PMap.find_opt compare a.(n) uniq with
      | Some n' →
        embedding.(n) ← n';
        scan num_uniq uniq elements (succ n)
      | None →
        embedding.(n) ← num_uniq;
        scan
          (succ num_uniq)
          (PMap.add compare a.(n) num_uniq uniq)
          (a.(n) :: elements)
          (succ n) in
    scan 0 PMap.empty [] 0

let uncompress a =
  Array.map (Array.get a.uniq) a.embedding

```



Using *transpose* simplifies the algorithms, but can be inefficient. If this turns out to be the case, we should add special treatments for symmetric matrices.

```

let transpose a =
  let dim1 = Array.length a
  and dim2 = Array.length a.(0) in
  let a' = Array.make_matrix dim2 dim1 a.(0).(0) in
  for i1 = 0 to pred dim1 do
    for i2 = 0 to pred dim2 do
      a'.(i2).(i1) ← a.(i1).(i2)
    done
  done;
  a'

let compress2 a =
  let c2 = compress a in
  let c12_transposed = compress (transpose c2.uniq) in
  { uniq2 = transpose c12_transposed.uniq;
    embedding1 = c12_transposed.embedding;

```



```

    embedding2 = c2.embedding }
let uncompress2 a =
  let a2 = uncompress { uniq = a.uniq2; embedding = a.embedding2 } in
  transpose (uncompress { uniq = transpose a2; embedding = a.embedding1 })

```

---

# — I —

## MORE ON STRINGS

### *I.1 Interface of ThoString*

This is a very simple library if stroing manipulation functions missing in O'Caml's standard library.

*strip\_prefix prefix string* returns *string* with 0 or 1 occurrences of a leading *prefix* removed.

```
val strip_prefix : string → string → string
```

*strip\_prefix\_star prefix string* returns *string* with any number of leading occurrences of *prefix* removed.

```
val strip_prefix_star : char → string → string
```

*strip\_prefix prefix string* returns *string* with a leading *prefix* removed, raises *Invalid\_argument* if there's no match.

```
val strip_required_prefix : string → string → string
```

*strip\_from\_first c s* returns *s* with everything starting from the first *c* removed.

*strip\_from\_last c s* returns *s* with everything starting from the last *c* removed.

```
val strip_from_first : char → string → string
```

```
val strip_from_last : char → string → string
```

*index\_string pattern string* returns the index of the first occurrence of *pattern* in *string*, if any. Raises *Not\_found*, if *pattern* is not in *string*.

```
val index_string : string → string → int
```

This silently fails if the argument contains both single and double quotes!

```
val quote : string → string
```

### *I.2 Implementation of ThoString*

```
let strip_prefix p s =  
  let lp = String.length p  
  and ls = String.length s in  
  if lp > ls then  
    s
```

```

else
  let rec strip_prefix' i =
    if i ≥ lp then
      String.sub s i (ls - i)
    else if p.[i] ≠ s.[i] then
      s
    else
      strip_prefix' (succ i)
  in
  strip_prefix' 0
let strip_prefix_star p s =
  let ls = String.length s in
  if ls < 1 then
    s
  else
    let rec strip_prefix_star' i =
      if i < ls then begin
        if p ≠ s.[i] then
          String.sub s i (ls - i)
        else
          strip_prefix_star' (succ i)
      end else
        ""
    in
    strip_prefix_star' 0
let strip_required_prefix p s =
  let lp = String.length p
  and ls = String.length s in
  if lp > ls then
    invalid_arg ("strip_required_prefix:␣expected␣'" ^ p ^ "'␣got␣'" ^ s ^ "'")
  else
    let rec strip_prefix' i =
      if i ≥ lp then
        String.sub s i (ls - i)
      else if p.[i] ≠ s.[i] then
        invalid_arg ("strip_required_prefix:␣expected␣'" ^ p ^ "'␣got␣'" ^ s ^ "'")
      else
        strip_prefix' (succ i)
    in
    strip_prefix' 0
let strip_from_first c s =
  try
    String.sub s 0 (String.index s c)
  with
  | Not_found → s
let strip_from_last c s =
  try
    String.sub s 0 (String.rindex s c)

```

```

with
| Not_found → s

let index_string pat s =
  let lpat = String.length pat
  and ls = String.length s in
  if lpat = 0 then
    0
  else
    let rec index_string' n =
      let i = String.index_from s n pat.[0] in
      if i + lpat > ls then
        raise Not_found
      else
        if String.compare pat (String.sub s i lpat) = 0 then
          i
        else
          index_string' (succ i)
    in
    index_string' 0

let quote s =
  if String.contains s ' ' ∨ String.contains s '\n' then begin
    if String.contains s '"' then
      "\"" ^ s ^ "\""
    else
      "\"" ^ s ^ "\"\"
  end else
    s

```

---

# —J—

## POLYMORPHIC MAPS

From [9].

### *J.1 Interface of Pmap*

Module *Pmap*: association tables over a polymorphic type<sup>1</sup>.

```

module type T =
  sig
    type ('key,  $\alpha$ ) t
    val empty : ('key,  $\alpha$ ) t
    val is_empty : ('key,  $\alpha$ ) t → bool
    val singleton : 'key →  $\alpha$  → ('key,  $\alpha$ ) t
    val add : ('key → 'key → int) → 'key →  $\alpha$  → ('key,  $\alpha$ ) t →
      ('key,  $\alpha$ ) t
    val update : ('key → 'key → int) → ( $\alpha$  →  $\alpha$  →  $\alpha$ ) →
      'key →  $\alpha$  → ('key,  $\alpha$ ) t → ('key,  $\alpha$ ) t
    val cons : ('key → 'key → int) → ( $\alpha$  →  $\alpha$  →  $\alpha$  option) →
      'key →  $\alpha$  → ('key,  $\alpha$ ) t → ('key,  $\alpha$ ) t
    val find : ('key → 'key → int) → 'key → ('key,  $\alpha$ ) t →  $\alpha$ 
    val find_opt : ('key → 'key → int) → 'key → ('key,  $\alpha$ ) t →  $\alpha$  option
    val choose : ('key,  $\alpha$ ) t → 'key ×  $\alpha$ 
    val choose_opt : ('key,  $\alpha$ ) t → ('key ×  $\alpha$ ) option
    val uncons : ('key,  $\alpha$ ) t → 'key ×  $\alpha$  × ('key,  $\alpha$ ) t
    val uncons_opt : ('key,  $\alpha$ ) t → ('key ×  $\alpha$  × ('key,  $\alpha$ ) t) option
    val elements : ('key,  $\alpha$ ) t → ('key ×  $\alpha$ ) list
    val mem : ('key → 'key → int) → 'key → ('key,  $\alpha$ ) t → bool
    val remove : ('key → 'key → int) → 'key → ('key,  $\alpha$ ) t → ('key,  $\alpha$ ) t
    val union : ('key → 'key → int) → ( $\alpha$  →  $\alpha$  →  $\alpha$ ) →
      ('key,  $\alpha$ ) t → ('key,  $\alpha$ ) t → ('key,  $\alpha$ ) t
    val compose : ('key → 'key → int) → ( $\alpha$  →  $\alpha$  →  $\alpha$  option) →
      ('key,  $\alpha$ ) t → ('key,  $\alpha$ ) t → ('key,  $\alpha$ ) t
    val iter : ('key →  $\alpha$  → unit) → ('key,  $\alpha$ ) t → unit
    val map : ( $\alpha$  →  $\beta$ ) → ('key,  $\alpha$ ) t → ('key,  $\beta$ ) t
    val mapi : ('key →  $\alpha$  →  $\beta$ ) → ('key,  $\alpha$ ) t → ('key,  $\beta$ ) t
    val fold : ('key →  $\alpha$  →  $\beta$  →  $\beta$ ) → ('key,  $\alpha$ ) t →  $\beta$  →  $\beta$ 
  end

```

---

<sup>1</sup>Extension of code © 1996 by Xavier Leroy

```

    val compare : ('key → 'key → int) → (α → α → int) →
      ('key, α) t → ('key, α) t → int
    val canonicalize : ('key → 'key → int) → ('key, α) t → ('key, α) t
  end

```

Balanced trees: logarithmic access, but representation not unique.

```
module Tree : T
```

Sorted lists: representation unique, but linear access.

```
module List : T
```

## J.2 Implementation of Pmap

```
module type T =
```

```

  sig
    type ('key, α) t
    val empty : ('key, α) t
    val is_empty : ('key, α) t → bool
    val singleton : 'key → α → ('key, α) t
    val add : ('key → 'key → int) → 'key → α → ('key, α) t →
      ('key, α) t
    val update : ('key → 'key → int) → (α → α → α) →
      'key → α → ('key, α) t → ('key, α) t
    val cons : ('key → 'key → int) → (α → α → α option) →
      'key → α → ('key, α) t → ('key, α) t
    val find : ('key → 'key → int) → 'key → ('key, α) t → α
    val find_opt : ('key → 'key → int) → 'key → ('key, α) t → α option
    val choose : ('key, α) t → 'key × α
    val choose_opt : ('key, α) t → ('key × α) option
    val uncons : ('key, α) t → 'key × α × ('key, α) t
    val uncons_opt : ('key, α) t → ('key × α × ('key, α) t) option
    val elements : ('key, α) t → ('key × α) list
    val mem : ('key → 'key → int) → 'key → ('key, α) t → bool
    val remove : ('key → 'key → int) → 'key → ('key, α) t → ('key, α) t
    val union : ('key → 'key → int) → (α → α → α) →
      ('key, α) t → ('key, α) t → ('key, α) t
    val compose : ('key → 'key → int) → (α → α → α option) →
      ('key, α) t → ('key, α) t → ('key, α) t
    val iter : ('key → 'key → unit) → ('key, α) t → unit
    val map : (α → β) → ('key, α) t → ('key, β) t
    val mapi : ('key → α → β) → ('key, α) t → ('key, β) t
    val fold : ('key → α → β → β) → ('key, α) t → β → β
    val compare : ('key → 'key → int) → (α → α → int) →
      ('key, α) t → ('key, α) t → int
    val canonicalize : ('key → 'key → int) → ('key, α) t → ('key, α) t
  end

```

```
module Tree =
```

```
  struct
```

```

type ('key,  $\alpha$ ) t =
| Empty
| Node of ('key,  $\alpha$ ) t  $\times$  'key  $\times$   $\alpha$   $\times$  ('key,  $\alpha$ ) t  $\times$  int

let empty = Empty

let is_empty = function
| Empty  $\rightarrow$  true
| _  $\rightarrow$  false

let singleton k d =
Node (Empty, k, d, Empty, 1)

let height = function
| Empty  $\rightarrow$  0
| Node (_, _, _, _, h)  $\rightarrow$  h

let create l x d r =
let hl = height l and hr = height r in
Node (l, x, d, r, (if hl  $\geq$  hr then hl + 1 else hr + 1))

let bal l x d r =
let hl = match l with Empty  $\rightarrow$  0 | Node (_, _, _, _, h)  $\rightarrow$  h in
let hr = match r with Empty  $\rightarrow$  0 | Node (_, _, _, _, h)  $\rightarrow$  h in
if hl > hr + 2 then begin
match l with
| Empty  $\rightarrow$  invalid_arg "Map.bal"
| Node (ll, lv, ld, lr, _)  $\rightarrow$ 
if height ll  $\geq$  height lr then
create ll lv ld (create lr x d r)
else begin
match lr with
| Empty  $\rightarrow$  invalid_arg "Map.bal"
| Node (lrl, lrv, lrd, lrr, _)  $\rightarrow$ 
create (create ll lv ld lrl) lrv lrd (create lrr x d r)
end
end else if hr > hl + 2 then begin
match r with
| Empty  $\rightarrow$  invalid_arg "Map.bal"
| Node (rl, rv, rd, rr, _)  $\rightarrow$ 
if height rr  $\geq$  height rl then
create (create l x d rl) rv rd rr
else begin
match rl with
| Empty  $\rightarrow$  invalid_arg "Map.bal"
| Node (rll, rlv, rld, rlr, _)  $\rightarrow$ 
create (create l x d rll) rlv rld (create rlr rv rd rr)
end
end else
Node (l, x, d, r, (if hl  $\geq$  hr then hl + 1 else hr + 1))

let rec join l x d r =
match bal l x d r with
| Empty  $\rightarrow$  invalid_arg "Pmap.join"

```

```

| Node (l', x', d', r', _) as t' →
  let d = height l' - height r' in
  if d < -2 ∨ d > 2 then
    join l' x' d' r'
  else
    t'

```

Merge two trees  $t1$  and  $t2$  into one. All elements of  $t1$  must precede the elements of  $t2$ . Assumes  $\text{height } t1 - \text{height } t2 \leq 2$ .

```

let rec merge t1 t2 =
  match t1, t2 with
  | Empty, t → t
  | t, Empty → t
  | Node (l1, v1, d1, r1, h1), Node (l2, v2, d2, r2, h2) →
    bal l1 v1 d1 (bal (merge r1 l2) v2 d2 r2)

```

Same as merge, but does not assume anything about  $t1$  and  $t2$ .

```

let rec concat t1 t2 =
  match t1, t2 with
  | Empty, t → t
  | t, Empty → t
  | Node (l1, v1, d1, r1, h1), Node (l2, v2, d2, r2, h2) →
    join l1 v1 d1 (join (concat r1 l2) v2 d2 r2)

```

Splitting

```

let rec split cmp x = function
| Empty → (Empty, None, Empty)
| Node (l, v, d, r, _) →
  let c = cmp x v in
  if c = 0 then
    (l, Some d, r)
  else if c < 0 then
    let ll, vl, rl = split cmp x l in
    (ll, vl, join rl v d r)
  else (* if c > 0 then *)
    let lr, vr, rr = split cmp x r in
    (join l v d lr, vr, rr)

let rec find cmp x = function
| Empty → raise Not_found
| Node (l, v, d, r, _) →
  let c = cmp x v in
  if c = 0 then
    d
  else if c < 0 then
    find cmp x l
  else (* if c > 0 *)
    find cmp x r

let rec find_opt cmp x = function
| Empty → None

```



```

| Node (l, v, d, r, _) →
  let c = cmp x v in
  if c = 0 then
    Some d
  else if c < 0 then
    find_opt cmp x l
  else (* if c > 0 *)
    find_opt cmp x r

let rec mem cmp x = function
| Empty → false
| Node (l, v, d, r, _) →
  let c = cmp x v in
  if c = 0 then
    true
  else if c < 0 then
    mem cmp x l
  else (* if c > 0 *)
    mem cmp x r

let choose = function
| Empty → raise Not_found
| Node (l, v, d, r, _) → (v, d)

let choose_opt = function
| Empty → None
| Node (l, v, d, r, _) → Some (v, d)

let uncons = function
| Empty → raise Not_found
| Node (l, v, d, r, h) → (v, d, merge l r)

let uncons_opt = function
| Empty → None
| Node (l, v, d, r, h) → Some (v, d, merge l r)

let rec remove cmp x = function
| Empty → Empty
| Node (l, v, d, r, h) →
  let c = cmp x v in
  if c = 0 then
    merge l r
  else if c < 0 then
    bal (remove cmp x l) v d r
  else (* if c > 0 *)
    bal l v d (remove cmp x r)

let rec cons cmp resolve x data' = function
| Empty → Node (Empty, x, data', Empty, 1)
| Node (l, v, data, r, h) →
  let c = cmp x v in
  if c = 0 then
    match resolve data' data with
    | Some data'' → Node (l, x, data'', r, h)

```

```

    | None → merge l r
  else if c < 0 then
    bal (cons cmp resolve x data' l) v data r
  else (* if c > 0 *)
    bal l v data (cons cmp resolve x data' r)
let rec update cmp resolve x data' = function
| Empty → Node (Empty, x, data', Empty, 1)
| Node (l, v, data, r, h) →
  let c = cmp x v in
  if c = 0 then
    Node (l, x, resolve data' data, r, h)
  else if c < 0 then
    bal (update cmp resolve x data' l) v data r
  else (* if c > 0 *)
    bal l v data (update cmp resolve x data' r)
let add cmp x data = update cmp (fun n o → n) x data
let rec compose cmp resolve s1 s2 =
  match s1, s2 with
  | Empty, t2 → t2
  | t1, Empty → t1
  | Node (l1, v1, d1, r1, h1), Node (l2, v2, d2, r2, h2) →
    if h1 ≥ h2 then
      if h2 = 1 then
        cons cmp (fun o n → resolve n o) v2 d2 s1
      else begin
        match split cmp v1 s2 with
        | l2', None, r2' →
          join (compose cmp resolve l1 l2') v1 d1
            (compose cmp resolve r1 r2')
        | l2', Some d, r2' →
          begin match resolve d1 d with
          | None →
            concat (compose cmp resolve l1 l2')
              (compose cmp resolve r1 r2')
          | Some d →
            join (compose cmp resolve l1 l2') v1 d
              (compose cmp resolve r1 r2')
          end
        end
      end
    else
      if h1 = 1 then
        cons cmp resolve v1 d1 s2
      else begin
        match split cmp v2 s1 with
        | l1', None, r1' →
          join (compose cmp resolve l1' l2) v2 d2
            (compose cmp resolve r1' r2)
        | l1', Some d, r1' →
          begin match resolve d d2 with
          | None →
            concat (compose cmp resolve l1' l2)
              (compose cmp resolve r1' r2)
          | Some d →
            join (compose cmp resolve l1' l2) v2 d
              (compose cmp resolve r1' r2)
          end
        end
      end
    end
  end

```

```

      | None →
        concat (compose cmp resolve l1' l2)
              (compose cmp resolve r1' r2)
      | Some d →
        join (compose cmp resolve l1' l2) v2 d
              (compose cmp resolve r1' r2)
    end
  end

let rec union cmp resolve s1 s2 =
  match s1, s2 with
  | Empty, t2 → t2
  | t1, Empty → t1
  | Node (l1, v1, d1, r1, h1), Node (l2, v2, d2, r2, h2) →
    if h1 ≥ h2 then
      if h2 = 1 then
        update cmp (fun o n → resolve n o) v2 d2 s1
      else begin
        match split cmp v1 s2 with
        | l2', None, r2' →
          join (union cmp resolve l1 l2') v1 d1
              (union cmp resolve r1 r2')
        | l2', Some d, r2' →
          join (union cmp resolve l1 l2') v1 (resolve d1 d)
              (union cmp resolve r1 r2')
        end
      end
    else
      if h1 = 1 then
        update cmp resolve v1 d1 s2
      else begin
        match split cmp v2 s1 with
        | l1', None, r1' →
          join (union cmp resolve l1' l2) v2 d2
              (union cmp resolve r1' r2)
        | l1', Some d, r1' →
          join (union cmp resolve l1' l2) v2 (resolve d d2)
              (union cmp resolve r1' r2)
        end
      end
    end

let rec iter f = function
  | Empty → ()
  | Node (l, v, d, r, _) → iter f l; f v d; iter f r

let rec map f = function
  | Empty → Empty
  | Node (l, v, d, r, h) → Node (map f l, v, f v d, map f r, h)

let rec mapi f = function
  | Empty → Empty
  | Node (l, v, d, r, h) → Node (mapi f l, v, f v d, mapi f r, h)

let rec fold f m accu =

```

```

match m with
| Empty → accu
| Node (l, v, d, r, _) → fold f l (f v d (fold f r accu))

let rec compare' cmp_k cmp_d l1 l2 =
  match l1, l2 with
  | [], [] → 0
  | [], _ → -1
  | _, [] → 1
  | Empty :: t1, Empty :: t2 → compare' cmp_k cmp_d t1 t2
  | Node (Empty, v1, d1, r1, _) :: t1,
    Node (Empty, v2, d2, r2, _) :: t2 →
    let cv = cmp_k v1 v2 in
    if cv ≠ 0 then begin
      cv
    end else begin
      let cd = cmp_d d1 d2 in
      if cd ≠ 0 then
        cd
      else
        compare' cmp_k cmp_d (r1 :: t1) (r2 :: t2)
    end
  | Node (l1, v1, d1, r1, _) :: t1, t2 →
    compare' cmp_k cmp_d (l1 :: Node (Empty, v1, d1, r1, 0) :: t1) t2
  | t1, Node (l2, v2, d2, r2, _) :: t2 →
    compare' cmp_k cmp_d t1 (l2 :: Node (Empty, v2, d2, r2, 0) :: t2)

let compare cmp_k cmp_d m1 m2 = compare' cmp_k cmp_d [m1] [m2]

let rec elements' accu = function
| Empty → accu
| Node (l, v, d, r, _) → elements' ((v, d) :: elements' accu r) l

let elements s =
  elements' [] s

let canonicalize cmp m =
  fold (add cmp) m empty

end

module List =
  struct
    type ('key, α) t = ('key × α) list

    let empty = []

    let is_empty = function
    | [] → true
    | _ → false

    let singleton k d = [(k, d)]

    let rec cons cmp resolve k' d' = function
    | [] → [(k', d')]
    | ((k, d) as kd :: rest) as list →

```

```

    let c = cmp k' k in
    if c = 0 then
      match resolve d' d with
      | None → rest
      | Some d'' → (k', d'') :: rest
    else if c < 0 then (* k' < k *)
      (k', d') :: list
    else (* if c > 0, i.e. k < k' *)
      kd :: cons cmp resolve k' d' rest

let rec update cmp resolve k' d' = function
| [] → [(k', d')]
| ((k, d) as kd :: rest) as list →
  let c = cmp k' k in
  if c = 0 then
    (k', resolve d' d) :: rest
  else if c < 0 then (* k' < k *)
    (k', d') :: list
  else (* if c > 0, i.e. k < k' *)
    kd :: update cmp resolve k' d' rest

let add cmp k' d' list =
  update cmp (fun n o → n) k' d' list

let rec find cmp k' = function
| [] → raise Not_found
| (k, d) :: rest →
  let c = cmp k' k in
  if c = 0 then
    d
  else if c < 0 then (* k' < k *)
    raise Not_found
  else (* if c > 0, i.e. k < k' *)
    find cmp k' rest

let rec find_opt cmp k' = function
| [] → None
| (k, d) :: rest →
  let c = cmp k' k in
  if c = 0 then
    Some d
  else if c < 0 then (* k' < k *)
    None
  else (* if c > 0, i.e. k < k' *)
    find_opt cmp k' rest

let choose = function
| [] → raise Not_found
| kd :: _ → kd

let rec choose_opt = function
| [] → None
| kd :: _ → Some kd

```

```

let uncons = function
| [] → raise Not_found
| (k, d) :: rest → (k, d, rest)

let uncons_opt = function
| [] → None
| (k, d) :: rest → Some (k, d, rest)

let elements list = list

let rec mem cmp k' = function
| [] → false
| (k, d) :: rest →
  let c = cmp k' k in
  if c = 0 then
    true
  else if c < 0 then (* k' < k *)
    false
  else (* if c > 0, i.e. k < k' *)
    mem cmp k' rest

let rec remove cmp k' = function
| [] → []
| ((k, d) as kd :: rest) as list →
  let c = cmp k' k in
  if c = 0 then
    rest
  else if c < 0 then (* k' < k *)
    list
  else (* if c > 0, i.e. k < k' *)
    kd :: remove cmp k' rest

let rec compare cmp_k cmp_d m1 m2 =
  match m1, m2 with
  | [], [] → 0
  | [], _ → -1
  | _, [] → 1
  | (k1, d1) :: rest1, (k2, d2) :: rest2 →
    let c = cmp_k k1 k2 in
    if c = 0 then begin
      let c' = cmp_d d1 d2 in
      if c' = 0 then
        compare cmp_k cmp_d rest1 rest2
      else
        c'
    end else
      c

let rec iter f = function
| [] → ()
| (k, d) :: rest → f k d; iter f rest

let rec map f = function
| [] → []

```

```

| (k, d) :: rest → (k, f d) :: map f rest

let rec mapi f = function
| [] → []
| (k, d) :: rest → (k, f k d) :: mapi f rest

let rec fold f m accu =
  match m with
  | [] → accu
  | (k, d) :: rest → fold f rest (f k d accu)

let rec compose cmp resolve m1 m2 =
  match m1, m2 with
  | [], [] → []
  | [], m → m
  | m, [] → m
  | ((k1, d1) as kd1 :: rest1), ((k2, d2) as kd2 :: rest2) →
    let c = cmp k1 k2 in
    if c = 0 then
      match resolve d1 d2 with
      | None → compose cmp resolve rest1 rest2
      | Some d → (k1, d) :: compose cmp resolve rest1 rest2
    else if c < 0 then (* k1 < k2 *)
      kd1 :: compose cmp resolve rest1 m2
    else (* if c > 0, i.e. k2 < k1 *)
      kd2 :: compose cmp resolve m1 rest2

let rec union cmp resolve m1 m2 =
  match m1, m2 with
  | [], [] → []
  | [], m → m
  | m, [] → m
  | ((k1, d1) as kd1 :: rest1), ((k2, d2) as kd2 :: rest2) →
    let c = cmp k1 k2 in
    if c = 0 then
      (k1, resolve d1 d2) :: union cmp resolve rest1 rest2
    else if c < 0 then (* k1 < k2 *)
      kd1 :: union cmp resolve rest1 m2
    else (* if c > 0, i.e. k2 < k1 *)
      kd2 :: union cmp resolve m1 rest2

let canonicalize cmp x = x
end

```

### J.3 Interface of *Partial*

Partial maps that are constructed from assoc lists.

```

module type T =
sig
  type domain
  type α t

```

```

    val of_list : (domain × α) list → α t
    val of_lists : domain list → α list → α t
    val apply : α t → domain → α
end

module Make : functor (D : Map.OrderedType) → T with type domain = D.t
module Test : sig val suite : OUnit.test end

```

## J.4 Implementation of *Partial*

```

module type T =
sig
  type domain
  type α t
  val of_list : (domain × α) list → α t
  val of_lists : domain list → α list → α t
  val apply : α t → domain → α
end

module Make (D : Map.OrderedType) : T with type domain = D.t =
struct

  module M = Map.Make (D)

  type domain = D.t
  type α t = α M.t

  let of_list l =
    List.fold_left (fun m (d, v) → M.add d v m) M.empty l

  let of_lists domain values =
    of_list
    (try
      List.rev_map2 (fun d v → (d, v)) domain values
    with
      | Invalid_argument "List.rev_map2" →
        invalid_arg "Partial.of_lists: length mismatch")

  let apply partial d = M.find d partial

end

module Test : sig val suite : OUnit.test end =
struct

  open OUnit

  module P = Make (struct type t = int let compare = compare end)

  let apply_ok =
    "apply/ok" >::
    (fun () →
      let p = P.of_list [ (0, "a"); (1, "b"); (2, "c") ]
      and l = [ 0; 1; 2 ] in
      assert_equal [ "a"; "b"; "c" ] (List.map (P.apply p) l))

```



```
let suite_apply =  
  "apply" >:::  
    [apply_ok]  
let suite =  
  "Partial" >:::  
    [suite_apply]  
let time () =  
  ()  
end
```

---

# —K—

## TRIES

From [4], extended for [9].

### *K.1 Interface of Trie*

#### *K.1.1 Monomorphically*

module type *T* =

sig

type *key*

type  $(+\alpha)$  *t*

val *empty* :  $\alpha$  *t*

val *is\_empty* :  $\alpha$  *t*  $\rightarrow$  *bool*

Standard trie interface:

val *add* : *key*  $\rightarrow$   $\alpha \rightarrow \alpha$  *t*  $\rightarrow$   $\alpha$  *t*

val *find* : *key*  $\rightarrow$   $\alpha$  *t*  $\rightarrow$   $\alpha$

Functionals:

val *remove* : *key*  $\rightarrow$   $\alpha$  *t*  $\rightarrow$   $\alpha$  *t*

val *mem* : *key*  $\rightarrow$   $\alpha$  *t*  $\rightarrow$  *bool*

val *map* :  $(\alpha \rightarrow \beta) \rightarrow \alpha$  *t*  $\rightarrow$   $\beta$  *t*

val *mapi* :  $(\text{key} \rightarrow \alpha \rightarrow \beta) \rightarrow \alpha$  *t*  $\rightarrow$   $\beta$  *t*

val *iter* :  $(\text{key} \rightarrow \alpha \rightarrow \text{unit}) \rightarrow \alpha$  *t*  $\rightarrow$  *unit*

val *fold* :  $(\text{key} \rightarrow \alpha \rightarrow \beta \rightarrow \beta) \rightarrow \alpha$  *t*  $\rightarrow$   $\beta \rightarrow \beta$

Try to match a longest prefix and return the unmatched rest.

val *longest* : *key*  $\rightarrow$   $\alpha$  *t*  $\rightarrow$   $\alpha$  *option*  $\times$  *key*

Try to match a shortest prefix and return the unmatched rest.

val *shortest* : *key*  $\rightarrow$   $\alpha$  *t*  $\rightarrow$   $\alpha$  *option*  $\times$  *key*

#### *K.1.2 New in O'Cam1 3.08*

val *compare* :  $(\alpha \rightarrow \alpha \rightarrow \text{int}) \rightarrow \alpha$  *t*  $\rightarrow$   $\alpha$  *t*  $\rightarrow$  *int*

val *equal* :  $(\alpha \rightarrow \alpha \rightarrow \text{bool}) \rightarrow \alpha$  *t*  $\rightarrow$   $\alpha$  *t*  $\rightarrow$  *bool*

### K.1.3 O'Mega customization

*export f\_open f\_close f\_descend f\_match trie* allows us to export the trie *trie* as source code to another programming language.

```

val export : (int → unit) → (int → unit) →
  (int → key → unit) → (int → key → α → unit) → α t → unit
end

```

O'Caml's *Map.S* prior to Version 3.12:

```

module type Map_S =
sig
  type key
  type (+α) t
  val empty : α t
  val is_empty : α t → bool
  val add : key → α → α t → α t
  val find : key → α t → α
  val remove : key → α t → α t
  val mem : key → α t → bool
  val iter : (key → α → unit) → α t → unit
  val map : (α → β) → α t → β t
  val mapi : (key → α → β) → α t → β t
  val fold : (key → α → β → β) → α t → β → β
  val compare : (α → α → int) → α t → α t → int
  val equal : (α → α → bool) → α t → α t → bool
end

```

```

module Make (M : Map_S) : T with type key = M.key list
module MakeMap (M : Map_S) : Map_S with type key = M.key list

```

### K.1.4 Polymorphically

```

module type Poly =
sig
  type (α, β) t
  val empty : (α, β) t

```

Standard trie interface:

```

val add : (α → α → int) → α list → β → (α, β) t → (α, β) t
val find : (α → α → int) → α list → (α, β) t → β

```

Functionals:

```

val remove : (α → α → int) → α list → (α, β) t → (α, β) t
val mem : (α → α → int) → α list → (α, β) t → bool
val map : (β → γ) → (α, β) t → (α, γ) t
val mapi : (α list → β → γ) → (α, β) t → (α, γ) t
val iter : (α list → β → unit) → (α, β) t → unit
val fold : (α list → β → γ → γ) → (α, β) t → γ → γ

```

Try to match a longest prefix and return the unmatched rest.

```
val longest : ( $\alpha \rightarrow \alpha \rightarrow \text{int}$ )  $\rightarrow$   $\alpha$  list  $\rightarrow$  ( $\alpha, \beta$ )  $t \rightarrow \beta$  option  $\times$   $\alpha$  list
```

Try to match a shortest prefix and return the unmatched rest.

```
val shortest : ( $\alpha \rightarrow \alpha \rightarrow \text{int}$ )  $\rightarrow$   $\alpha$  list  $\rightarrow$  ( $\alpha, \beta$ )  $t \rightarrow \beta$  option  $\times$   $\alpha$  list
```

### K.1.5 O'Mega customization

`export f_open f_close f_descend f_match trie` allows us to export the trie *trie* as source code to another programming language.

```
val export : ( $\text{int} \rightarrow \text{unit}$ )  $\rightarrow$  ( $\text{int} \rightarrow \text{unit}$ )  $\rightarrow$   

  ( $\text{int} \rightarrow \alpha$  list  $\rightarrow \text{unit}$ )  $\rightarrow$  ( $\text{int} \rightarrow \alpha$  list  $\rightarrow \beta \rightarrow \text{unit}$ )  $\rightarrow$  ( $\alpha, \beta$ )  $t \rightarrow$   

  unit  

end  

module MakePoly (M : Pmap.T) : Poly
```

## K.2 Implementation of *Trie*

### K.2.1 Monomorphically

```
module type T =  

  sig  

    type key  

    type ( $+\alpha$ )  $t$   

    val empty :  $\alpha$   $t$   

    val is_empty :  $\alpha$   $t \rightarrow \text{bool}$   

    val add : key  $\rightarrow \alpha \rightarrow \alpha$   $t \rightarrow \alpha$   $t$   

    val find : key  $\rightarrow \alpha$   $t \rightarrow \alpha$   

    val remove : key  $\rightarrow \alpha$   $t \rightarrow \alpha$   $t$   

    val mem : key  $\rightarrow \alpha$   $t \rightarrow \text{bool}$   

    val map : ( $\alpha \rightarrow \beta$ )  $\rightarrow \alpha$   $t \rightarrow \beta$   $t$   

    val mapi : (key  $\rightarrow \alpha \rightarrow \beta$ )  $\rightarrow \alpha$   $t \rightarrow \beta$   $t$   

    val iter : (key  $\rightarrow \alpha \rightarrow \text{unit}$ )  $\rightarrow \alpha$   $t \rightarrow \text{unit}$   

    val fold : (key  $\rightarrow \alpha \rightarrow \beta \rightarrow \beta$ )  $\rightarrow \alpha$   $t \rightarrow \beta \rightarrow \beta$   

    val longest : key  $\rightarrow \alpha$   $t \rightarrow \alpha$  option  $\times$  key  

    val shortest : key  $\rightarrow \alpha$   $t \rightarrow \alpha$  option  $\times$  key  

    val compare : ( $\alpha \rightarrow \alpha \rightarrow \text{int}$ )  $\rightarrow \alpha$   $t \rightarrow \alpha$   $t \rightarrow \text{int}$   

    val equal : ( $\alpha \rightarrow \alpha \rightarrow \text{bool}$ )  $\rightarrow \alpha$   $t \rightarrow \alpha$   $t \rightarrow \text{bool}$   

    val export : ( $\text{int} \rightarrow \text{unit}$ )  $\rightarrow$  ( $\text{int} \rightarrow \text{unit}$ )  $\rightarrow$   

      ( $\text{int} \rightarrow \text{key} \rightarrow \text{unit}$ )  $\rightarrow$  ( $\text{int} \rightarrow \text{key} \rightarrow \alpha \rightarrow \text{unit}$ )  $\rightarrow \alpha$   $t \rightarrow \text{unit}$   

  end
```

O'Caml's *Map.S* prior to Version 3.12:

```
module type Map_S =  

  sig  

    type key
```

```

type (+α) t
val empty : α t
val is_empty : α t → bool
val add : key → α → α t → α t
val find : key → α t → α
val remove : key → α t → α t
val mem : key → α t → bool
val iter : (key → α → unit) → α t → unit
val map : (α → β) → α t → β t
val mapi : (key → α → β) → α t → β t
val fold : (key → α → β → β) → α t → β → β
val compare : (α → α → int) → α t → α t → int
val equal : (α → α → bool) → α t → α t → bool
end

module Make (M : Map_S) : (T with type key = M.key list) =
  struct

```

Derived from SML code by Chris Okasaki [4].

```

type key = M.key list
type α t = Trie of α option × α t M.t
let empty = Trie (None, M.empty)
let is_empty = function
| Trie (None, m) →
    m = M.empty (* after O'Caml 3.08: M.is_empty m *)
| _ → false
let rec add key data trie =
  match key, trie with
  | [], Trie (_, children) → Trie (Some data, children)
  | k :: rest, Trie (node, children) →
    let t = try M.find k children with Not_found → empty in
    Trie (node, M.add k (add rest data t) children)
let rec find key trie =
  match key, trie with
  | [], Trie (None, _) → raise Not_found
  | [], Trie (Some data, _) → data
  | k :: rest, Trie (_, children) → find rest (M.find k children)

```

The rest is my own fault ...

```

let find1 k children =
  try Some (M.find k children) with Not_found → None
let add_non_empty k t children =
  if t = empty then
    M.remove k children
  else
    M.add k t children
let rec remove key trie =

```

```

match key, trie with
| [], Trie (_, children) → Trie (None, children)
| k :: rest, (Trie (node, children) as orig) →
  match find1 k children with
  | None → orig
  | Some t → Trie (node, add_non_empty k (remove rest t) children)

let rec mem key trie =
  match key, trie with
  | [], Trie (None, _) → false
  | [], Trie (Some data, _) → true
  | k :: rest, Trie (_, children) →
    match find1 k children with
    | None → false
    | Some t → mem rest t

let rec map f = function
| Trie (Some data, children) →
  Trie (Some (f data), M.map (map f) children)
| Trie (None, children) → Trie (None, M.map (map f) children)

let rec mapi' key f = function
| Trie (Some data, children) →
  Trie (Some (f key data), descend key f children)
| Trie (None, children) → Trie (None, descend key f children)
and descend key f = M.mapi (fun k → mapi' (key @ [k]) f)
let mapi f = mapi' [] f

let rec iter' key f = function
| Trie (Some data, children) → f key data; descend key f children
| Trie (None, children) → descend key f children
and descend key f = M.iter (fun k → iter' (key @ [k]) f)
let iter f = iter' [] f

let rec fold' key f t acc =
  match t with
  | Trie (Some data, children) → descend key f children (f key data acc)
  | Trie (None, children) → descend key f children acc
and descend key f = M.fold (fun k → fold' (key @ [k]) f)
let fold f t acc = fold' [] f t acc

let rec longest' partial partial_rest key trie =
  match key, trie with
  | [], Trie (data, _) → (data, [])
  | k :: rest, Trie (data, children) →
    match data, find1 k children with
    | None, None → (partial, partial_rest)
    | Some _, None → (data, key)
    | _, Some t → longest' partial partial_rest rest t
let longest key = longest' None key key

let rec shortest' partial partial_rest key trie =
  match key, trie with
  | [], Trie (data, _) → (data, [])

```

```

| k :: rest, Trie (Some _ as data, children) → (data, key)
| k :: rest, Trie (None, children) →
  match find1 k children with
  | None → (partial, partial_rest)
  | Some t → shortest' partial partial_rest rest t
let shortest key = shortest' None key key

```

### K.2.2 O'Mega customization

```

let rec export' n key f_open f_close f_descend f_match = function
| Trie (Some data, children) →
  f_match n key data;
  if children ≠ M.empty then
    descend n key f_open f_close f_descend f_match children
| Trie (None, children) →
  if children ≠ M.empty then begin
    f_descend n key;
    descend n key f_open f_close f_descend f_match children
  end
and descend n key f_open f_close f_descend f_match children =
  f_open n;
  M.iter (fun k →
    export' (succ n) (k :: key) f_open f_close f_descend f_match) children;
  f_close n

let export f_open f_close f_descend f_match =
  export' 0 [] f_open f_close f_descend f_match

let compare _ _ _ =
  failwith "incomplete"

let equal _ _ _ =
  failwith "incomplete"

end

module MakeMap (M : Map_S) : (Map_S with type key = M.key list) = Make(M)

```

### K.2.3 Polymorphically

```

module type Poly =
sig
  type (α, β) t
  val empty : (α, β) t
  val add : (α → α → int) → α list → β → (α, β) t → (α, β) t
  val find : (α → α → int) → α list → (α, β) t → β
  val remove : (α → α → int) → α list → (α, β) t → (α, β) t
  val mem : (α → α → int) → α list → (α, β) t → bool
  val map : (β → γ) → (α, β) t → (α, γ) t
  val mapi : (α list → β → γ) → (α, β) t → (α, γ) t
  val iter : (α list → β → unit) → (α, β) t → unit

```

```

val fold : ( $\alpha$  list  $\rightarrow \beta \rightarrow \gamma \rightarrow \gamma$ )  $\rightarrow (\alpha, \beta) t \rightarrow \gamma \rightarrow \gamma$ 
val longest : ( $\alpha \rightarrow \alpha \rightarrow \text{int}$ )  $\rightarrow \alpha$  list  $\rightarrow (\alpha, \beta) t \rightarrow \beta$  option  $\times \alpha$  list
val shortest : ( $\alpha \rightarrow \alpha \rightarrow \text{int}$ )  $\rightarrow \alpha$  list  $\rightarrow (\alpha, \beta) t \rightarrow \beta$  option  $\times \alpha$  list
val export : ( $\text{int} \rightarrow \text{unit}$ )  $\rightarrow (\text{int} \rightarrow \text{unit}) \rightarrow$ 
  ( $\text{int} \rightarrow \alpha$  list  $\rightarrow \text{unit}$ )  $\rightarrow (\text{int} \rightarrow \alpha$  list  $\rightarrow \beta \rightarrow \text{unit}) \rightarrow (\alpha, \beta) t \rightarrow$ 
  unit
end

module MakePoly (M : Pmap.T) : Poly =
  struct

```

Derived from SML code by Chris Okasaki [4].

```

type ( $\alpha, \beta$ ) t = Trie of  $\beta$  option  $\times (\alpha, (\alpha, \beta) t)$  M.t
let empty = Trie (None, M.empty)

let rec add cmp key data trie =
  match key, trie with
  | [], Trie (_, children)  $\rightarrow$  Trie (Some data, children)
  | k :: rest, Trie (node, children)  $\rightarrow$ 
    let t = try M.find cmp k children with Not_found  $\rightarrow$  empty in
    Trie (node, M.add cmp k (add cmp rest data t) children)

let rec find cmp key trie =
  match key, trie with
  | [], Trie (None, _)  $\rightarrow$  raise Not_found
  | [], Trie (Some data, _)  $\rightarrow$  data
  | k :: rest, Trie (_, children)  $\rightarrow$  find cmp rest (M.find cmp k children)

```

The rest is my own fault ...

```

let find1 cmp k children =
  try Some (M.find cmp k children) with Not_found  $\rightarrow$  None

let add_non_empty cmp k t children =
  if t = empty then
    M.remove cmp k children
  else
    M.add cmp k t children

let rec remove cmp key trie =
  match key, trie with
  | [], Trie (_, children)  $\rightarrow$  Trie (None, children)
  | k :: rest, (Trie (node, children) as orig)  $\rightarrow$ 
    match find1 cmp k children with
    | None  $\rightarrow$  orig
    | Some t  $\rightarrow$  Trie (node, add_non_empty cmp k (remove cmp rest t) children)

let rec mem cmp key trie =
  match key, trie with
  | [], Trie (None, _)  $\rightarrow$  false
  | [], Trie (Some data, _)  $\rightarrow$  true
  | k :: rest, Trie (_, children)  $\rightarrow$ 
    match find1 cmp k children with
    | None  $\rightarrow$  false

```



```

    | Some t → mem cmp rest t

let rec map f = function
| Trie (Some data, children) →
    Trie (Some (f data), M.map (map f) children)
| Trie (None, children) → Trie (None, M.map (map f) children)

let rec mapi' key f = function
| Trie (Some data, children) →
    Trie (Some (f key data), descend key f children)
| Trie (None, children) → Trie (None, descend key f children)
and descend key f = M.mapi (fun k → mapi' (key @ [k]) f)
let mapi f = mapi' [] f

let rec iter' key f = function
| Trie (Some data, children) → f key data; descend key f children
| Trie (None, children) → descend key f children
and descend key f = M.iter (fun k → iter' (key @ [k]) f)
let iter f = iter' [] f

let rec fold' key f t acc =
    match t with
    | Trie (Some data, children) → descend key f children (f key data acc)
    | Trie (None, children) → descend key f children acc
and descend key f = M.fold (fun k → fold' (key @ [k]) f)
let fold f t acc = fold' [] f t acc

let rec longest' cmp partial partial_rest key trie =
    match key, trie with
    | [], Trie (data, _) → (data, [])
    | k :: rest, Trie (data, children) →
        match data, find1 cmp k children with
        | None, None → (partial, partial_rest)
        | Some _, None → (data, key)
        | _, Some t → longest' cmp partial partial_rest rest t
let longest cmp key = longest' cmp None key key

let rec shortest' cmp partial partial_rest key trie =
    match key, trie with
    | [], Trie (data, _) → (data, [])
    | k :: rest, Trie (Some _ as data, children) → (data, key)
    | k :: rest, Trie (None, children) →
        match find1 cmp k children with
        | None → (partial, partial_rest)
        | Some t → shortest' cmp partial partial_rest rest t
let shortest cmp key = shortest' cmp None key key

```

#### K.2.4 O'Mega customization

```

let rec export' n key f_open f_close f_descend f_match = function
| Trie (Some data, children) →
    f_match n key data;

```

```

      if children  $\neq$  M.empty then
        descend n key f_open f_close f_descend f_match children
    | Trie (None, children)  $\rightarrow$ 
      if children  $\neq$  M.empty then begin
        f_descend n key;
        descend n key f_open f_close f_descend f_match children
      end
    and descend n key f_open f_close f_descend f_match children =
      f_open n;
      M.iter (fun k  $\rightarrow$ 
        export' (succ n) (k :: key) f_open f_close f_descend f_match) children;
      f_close n
    let export f_open f_close f_descend f_match =
      export' 0 [] f_open f_close f_descend f_match
  end

```

---

# —L—

## TENSOR PRODUCTS

From [9].

### *L.1 Interface of Product*

#### *L.1.1 Lists*

Since April 2001, we preserve lexicographic ordering.

```
val fold2 : ( $\alpha \rightarrow \beta \rightarrow \gamma \rightarrow \gamma$ )  $\rightarrow \alpha$  list  $\rightarrow \beta$  list  $\rightarrow \gamma \rightarrow \gamma$ 
val fold3 : ( $\alpha \rightarrow \beta \rightarrow \gamma \rightarrow \delta \rightarrow \delta$ )  $\rightarrow \alpha$  list  $\rightarrow \beta$  list  $\rightarrow \gamma$  list  $\rightarrow \delta \rightarrow \delta$ 
val fold : ( $\alpha$  list  $\rightarrow \beta \rightarrow \beta$ )  $\rightarrow \alpha$  list list  $\rightarrow \beta \rightarrow \beta$ 

val list2 : ( $\alpha \rightarrow \beta \rightarrow \gamma$ )  $\rightarrow \alpha$  list  $\rightarrow \beta$  list  $\rightarrow \gamma$  list
val list3 : ( $\alpha \rightarrow \beta \rightarrow \gamma \rightarrow \delta$ )  $\rightarrow \alpha$  list  $\rightarrow \beta$  list  $\rightarrow \gamma$  list  $\rightarrow \delta$  list
val list : ( $\alpha$  list  $\rightarrow \beta$ )  $\rightarrow \alpha$  list list  $\rightarrow \beta$  list

val power : int  $\rightarrow \alpha$  list  $\rightarrow \alpha$  list list
val thread :  $\alpha$  list list  $\rightarrow \alpha$  list list
```

#### *L.1.2 Sets*

'a\_set is actually  $\alpha$  set for a suitable *set*, but this relation can not be expressed polymorphically (in *set*) in O'Caml. The two sets can be of different type, but we provide a symmetric version as syntactic sugar.

type  $\alpha$  set

```
type ( $\alpha$ , 'a_set,  $\beta$ ) fold = ( $\alpha \rightarrow \beta \rightarrow \beta$ )  $\rightarrow$  'a_set  $\rightarrow \beta \rightarrow \beta$ 
type ( $\alpha$ , 'a_set,  $\beta$ , 'b_set,  $\gamma$ ) fold2 =
  ( $\alpha \rightarrow \beta \rightarrow \gamma \rightarrow \gamma$ )  $\rightarrow$  'a_set  $\rightarrow$  'b_set  $\rightarrow \gamma \rightarrow \gamma$ 

val outer : ( $\alpha$ , 'a_set,  $\gamma$ ) fold  $\rightarrow$  ( $\beta$ , 'b_set,  $\gamma$ ) fold  $\rightarrow$ 
  ( $\alpha$ , 'a_set,  $\beta$ , 'b_set,  $\gamma$ ) fold2
val outer_self : ( $\alpha$ , 'a_set,  $\beta$ ) fold  $\rightarrow$  ( $\alpha$ , 'a_set,  $\alpha$ , 'a_set,  $\beta$ ) fold2
```

## L.2 Implementation of *Product*

### L.2.1 Lists

We use the tail recursive *List.fold\_left* over *List.fold\_right* for efficiency, but revert the argument lists in order to preserve lexicographic ordering. The argument lists are much shorter than the results, so the cost of the *List.rev* is negligible.

```
let fold2_rev f l1 l2 acc =
  List.fold_left (fun acc1 x1 →
    List.fold_left (fun acc2 x2 → f x1 x2 acc2) acc1 l2) acc l1
```

```
let fold2 f l1 l2 acc =
  fold2_rev f (List.rev l1) (List.rev l2) acc
```

```
let fold3_rev f l1 l2 l3 acc =
  List.fold_left (fun acc1 x1 → fold2 (f x1) l2 l3 acc1) acc l1
```

```
let fold3 f l1 l2 l3 acc =
  fold3_rev f (List.rev l1) (List.rev l2) (List.rev l3) acc
```

If all lists have the same type, there's also

```
let rec fold_rev f ll acc =
  match ll with
  | [] → acc
  | [l] → List.fold_left (fun acc' x → f [x] acc') acc l
  | l :: rest →
    List.fold_left (fun acc' x → fold_rev (fun xr → f (x :: xr)) rest acc') acc l
```

```
let fold f ll acc = fold_rev f (List.map List.rev ll) acc
```

```
let list2 op l1 l2 =
  fold2 (fun x1 x2 c → op x1 x2 :: c) l1 l2 []
```

```
let list3 op l1 l2 l3 =
  fold3 (fun x1 x2 x3 c → op x1 x2 x3 :: c) l1 l2 l3 []
```

```
let list op ll =
  fold (fun l c → op l :: c) ll []
```

```
let power n l =
  list (fun x → x) (ThoList.clone n l)
```

Reshuffling lists:

$$[[a_1; \dots; a_k]; [b_1; \dots; b_k]; [c_1; \dots; c_k]; \dots] \rightarrow [[a_1; b_1; c_1; \dots]; [a_2; b_2; c_2; \dots]; \dots] \quad (\text{L.1})$$



*tho* : Is this really an optimal implementation?

```
let thread = function
  | head :: tail →
    List.map List.rev
      (List.fold_left (fun i acc → List.map2 (fun a b → b :: a) i acc)
        (List.map (fun i → [i]) head) tail)
  | [] → []
```

*L.2.2 Sets*

The implementation is amazingly simple:

```
type  $\alpha$  set
```

```
type ( $\alpha$ , 'a_set,  $\beta$ ) fold = ( $\alpha \rightarrow \beta \rightarrow \beta$ )  $\rightarrow$  'a_set  $\rightarrow \beta \rightarrow \beta$ 
```

```
type ( $\alpha$ , 'a_set,  $\beta$ , 'b_set,  $\gamma$ ) fold2 =  
  ( $\alpha \rightarrow \beta \rightarrow \gamma \rightarrow \gamma$ )  $\rightarrow$  'a_set  $\rightarrow$  'b_set  $\rightarrow \gamma \rightarrow \gamma$ 
```

```
let outer fold1 fold2 f l1 l2 = fold1 (fun x1  $\rightarrow$  fold2 (f x1) l2) l1
```

```
let outer_self fold f l1 l2 = fold (fun x1  $\rightarrow$  fold (f x1) l2) l1
```

---

# —M—

## (FIBER) BUNDLES

### *M.1 Interface of Bundle*

See figure [M.1](#) for the geometric intuition behind the bundle structure.



Does the current implementation support faithful projections with a forgetful comparison in the base?

```
module type Elt_Base =  
  sig  
    type elt  
    type base  
    val compare_elt : elt → elt → int
```

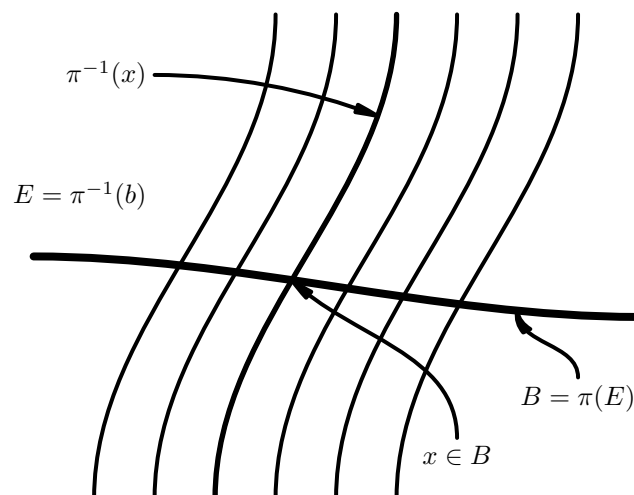


Figure M.1: The bundle structure implemented by *Bundle.T*

---

```

    val compare_base : base → base → int
  end
module type Projection =
  sig
    include Elt_Base
  end
  π : E → B
  val pi : elt → base
end
module type T =
  sig
    type t
    type elt
    type fiber = elt list
    type base

    val add : elt → t → t
    val of_list : elt list → t
  end
  π : E → B
  val pi : elt → base
  π-1 : B → E
  val inv_pi : base → t → fiber
  val base : t → base list
  π-1 ∘ π
  val fiber : elt → t → fiber
  val fibers : t → (base × fiber) list
end
module Make (P : Projection) : T with type elt = P.elt and type base = P.base

```

The same thing again, but with a projection that is not hardcoded, but passed as an argument at runtime.

```

module type Dyn =
  sig
    type t
    type elt
    type fiber = elt list
    type base

    val add : (elt → base) → elt → t → t
    val of_list : (elt → base) → elt list → t
    val inv_pi : base → t → fiber
    val base : t → base list
    val fiber : (elt → base) → elt → t → fiber
    val fibers : t → (base × fiber) list
  end
module Dyn (P : Elt_Base) : Dyn with type elt = P.elt and type base = P.base

```

## *M.2 Implementation of Bundle*

```

module type Elt_Base =
  sig
    type elt
    type base
    val compare_elt : elt → elt → int
    val compare_base : base → base → int
  end

module type Dyn =
  sig
    type t
    type elt
    type fiber = elt list
    type base
    val add : (elt → base) → elt → t → t
    val of_list : (elt → base) → elt list → t
    val inv_pi : base → t → fiber
    val base : t → base list
    val fiber : (elt → base) → elt → t → fiber
    val fibers : t → (base × fiber) list
  end

module Dyn (P : Elt_Base) =
  struct

    type elt = P.elt
    type base = P.base

    type fiber = elt list

    module InvPi = Map.Make (struct type t = P.base let compare = P.compare_base end)
    module Fiber = Set.Make (struct type t = P.elt let compare = P.compare_elt end)

    type t = Fiber.t InvPi.t

    let add_pi element fibers =
      let base = pi element in
      let fiber =
        try InvPi.find base fibers with Not_found → Fiber.empty in
      InvPi.add base (Fiber.add element fiber) fibers

    let of_list pi list =
      List.fold_right (add_pi) list InvPi.empty

    let fibers bundle =
      InvPi.fold
        (fun base fiber acc → (base, Fiber.elements fiber) :: acc) bundle []

    let base bundle =
      InvPi.fold
        (fun base fiber acc → base :: acc) bundle []

    let inv_pi base bundle =

```



```

    try
      Fiber.elements (InvPi.find base bundle)
    with
    | Not_found → []
  let fiber pi elt bundle =
    inv_pi (pi elt) bundle
end

module type Projection =
sig
  include Elt_Base
  val pi : elt → base
end

module type T =
sig
  type t
  type elt
  type fiber = elt list
  type base
  val add : elt → t → t
  val of_list : elt list → t
  val pi : elt → base
  val inv_pi : base → t → fiber
  val base : t → base list
  val fiber : elt → t → fiber
  val fibers : t → (base × fiber) list
end

module Make (P : Projection) =
struct
  module D = Dyn (P)

  type elt = D.elt
  type base = D.base
  type fiber = D.fiber
  type t = D.t

  let pi = P.pi

  let add = D.add pi
  let of_list = D.of_list pi
  let base = D.base
  let inv_pi = D.inv_pi
  let fibers = D.fibers

  let fiber elt bundle =
    inv_pi (pi elt) bundle
end

```

---

# —N—

## POWER SETS

### *N.1 Interface of PowSet*

Manipulate the power set, i. e. the set of all subsets, of an set *Ordered\_Type*. The concrete order is actually irrelevant, we just need it to construct *Set.Ss* in the implementation. In fact, what we are implementating is the *free semilattice* generated from the set of subsets of *Ordered\_Type*, where the join operation is the set union.

The non trivial operation is *basis*, which takes a set of subsets and returns the smallest set of disjoint subsets from which the argument can be reconstructed by forming unions. It is used in O’Mega for finding coarsest partitions of sets of partiticles.



Eventually, this could be generalized from *power set* or *semi lattice* to *lattice* with a notion of subtraction.

```
module type Ordered_Type =
  sig
    type t
    val compare : t → t → int
```

Debugging ...

```
    val to_string : t → string
  end
```

```
module type T =
```

```
  sig
    type elt
    type t

    val empty : t
    val is_empty : t → bool
```

Set union (a. k. a. join).

```
    val union : t list → t
```

Construct the abstract type from a list of subsets represented as lists and the inverse operation.

```
    val of_lists : elt list list → t
```

```
val to_lists : t → elt list list
```

The smallest set of disjoint subsets that generates the given subset.

```
val basis : t → t
```

Debugging ...

```
val to_string : t → string
end
```

```
module Make (E : Ordered_Type) : T with type elt = E.t
```

## N.2 Implementation of *PowSet*

```
module type Ordered_Type =
sig
  type t
  val compare : t → t → int
  val to_string : t → string
end
```

```
module type T =
sig
  type elt
  type t
  val empty : t
  val is_empty : t → bool
  val union : t list → t
  val of_lists : elt list list → t
  val to_lists : t → elt list list
  val basis : t → t
  val to_string : t → string
end
```

```
module Make (E : Ordered_Type) =
struct
  type elt = E.t

  module ESet = Set.Make (E)
  type set = ESet.t

  module EPowSet = Set.Make (ESet)
  type t = EPowSet.t

  let empty = EPowSet.empty
  let is_empty = EPowSet.is_empty

  let union s_list =
    List.fold_right EPowSet.union s_list EPowSet.empty

  let set_to_string set =
    "{" ^ String.concat "," (List.map E.to_string (ESet.elements set)) ^ "}"
```

```

let to_string powset =
  "{" ^ String.concat "," (List.map set_to_string (EPowSet.elements powset)) ^ "}"

let set_of_list list =
  List.fold_right ESet.add list ESet.empty

let of_lists lists =
  List.fold_right
    (fun list acc → EPowSet.add (set_of_list list) acc)
    lists EPowSet.empty

let to_lists ps =
  List.map ESet.elements (EPowSet.elements ps)

product (s1, s2) = s1 ∘ s2 = {s1 \ s2, s1 ∩ s2, s2 \ s1} \ {∅}

let product s1 s2 =
  List.fold_left
    (fun pset set → if ESet.is_empty set then pset else EPowSet.add set pset)
    EPowSet.empty [ESet.diff s1 s2; ESet.inter s1 s2; ESet.diff s2 s1]

let disjoint s1 s2 =
  ESet.is_empty (ESet.inter s1 s2)

```

In *augment\_basis\_overlapping* ( $s, \{s_i\}_i$ ), we are guaranteed that

$$\forall_i : s \cap s_i \neq \emptyset \quad (\text{N.1a})$$

$$\forall_{i \neq j} : s_i \cap s_j = \emptyset. \quad (\text{N.1b})$$

Therefore from (N.1b)

$$\forall_{i \neq j} : (s \cap s_i) \cap (s \cap s_j) = s \cap (s_i \cap s_j) = s \cap \emptyset = \emptyset \quad (\text{N.2a})$$

$$\forall_{i \neq j} : (s_i \setminus s) \cap (s_j \setminus s) \subset s_i \cap s_j = \emptyset \quad (\text{N.2b})$$

$$\forall_{i \neq j} : (s \setminus s_i) \cap (s_j \setminus s) \subset s \cap \bar{s} = \emptyset \quad (\text{N.2c})$$

$$\forall_{i \neq j} : (s \cap s_i) \cap (s_j \setminus s) \subset s \cap \bar{s} = \emptyset, \quad (\text{N.2d})$$

but in general

$$\exists_{i \neq j} : (s \setminus s_i) \cap (s \setminus s_j) \neq \emptyset \quad (\text{N.3a})$$

$$\exists_{i \neq j} : (s \setminus s_i) \cap (s \cap s_j) \neq \emptyset, \quad (\text{N.3b})$$

because, e. g., for  $s_i = \{i\}$  and  $s = \{1, 2, 3\}$

$$(s \setminus s_1) \cap (s \setminus s_2) = \{2, 3\} \cap \{1, 3\} = \{3\} \quad (\text{N.4a})$$

$$(s \setminus s_1) \cap (s \cap s_2) = \{2, 3\} \cap \{2\} = \{2\}. \quad (\text{N.4b})$$

Summarizing:

$\forall_{i \neq j} : A_i \cap A_j$	$s_j \setminus s$	$s \cap s_j$	$s \setminus s_j$
$s_i \setminus s$	$\emptyset$	$\emptyset$	$\emptyset$
$s \cap s_i$	$\emptyset$	$\emptyset$	$\neq \emptyset$
$s \setminus s_i$	$\emptyset$	$\neq \emptyset$	$\neq \emptyset$

Fortunately, we also know from (N.1a) that

$$\forall_i : |s \setminus s_i| < |s| \quad (\text{N.5a})$$

$$\forall_i : |s \cap s_i| < \min(|s|, |s_i|) \quad (\text{N.5b})$$

$$\forall_i : |s_i \setminus s| < |s_i| \quad (\text{N.5c})$$

and can call *basis* recursively without risking non-termination.

```

let rec basis ps =
  EPowSet.fold augment_basis ps EPowSet.empty
and augment_basis s ps =
  if EPowSet.mem s ps then
    ps
  else
    let no_overlaps, overlaps = EPowSet.partition (disjoint s) ps in
    if EPowSet.is_empty overlaps then
      EPowSet.add s ps
    else
      EPowSet.union no_overlaps (augment_basis_overlapping s overlaps)
and augment_basis_overlapping s ps =
  basis (EPowSet.fold (fun s' → EPowSet.union (product s s')) ps EPowSet.empty)
end

```

---

# —O—

## COMBINATORICS

### *O.1 Interface of Combinatorics*

This type is defined just for documentation. Below, most functions will construct a (possibly nested) *list* of partitions or permutations of a  $\alpha$  *seq*.

`type  $\alpha$  seq =  $\alpha$  list`

#### *O.1.1 Simple Combinatorial Functions*

The functions

$$\text{factorial} : n \rightarrow n! \quad (\text{O.1a})$$

$$\text{binomial} : (n, k) \rightarrow \binom{n}{k} = \frac{n!}{k!(n-k)!} \quad (\text{O.1b})$$

$$\text{multinomial} : [n_1; n_2; \dots; n_k] \rightarrow \binom{n_1 + n_2 + \dots + n_k}{n_1, n_2, \dots, n_k} = \frac{(n_1 + n_2 + \dots + n_k)!}{n_1! n_2! \dots n_k!} \quad (\text{O.1c})$$

have not been optimized. They can quickly run out of the range of native integers.

`val factorial : int → int`  
`val binomial : int → int → int`  
`val multinomial : int list → int`

*symmetry*  $l$  returns the size of the symmetric group on  $l$ , i.e. the product of the factorials of the numbers of identical elements.

`val symmetry :  $\alpha$  list → int`

#### *O.1.2 Partitions*

*partitions*  $[n_1; n_2; \dots; n_k] [x_1; x_2; \dots; x_n]$ , where  $n = n_1 + n_2 + \dots + n_k$ , returns all inequivalent partitions of  $[x_1; x_2; \dots; x_n]$  into parts of size  $n_1, n_2, \dots, n_k$ . The order of the  $n_i$  is not respected. There are

$$\frac{1}{S(n_1, n_2, \dots, n_k)} \binom{n_1 + n_2 + \dots + n_k}{n_1, n_2, \dots, n_k} \quad (\text{O.2})$$

such partitions, where the symmetry factor  $S(n_1, n_2, \dots, n_k)$  is the size of the permutation group of  $[n_1; n_2; \dots; n_k]$  as determined by the function *symmetry*.

*val partitions* : *int list*  $\rightarrow$   $\alpha$  *seq*  $\rightarrow$   $\alpha$  *seq list list*

*ordered\_partitions* is identical to *partitions*, except that the order of the  $n_i$  is respected. There are

$$\binom{n_1 + n_2 + \dots + n_k}{n_1, n_2, \dots, n_k} \quad (\text{O.3})$$

such partitions.

*val ordered\_partitions* : *int list*  $\rightarrow$   $\alpha$  *seq*  $\rightarrow$   $\alpha$  *seq list list*

*keystones m l* is equivalent to *partitions m l*, except for the special case when the length of  $l$  is even and  $m$  contains a part that has exactly half the length of  $l$ . In this case only the half of the partitions is created that has the head of  $l$  in the longest part.

*val keystones* : *int list*  $\rightarrow$   $\alpha$  *seq*  $\rightarrow$   $\alpha$  *seq list list*

It can be beneficial to factorize a common part in the partitions and keystones:

*val factorized\_partitions* : *int list*  $\rightarrow$   $\alpha$  *seq*  $\rightarrow$  ( $\alpha$  *seq*  $\times$   $\alpha$  *seq list list*) *list*

*val factorized\_keystones* : *int list*  $\rightarrow$   $\alpha$  *seq*  $\rightarrow$  ( $\alpha$  *seq*  $\times$   $\alpha$  *seq list list*) *list*

### Special Cases

*partitions* is built from components that can be convenient by themselves, even though they are just special cases of *partitions*.

*split k l* returns the list of all inequivalent splits of the list  $l$  into one part of length  $k$  and the rest. There are

$$\frac{1}{S(|l| - k, k)} \binom{|l|}{k} \quad (\text{O.4})$$

such splits. After replacing the pairs by two-element lists, *split k l* is equivalent to *partitions [k; length l - k] l*.

*val split* : *int*  $\rightarrow$   $\alpha$  *seq*  $\rightarrow$  ( $\alpha$  *seq*  $\times$   $\alpha$  *seq*) *list*

Create both equipartitions of lists of even length. There are

$$\binom{|l|}{k} \quad (\text{O.5})$$

such splits. After replacing the pairs by two-element lists, the result of *ordered\_split k l* is equivalent to *ordered\_partitions [k; length l - k] l*.

*val ordered\_split* : *int*  $\rightarrow$   $\alpha$  *seq*  $\rightarrow$  ( $\alpha$  *seq*  $\times$   $\alpha$  *seq*) *list*

*multi\_split n k l* returns the list of all inequivalent splits of the list  $l$  into  $n$  parts of length  $k$  and the rest.

*val multi\_split* : *int*  $\rightarrow$  *int*  $\rightarrow$   $\alpha$  *seq*  $\rightarrow$  ( $\alpha$  *seq list*  $\times$   $\alpha$  *seq*) *list*

*val ordered\_multi\_split* : *int*  $\rightarrow$  *int*  $\rightarrow$   $\alpha$  *seq*  $\rightarrow$  ( $\alpha$  *seq list*  $\times$   $\alpha$  *seq*) *list*

### O.1.3 Choices

*choose*  $n$   $[x_1; x_2; \dots; x_n]$  returns the list of all  $n$ -element subsets of  $[x_1; x_2; \dots; x_n]$ .  
*choose*  $n$  is equivalent to  $(\text{map fst}) \circ (\text{ordered\_split } n)$ .

`val choose : int → α seq → α seq list`

*multi\_choose*  $n$   $k$  is equivalent to  $(\text{map fst}) \circ (\text{multi\_split } n \ k)$ .

`val multi_choose : int → int → α seq → α seq list list`

`val ordered_multi_choose : int → int → α seq → α seq list list`

### O.1.4 Permutations

`val permute : α seq → α seq list`

#### Graded Permutations

`val permute_signed : α seq → (int × α seq) list`

`val permute_even : α seq → α seq list`

`val permute_odd : α seq → α seq list`

#### Tensor Products of Permutations

In other words: permutations which respect compartmentalization.

`val permute_tensor : α seq list → α seq list list`

`val permute_tensor_signed : α seq list → (int × α seq list) list`

`val permute_tensor_even : α seq list → α seq list list`

`val permute_tensor_odd : α seq list → α seq list list`

#### Sorting

`val sort_signed : (α → α → int) → α list → int × α list`

## O.2 Implementation of Combinatorics

`type α seq = α list`

### O.2.1 Simple Combinatorial Functions

```
let rec factorial' fn n =
  if n < 1 then
    fn
  else
    factorial' (n × fn) (pred n)
```

```
let factorial n =
  let result = factorial' 1 n in
```



```

if result < 0 then
  invalid_arg "Combinatorics.factorial_overflow"
else
  result

```

$$\begin{aligned}
\binom{n}{k} &= \frac{n!}{k!(n-k)!} = \frac{n(n-1)\cdots(n-k+1)}{k(k-1)\cdots 1} \\
&= \frac{n(n-1)\cdots(k+1)}{(n-k)(n-k-1)\cdots 1} = \begin{cases} B_{n-k+1}(n, k) & \text{for } k \leq \lfloor n/2 \rfloor \\ B_{k+1}(n, n-k) & \text{for } k > \lfloor n/2 \rfloor \end{cases} \quad (\text{O.6})
\end{aligned}$$

where

$$B_{n_{\min}}(n, k) = \begin{cases} nB_{n_{\min}}(n-1, k) & \text{for } n \geq n_{\min} \\ \frac{1}{k}B_{n_{\min}}(n, k-1) & \text{for } k > 1 \\ 1 & \text{otherwise} \end{cases} \quad (\text{O.7})$$

```

let rec binomial' n_min n k acc =
  if n ≥ n_min then
    binomial' n_min (pred n) k (n × acc)
  else if k > 1 then
    binomial' n_min n (pred k) (acc / k)
  else
    acc

```

```

let binomial n k =
  if k > n / 2 then
    binomial' (k + 1) n (n - k) 1
  else
    binomial' (n - k + 1) n k 1

```

Overflows later, but takes much more time:

$$\binom{n}{k} = \binom{n-1}{k} + \binom{n-1}{k-1} \quad (\text{O.8})$$

```

let rec slow_binomial n k =
  if n < 0 ∨ k < 0 then
    invalid_arg "Combinatorics.binomial"
  else if k = 0 ∨ k = n then
    1
  else
    slow_binomial (pred n) k + slow_binomial (pred n) (pred k)

let multinomial n_list =
  List.fold_left (fun acc n → acc / (factorial n))
    (factorial (List.fold_left (+) 0 n_list)) n_list

let symmetry l =
  List.fold_left (fun s (n, _) → s × factorial n) 1 (ThoList.classify l)

```

### O.2.2 Partitions

The inner steps of the recursion (i.e.  $n = 1$ ) are expanded as follows

$$\begin{aligned} \text{split}'(1, [p_k; p_{k-1}; \dots; p_1], [x_l; x_{l-1}; \dots; x_1], [x_{l+1}; x_{l+2}; \dots; x_m]) = \\ \begin{aligned} & [[p_1; \dots; p_k; x_{l+1}], [x_1; \dots; x_l; x_{l+2}; \dots; x_m]]; \\ & ([p_1; \dots; p_k; x_{l+2}], [x_1; \dots; x_l; x_{l+1}; x_{l+3}; \dots; x_m]); \dots; \\ & ([p_1; \dots; p_k; x_m], [x_1; \dots; x_l; x_{l+1}; \dots; x_{m-1}]) \end{aligned} \quad (\text{O.9}) \end{aligned}$$

while the outer steps (i.e.  $n > 1$ ) perform the same with one element moved from the last argument to the first argument. At the  $n$ th level we have

$$\begin{aligned} \text{split}'(n, [p_k; p_{k-1}; \dots; p_1], [x_l; x_{l-1}; \dots; x_1], [x_{l+1}; x_{l+2}; \dots; x_m]) = \\ \begin{aligned} & [[p_1; \dots; p_k; x_{l+1}; x_{l+2}; \dots; x_{l+n}], [x_1; \dots; x_l; x_{l+n+1}; \dots; x_m]]; \dots; \\ & ([p_1; \dots; p_k; x_{m-n+1}; x_{m-n+2}; \dots; x_m], [x_1; \dots; x_l; x_{l+1}; \dots; x_{m-n}]) \end{aligned} \quad (\text{O.10}) \end{aligned}$$

where the order of the  $[x_1; x_2; \dots; x_m]$  is maintained in the partitions. Variations on this multiple recursion idiom are used many times below.

```
let rec split' n rev_part rev_head = function
| [] → []
| x :: tail →
    let rev_part' = x :: rev_part
    and parts = split' n rev_part (x :: rev_head) tail in
    if n < 1 then
        failwith "Combinatorics.split': can't happen"
    else if n = 1 then
        (List.rev rev_part', List.rev_append rev_head tail) :: parts
    else
        split' (pred n) rev_part' rev_head tail @ parts
```

Kick off the recursion for  $0 < n < |l|$  and handle the cases  $n \in \{0, |l|\}$  explicitly. Use reflection symmetry for a small optimization.

```
let ordered_split_unsafe n abs_l l =
    let abs_l = List.length l in
    if n = 0 then
        [[], l]
    else if n = abs_l then
        [l, []]
    else if n ≤ abs_l / 2 then
        split' n [] [] l
    else
        List.rev_map (fun (a, b) → (b, a)) (split' (abs_l - n) [] [] l)
```

Check the arguments and call the workhorse:

```
let ordered_split n l =
    let abs_l = List.length l in
    if n < 0 ∨ n > abs_l then
        invalid_arg "Combinatorics.ordered_split"
    else
```

*ordered\_split\_unsafe n abs\_l l*

Handle equipartitions specially:

```

let split n l =
  let abs_l = List.length l in
  if n < 0 ∨ n > abs_l then
    invalid_arg "Combinatorics.split"
  else begin
    if 2 × n = abs_l then
      match l with
      | [] → failwith "Combinatorics.split: can't happen"
      | x :: tail →
          List.map (fun (p1, p2) → (x :: p1, p2)) (split' (pred n) [] [] tail)
    else
      ordered_split_unsafe n abs_l l
  end
end

```

If we chop off parts repeatedly, we can either keep permutations or suppress them. Generically, *attach\_to\_fst* has type

$$(\alpha \times \beta) \text{ list} \rightarrow \alpha \text{ list} \rightarrow (\alpha \text{ list} \times \beta) \text{ list} \rightarrow (\alpha \text{ list} \times \beta) \text{ list}$$

and semantics

$$\begin{aligned} \text{attach\_to\_fst}([(a_1, b_1), (a_2, b_2), \dots, (a_m, b_m)], [a'_1, a'_2, \dots]) = \\ [[a_1, a'_1, \dots], b_1], [[a_2, a'_1, \dots], b_2], \dots, [[a_m, a'_1, \dots], b_m] \end{aligned} \quad (\text{O.11})$$

(where some of the result can be filtered out), assumed to be prepended to the final argument.

```

let rec multi_split' attach_to_fst n size splits =
  if n ≤ 0 then
    splits
  else
    multi_split' attach_to_fst (pred n) size
    (List.fold_left (fun acc (parts, tail) →
      attach_to_fst (ordered_split size tail) parts acc) [] splits)

```

```

let attach_to_fst_unsorted splits parts acc =
  List.fold_left (fun acc' (p, rest) → (p :: parts, rest) :: acc') acc splits

```

Similarly, if the second argument is a list of lists:

```

let prepend_to_fst_unsorted splits parts acc =
  List.fold_left (fun acc' (p, rest) → (p @ parts, rest) :: acc') acc splits

```

```

let attach_to_fst_sorted splits parts acc =
  match parts with
  | [] → List.fold_left (fun acc' (p, rest) → ([p], rest) :: acc') acc splits
  | p :: _ as parts →
      List.fold_left (fun acc' (p', rest) →
        if p' > p then
          (p' :: parts, rest) :: acc'
        else

```

```

    acc') acc splits
let multi_split n size l =
  multi_split' attach_to_fst_sorted n size [[], l]
let ordered_multi_split n size l =
  multi_split' attach_to_fst_unsorted n size [[], l]
let rec partitions' splits = function
  | [] → List.map (fun (h, r) → (List.rev h, r)) splits
  | (1, size) :: more →
    partitions'
    (List.fold_left (fun acc (parts, rest) →
      attach_to_fst_unsorted (split size rest) parts acc)
      [] splits) more
  | (n, size) :: more →
    partitions'
    (List.fold_left (fun acc (parts, rest) →
      prepend_to_fst_unsorted (multi_split n size rest) parts acc)
      [] splits) more
let partitions multiplicities l =
  if List.fold_left (+) 0 multiplicities ≠ List.length l then
    invalid_arg "Combinatorics.partitions"
  else
    List.map fst (partitions' [[], l]
      (ThoList.classify (List.sort compare multiplicities)))
let rec ordered_partitions' splits = function
  | [] → List.map (fun (h, r) → (List.rev h, r)) splits
  | size :: more →
    ordered_partitions'
    (List.fold_left (fun acc (parts, rest) →
      attach_to_fst_unsorted (ordered_split size rest) parts acc)
      [] splits) more
let ordered_partitions multiplicities l =
  if List.fold_left (+) 0 multiplicities ≠ List.length l then
    invalid_arg "Combinatorics.ordered_partitions"
  else
    List.map fst (ordered_partitions' [[], l] multiplicities)
let hdtl = function
  | [] → invalid_arg "Combinatorics.hdtl"
  | h :: t → (h, t)
let factorized_partitions multiplicities l =
  ThoList.factorize (List.map hdtl (partitions multiplicities l))

```

In order to construct keystones (cf. chapter 3), we must eliminate reflections consistently. For this to work, the lengths of the parts *must not* be reordered arbitrarily. Ordering with monotonously fallings lengths would be incorrect however, because then some remainders could fake a reflection symmetry and partitions would be dropped erroneously. Therefore we put the longest first and order the remaining with rising lengths:

```

let longest_first l =
  match ThoList.classify (List.sort (fun n1 n2 → compare n2 n1) l) with
  | [] → []
  | longest :: rest → longest :: List.rev rest

let keystones multiplicities l =
  if List.fold_left (+) 0 multiplicities ≠ List.length l then
    invalid_arg "Combinatorics.keystones"
  else
    List.map fst (partitions' ([], l) (longest_first multiplicities))

let factorized_keystones multiplicities l =
  ThoList.factorize (List.map hdtl (keystones multiplicities l))

```

### O.2.3 Choices

The implementation is very similar to *split'*, but here we don't have to keep track of the complements of the chosen sets.

```

let rec choose' n rev_choice = function
| [] → []
| x :: tail →
  let rev_choice' = x :: rev_choice
  and choices = choose' n rev_choice tail in
  if n < 1 then
    failwith "Combinatorics.choose': can't happen"
  else if n = 1 then
    List.rev rev_choice' :: choices
  else
    choose' (pred n) rev_choice' tail @ choices

```

*choose* *n* is equivalent to  $(List.map\ fst) \circ (split\_ordered\ n)$ , but more efficient.

```

let choose n l =
  let abs_l = List.length l in
  if n < 0 then
    invalid_arg "Combinatorics.choose"
  else if n > abs_l then
    []
  else if n = 0 then
    [[]]
  else if n = abs_l then
    [l]
  else
    choose' n [] l

let multi_choose n size l =
  List.map fst (multi_split n size l)

let ordered_multi_choose n size l =
  List.map fst (ordered_multi_split n size l)

```

*O.2.4 Permutations*

```

let rec insert x = function
| [] → [[x]]
| h :: t as l →
    (x :: l) :: List.rev_map (fun l' → h :: l') (insert x t)
let permute l =
    List.fold_left (fun acc x → ThoList.rev_flatmap (insert x) acc) [[]] l

```

*Graded Permutations*

```

let rec insert_signed x = function
| (eps, []) → [(eps, [x])]
| (eps, h :: t) → (eps, x :: h :: t) ::
    (List.map (fun (eps', l') → (-eps', h :: l')) (insert_signed x (eps, t)))
let rec permute_signed' = function
| (eps, []) → [(eps, [])]
| (eps, h :: t) → ThoList.flatmap (insert_signed h) (permute_signed' (eps, t))
let permute_signed l =
    permute_signed' (1, l)

```

The following are wasting at most a factor of two and there's probably no point in improving on this ...

```

let filter_sign s l =
    List.map snd (List.filter (fun (eps, _) → eps = s) l)
let permute_even l =
    filter_sign 1 (permute_signed l)
let permute_odd l =
    filter_sign (-1) (permute_signed l)

```

*Tensor Products of Permutations*

```

let permute_tensor ll =
    Product.list (fun l → l) (List.map permute ll)
let join_signs l =
    let el, pl = List.split l in
    (List.fold_left (fun acc x → x × acc) 1 el, pl)
let permute_tensor_signed ll =
    Product.list join_signs (List.map permute_signed ll)
let permute_tensor_even l =
    filter_sign 1 (permute_tensor_signed l)
let permute_tensor_odd l =
    filter_sign (-1) (permute_tensor_signed l)
let insert_inorder_signed order x (eps, l) =

```

```

let rec insert eps' accu = function
| [] → (eps × eps', List.rev_append accu [x])
| h :: t →
    if order x h = 0 then
        invalid_arg
            "Combinatorics.insert_inorder_signed: identical elements"
    else if order x h < 0 then
        (eps × eps', List.rev_append accu (x :: h :: t))
    else
        insert (-eps') (h :: accu) t
in
insert 1 [] l

```

### Sorting

```

let sort_signed order l =
    List.fold_left (fun acc x → insert_inorder_signed order x acc) (1, []) l

```

## O.3 Interface of *Permutation*

```

module type T =
sig
    type t
    val of_list : int list → t
    val of_array : int array → t
    val inverse : t → t
    val compose : t → t → t
    val list : t → α list → α list
    val array : t → α array → α array
end

module Using_Lists : T
module Using_Arrays : T
module Default : T

module Test : functor (P : T) →
    sig val suite : OUnit.test val time : unit → unit end

```

## O.4 Implementation of *Permutation*

```

module type T =
sig
    type t
    val of_list : int list → t
    val of_array : int array → t
    val inverse : t → t
    val compose : t → t → t
    val list : t → α list → α list

```

```

    val array : t → α array → α array
  end

module Using_Lists : T =
  struct

    type t = int list

    let of_list p =
      if List.sort compare p ≠ (ThoList.range 0 (List.length p - 1)) then
        invalid_arg "Permutation.of_list"
      else
        p

    let of_array p =
      try
        of_list (Array.to_list p)
      with
      | Invalid_argument "Permutation.of_list" →
        invalid_arg "Permutation.of_array"

    let inverse p = snd (ThoList.ariadne_sort p)

    let list p l =
      List.map snd
        (List.sort compare
          (try
             List.rev_map2 (fun i x → (i, x)) p l
           with
           | Invalid_argument "List.rev_map2" →
             invalid_arg "Permutation.list:_length_mismatch"))

    let array p a =
      try
        Array.of_list (list p (Array.to_list a))
      with
      | Invalid_argument "Permutation.list:_length_mismatch" →
        invalid_arg "Permutation.array:_length_mismatch"
  end

```

Probably not optimal (or really inefficient), but correct by associativity.

```

    let compose p q =
      list (inverse q) p
  end

module Using_Arrays : T =
  struct

    type t = int array

    let of_list p =
      if List.sort compare p ≠ (ThoList.range 0 (List.length p - 1)) then
        invalid_arg "Permutation.of_list"
      else
        Array.of_list p
  end

```



```

let of_array p =
  try
    of_list (Array.to_list p)
  with
  | Invalid_argument "Permutation.of_list" →
    invalid_arg "Permutation.of_array"

let inverse p =
  let len_p = Array.length p in
  let p' = Array.make len_p p.(0) in
  for i = 0 to pred len_p do
    p'.(p.(i)) ← i
  done;
  p'

let array p a =
  let len_a = Array.length a
  and len_p = Array.length p in
  if len_a ≠ len_p then
    invalid_arg "Permutation.array:␣length␣mismatch";
  let a' = Array.make len_a a.(0) in
  for i = 0 to pred len_a do
    a'.(p.(i)) ← a.(i)
  done;
  a'

let list p l =
  try
    Array.to_list (array p (Array.of_list l))
  with
  | Invalid_argument "Permutation.array:␣length␣mismatch" →
    invalid_arg "Permutation.list:␣length␣mismatch"

let compose p q =
  array (inverse q) p

end

module Default = Using_Arrays

To shuffle an array a of n elements (indices 0..n-1):
  for i from n - 1 downto 1 do j = random integer with 0 ≤ j ≤ i exchange aj and ai
  To initialize an array a of n elements to a randomly shuffled copy of source,
  both 0-based:
    a[0] = source[0] for i from 1 to n - 1 do j = random integer with 0 ≤ j ≤ i ai = aj aj =
    source[i]

let shuffle l =
  let a = Array.of_list l in
  for n = Array.length a - 1 downto 1 do
    let k = Random.int (succ n) in
    if k ≠ n then
      let tmp = Array.get a n in
      Array.set a n (Array.get a k);

```

```

      Array.set a k tmp
done;
Array.to_list a

let time f x =
  let start = Sys.time () in
  let f_x = f x in
  let stop = Sys.time () in
  (f_x, stop -. start)

let print_time msg f x =
  let f_x, seconds = time f x in
  Printf.printf "%s took %.2f ms\n" msg (seconds *. 1000.);
  f_x

module Test (P : T) : sig val suite : OUnit.test val time : unit → unit end =
struct
  open OUnit
  open P

  let of_list_overlap =
    "overlap" >::
      (fun () →
        assert_raises (Invalid_argument "Permutation.of_list")
          (fun () →
            of_list [0; 1; 2; 2]))

  let of_list_gap =
    "gap" >::
      (fun () →
        assert_raises (Invalid_argument "Permutation.of_list")
          (fun () →
            of_list [0; 1; 2; 4; 5]))

  let of_list_ok =
    "ok" >::
      (fun () →
        let l = ThoList.range 0 10 in
        assert_equal (of_list l) (of_list l))

  let suite_of_list =
    "of_list" >:::
      [of_list_overlap;
       of_list_gap;
       of_list_ok]

  let apply_invalid_lengths =
    "invalid/lengths" >::
      (fun () →
        assert_raises
          (Invalid_argument "Permutation.list: length mismatch")
          (fun () →
            list (of_list [0; 1; 2; 3; 4]) [0; 1; 2; 3]))

```

```

let apply_ok =
  "ok" >::
    (fun () →
      assert_equal [2; 0; 1; 3; 5; 4]
        (list (of_list [1; 2; 0; 3; 5; 4]) [0; 1; 2; 3; 4; 5]))

let suite_apply =
  "apply" >:::
    [apply_invalid_lengths;
     apply_ok]

let inverse_ok =
  "ok" >::
    (fun () →
      let l = shuffle (ThoList.range 0 1000) in
      let p = of_list (shuffle l) in
      assert_equal l (list (inverse p) (list p l)))

let suite_inverse =
  "inverse" >:::
    [inverse_ok]

let compose_ok =
  "ok" >::
    (fun () →
      let id = ThoList.range 0 1000 in
      let p = of_list (shuffle id)
      and q = of_list (shuffle id)
      and l = id in
      assert_equal (list p (list q l)) (list (compose p q) l))

let compose_inverse_ok =
  "inverse/ok" >::
    (fun () →
      let id = ThoList.range 0 1000 in
      let p = of_list (shuffle id)
      and q = of_list (shuffle id) in
      assert_equal
        (compose (inverse p) (inverse q))
        (inverse (compose q p)))

let suite_compose =
  "compose" >:::
    [compose_ok;
     compose_inverse_ok]

let suite =
  "Permutations" >:::
    [suite_of_list;
     suite_apply;
     suite_inverse;
     suite_compose]

let repeat repetitions size =

```

```
let id = ThoList.range 0 size in
let p = of_list (shuffle id)
and l = shuffle (List.map string_of_int id) in
print_time (Printf.sprintf "reps=%d, len=%d" repetitions size)
  (fun () →
    for i = 1 to repetitions do
      ignore (P.list p l)
    done)
  ())

let time () =
  repeat 100000 10;
  repeat 10000 100;
  repeat 1000 1000;
  repeat 100 10000;
  repeat 10 100000;
  ()

end
```

---

# —P—

## PARTITIONS

### *P.1 Interface of Partition*

*pairs*  $n$   $n1$   $n2$  returns all (unordered) pairs of integers with the sum  $n$  in the range from  $n1$  to  $n2$ .

`val pairs : int → int → int → (int × int) list`  
`val triples : int → int → int → (int × int × int) list`

*tuples*  $d$   $n$   $n_{\min}$   $n_{\max}$  returns all  $[n_1; n_2; \dots; n_d]$  with  $n_{\min} \leq n_1 \leq n_2 \leq \dots \leq n_d \leq n_{\max}$  and

$$\sum_{i=1}^d n_i = n \quad (\text{P.1})$$

`val tuples : int → int → int → int → int list list`  
`val rcs : RCS.t`

### *P.2 Implementation of Partition*

```
let rcs = RCS.parse "Partition" ["Partitions"]
  { RCS.revision = "$Revision: 4926$";
    RCS.date = "$Date: 2013-12-04 13:35:06 +0100 (Wed, 04 Dec 2013)$";
    RCS.author = "$Author: jr-reuter$";
    RCS.source
      = "$URL: svn+ssh://jr-reuter@login.hepforge.org/hepforge/svn/whizard/trunk/omega/s"
```

All unordered pairs of integers with the same sum  $n$  in a given range  $\{n_1, \dots, n_2\}$ :

$$\text{pairs} : (n, n_1, n_2) \rightarrow \{(i, j) \mid i + j = n \wedge n_1 \leq i \leq j \leq n_2\} \quad (\text{P.2})$$

```
let rec pairs' acc n1 n2 =
  if n1 > n2 then
    List.rev acc
  else
    pairs' ((n1, n2) :: acc) (succ n1) (pred n2)
let pairs sum min_n1 max_n2 =
  let n1 = max min_n1 (sum - max_n2) in
```

```

let n2 = sum - n1 in
if n2 ≤ max_n2 then
  pairs' [] n1 n2
else
  []

let rec tuples d sum n_min n_max =
  if d ≤ 0 then
    invalid_arg "tuples"
  else if d > 1 then
    tuples' d sum n_min n_max n_min
  else if sum ≥ n_min ∧ sum ≤ n_max then
    [[sum]]
  else
    []

and tuples' d sum n_min n_max n =
  if n > n_max then
    []
  else
    List.fold_right (fun l ll → (n :: l) :: ll)
      (tuples (pred d) (sum - n) (max n_min n) n_max)
      (tuples' d sum n_min n_max (succ n))

```



When I find a little spare time, I can provide a dedicated implementation, but we *know* that *Impossible* is *never* raised and the present approach is just as good (except for a possible tiny inefficiency).

```

exception Impossible of string
let impossible name = raise (Impossible name)

let triples sum n_min n_max =
  List.map (function [n1; n2; n3] → (n1, n2, n3) | _ → impossible "triples")
    (tuples 3 sum n_min n_max)

```

---

## Q TREES

From [10]: Trees with one root admit a straightforward recursive definition

$$T(N, L) = L \cup N \times T(N, L) \times T(N, L) \quad (\text{Q.1})$$

that is very well adapted to mathematical reasoning. Such recursive definitions are useful because they allow us to prove properties of elements by induction

$$\begin{aligned} \forall l \in L : p(l) \wedge (\forall n \in N : \forall t_1, t_2 \in T(N, L) : p(t_1) \wedge p(t_2) \Rightarrow p(n \times t_1 \times t_2)) \\ \implies \forall t \in T(N, L) : p(t) \end{aligned} \quad (\text{Q.2})$$

i. e. establishing a property for all leaves and showing that a node automatically satisfies the property if it is true for all children proves the property for *all* trees. This induction is of course modelled after standard mathematical induction

$$p(1) \wedge (\forall n \in \mathbf{N} : p(n) \Rightarrow p(n+1)) \implies \forall n \in \mathbf{N} : p(n) \quad (\text{Q.3})$$

The recursive definition (Q.1) is mirrored by the two tree construction functions<sup>1</sup>

$$\text{leaf} : \nu \times \lambda \rightarrow (\nu, \lambda)T \quad (\text{Q.4a})$$

$$\text{node} : \nu \times (\nu, \lambda)T \times (\nu, \lambda)T \rightarrow (\nu, \lambda)T \quad (\text{Q.4b})$$

Renaming leaves and nodes leaves the structure of the tree invariant. Therefore, morphisms  $L \rightarrow L'$  and  $N \rightarrow N'$  of the sets of leaves and nodes induce natural homomorphisms  $T(N, L) \rightarrow T(N', L')$  of trees

$$\text{map} : (\nu \rightarrow \nu') \times (\lambda \rightarrow \lambda') \times (\nu, \lambda)T \rightarrow (\nu', \lambda')T \quad (\text{Q.5})$$

The homomorphisms constructed by *map* are trivial, but ubiquitous. More interesting are the morphisms

$$\begin{aligned} \text{fold} : (\nu \times \lambda \rightarrow \alpha) \times (\nu \times \alpha \times \alpha \rightarrow \alpha) \times (\nu, \lambda)T &\rightarrow \alpha \\ (f_1, f_2, l \in L) &\mapsto f_1(l) \\ (f_1, f_2, (n, t_1, t_2)) &\mapsto f_2(n, \text{fold}(f_1, f_2, t_1), \text{fold}(f_1, f_2, t_2)) \end{aligned} \quad (\text{Q.6})$$

---

<sup>1</sup>To make the introduction more accessible to non-experts, I avoid the ‘curried’ notation for functions with multiple arguments and use tuples instead. The actual implementation takes advantage of curried functions, however. Experts can read  $\alpha \rightarrow \beta \rightarrow \gamma$  for  $\alpha \times \beta \rightarrow \gamma$ .

and

$$\begin{aligned}
fan : (\nu \times \lambda \rightarrow \{\alpha\}) \times (\nu \times \alpha \times \alpha \rightarrow \{\alpha\}) \times (\nu, \lambda)T &\rightarrow \{\alpha\} \\
(f_1, f_2, l \in L) &\mapsto f_1(l) \\
(f_1, f_2, (n, t_1, t_2)) &\mapsto f_2(n, fold(f_1, f_2, t_1) \otimes fold(f_1, f_2, t_2))
\end{aligned} \tag{Q.7}$$

where the tensor product notation means that  $f_2$  is applied to all combinations of list members in the argument:

$$\phi(\{x\} \otimes \{y\}) = \{\phi(x, y) | x \in \{x\} \wedge y \in \{y\}\} \tag{Q.8}$$

But note that due to the recursive nature of trees, *fan* is *not* a morphism from  $T(N, L)$  to  $T(N \otimes N, L)$ .

If we identify singleton sets with their members, *fold* could be viewed as a special case of *fan*, but that is probably more confusing than helpful. Also, using the special case  $\alpha = (\nu', \lambda')T$ , the homomorphism *map* can be expressed in terms of *fold* and the constructors

$$\begin{aligned}
map : (\nu \rightarrow \nu') \times (\lambda \rightarrow \lambda') \times (\nu, \lambda)T &\rightarrow (\nu', \lambda')T \\
(f, g, t) &\mapsto fold(leaf \circ (f \times g), node \circ (f \times id \times id), t)
\end{aligned} \tag{Q.9}$$

*fold* is much more versatile than *map*, because it can be used with constructors for other tree representations to translate among different representations. The target type can also be a mathematical expression. This is used extensively below for evaluating Feynman diagrams.

Using *fan* with  $\alpha = (\nu', \lambda')T$  can be used to construct a multitude of homomorphic trees. In fact, below it will be used extensively to construct all Feynman diagrams  $\{(\nu, \{p_1, \dots, p_n\})T\}$  of a given topology  $t \in (\emptyset, \{1, \dots, n\})T$ .



The physicist in me guesses that there is another morphism of trees that is related to *fan* like a Lie-algebra is related to the it's Lie-group. I have not been able to pin it down, but I guess that it is a generalization of *grow* below.

## Q.1 Interface of *Tree*

This module provides utilities for generic decorated trees, such as FeynMF output.

### Q.1.1 Abstract Data Type

**type**  $(\nu, \lambda) t$

*leaf*  $n l$  returns a tree consisting of a single leaf node of type  $n$  with a label  $l$ .

**val** *leaf* :  $\nu \rightarrow \lambda \rightarrow (\nu, \lambda) t$

*cons*  $n ch$  returns a tree node.

**val** *cons* :  $\nu \rightarrow (\nu, \lambda) t list \rightarrow (\nu, \lambda) t$

Note that *cons node []* constructs a terminal node, but *not* a leaf, since the latter *must* have a label!





This approach was probably tailored to Feynman diagrams, where we have external propagators as nodes with additional labels (cf. the function *to\_feynmf* on page 807 below). I'm not so sure anymore that this was a good choice.

*node t* returns the top node of the tree *t*.

**val node** : ( $\nu$ ,  $\lambda$ ) *t*  $\rightarrow \nu$

*leafs t* returns a list of all leaf labels *in order*.

**val leafs** : ( $\nu$ ,  $\lambda$ ) *t*  $\rightarrow \lambda$  *list*

*nodes t* returns a list of all nodes that are not leafs in post-order. This guarantees that the root node can be stripped from the result by *List.tl*.

**val nodes** : ( $\nu$ ,  $\lambda$ ) *t*  $\rightarrow \nu$  *list*

*fuse conjg root contains\_root trees* joins the *trees*, using the leaf *root* in one of the trees as root of the new tree. *contains\_root* guides the search for the subtree containing *root* as a leaf. **fun** *t*  $\rightarrow$  *List.mem root (leafs t)* is acceptable, but more efficient solutions could be available in special circumstances.

**val fuse** : ( $\nu \rightarrow \nu$ )  $\rightarrow \lambda \rightarrow ((\nu, \lambda) t \rightarrow \text{bool}) \rightarrow (\nu, \lambda) t$  *list*  $\rightarrow (\nu, \lambda) t$

*sort lesseq t* return a sorted copy of the tree *t*: node labels are ignored and nodes are according to the supremum of the leaf labels in the corresponding subtree.

**val sort** : ( $\lambda \rightarrow \lambda \rightarrow \text{bool}$ )  $\rightarrow (\nu, \lambda) t \rightarrow (\nu, \lambda) t$

**val canonicalize** : ( $\nu, \lambda$ ) *t*  $\rightarrow (\nu, \lambda) t$

### Q.1.2 Homomorphisms

**val map** : ( $'n1 \rightarrow 'n2$ )  $\rightarrow ('l1 \rightarrow 'l2) \rightarrow ('n1, 'l1) t \rightarrow ('n2, 'l2) t$

**val fold** : ( $\nu \rightarrow \lambda \rightarrow \alpha$ )  $\rightarrow (\nu \rightarrow \alpha$  *list*  $\rightarrow \alpha$ )  $\rightarrow (\nu, \lambda) t \rightarrow \alpha$

**val fan** : ( $\nu \rightarrow \lambda \rightarrow \alpha$  *list*)  $\rightarrow (\nu \rightarrow \alpha$  *list*  $\rightarrow \alpha$  *list*)  $\rightarrow (\nu, \lambda) t \rightarrow \alpha$  *list*

### Q.1.3 Output

**val to\_string** : (*string*, *string*) *t*  $\rightarrow$  *string*

*Feynmf*



*style* : (*string*  $\times$  *string*) *option* should be replaced by *style* : *string option*; *tex\_label* : *string option*

**type feynmf** =  
 { *style* : (*string*  $\times$  *string*) *option*;  
   *rev* : *bool*;  
   *label* : *string option*;  
   *tension* : *float option* }

`val vanilla : feynmf`  
`val sty : (string × string) × bool × string → feynmf`  
*to\_feynmf file to\_string incoming t* write the trees in the list *t* to the file named *file*. The leaves *incoming* are used as incoming particles and *to\_string* is use to convert leaf labels to L<sup>A</sup>T<sub>E</sub>X-strings.

```

type λ feynmf_set =
  { header : string;
    incoming : λ list;
    diagrams : (feynmf, λ) t list }

type (λ, μ) feynmf_sets =
  { outer : λ feynmf_set;
    inner : μ feynmf_set list }

val feynmf_sets_plain : bool → int → string →
  (λ → string) → (λ → string) →
  (μ → string) → (μ → string) → (λ, μ) feynmf_sets list → unit

val feynmf_sets_wrapped : bool → string →
  (λ → string) → (λ → string) →
  (μ → string) → (μ → string) → (λ, μ) feynmf_sets list → unit

```

If the diagrams at all levels are of the same type, we can recurse to arbitrary depth.

```

type λ feynmf_levels =
  { this : λ feynmf_set;
    lower : λ feynmf_levels list }

to_feynmf_levels_plain sections level file wf_to_TeX p_to_TeX levels ...

val feynmf_levels_plain : bool → int → string →
  (λ → string) → (λ → string) → λ feynmf_levels list → unit

to_feynmf_levels_wrapped file wf_to_TeX p_to_TeX levels ...

val feynmf_levels_wrapped : string →
  (λ → string) → (λ → string) → λ feynmf_levels list → unit

```

### Least Squares Layout

A general graph with edges of type  $\varepsilon$ , internal nodes of type  $\nu$ , and external nodes of type *'ext'*.

```

type (ε, ν, 'ext) graph
val graph_of_tree : (ν → ν → ε) → (ν → ν) →
  ν → (ν, ν) t → (ε, ν, ν) graph

```

A general graph with the layout of the external nodes fixed.

```

type (ε, ν, 'ext) ext_layout
val left_to_right : int → (ε, ν, 'ext) graph → (ε, ν, 'ext) ext_layout

```

A general graph with the layout of all nodes fixed.

```

type ( $\varepsilon$ ,  $\nu$ , 'ext) layout
val layout : ( $\varepsilon$ ,  $\nu$ , 'ext) ext_layout  $\rightarrow$  ( $\varepsilon$ ,  $\nu$ , 'ext) layout

val dump : ( $\varepsilon$ ,  $\nu$ , 'ext) layout  $\rightarrow$  unit
val iter_edges : ( $\varepsilon \rightarrow$  float  $\times$  float  $\rightarrow$  float  $\times$  float  $\rightarrow$  unit)  $\rightarrow$ 
  ( $\varepsilon$ ,  $\nu$ , 'ext) layout  $\rightarrow$  unit
val iter_internal : (float  $\times$  float  $\rightarrow$  unit)  $\rightarrow$ 
  ( $\varepsilon$ ,  $\nu$ , 'ext) layout  $\rightarrow$  unit
val iter_incoming : ('ext  $\times$  float  $\times$  float  $\rightarrow$  unit)  $\rightarrow$ 
  ( $\varepsilon$ ,  $\nu$ , 'ext) layout  $\rightarrow$  unit
val iter_outgoing : ('ext  $\times$  float  $\times$  float  $\rightarrow$  unit)  $\rightarrow$ 
  ( $\varepsilon$ ,  $\nu$ , 'ext) layout  $\rightarrow$  unit

```

## Q.2 Implementation of *Tree*

### Q.2.1 Abstract Data Type

```

type ( $\nu$ ,  $\lambda$ ) t =
  | Leaf of  $\nu \times \lambda$ 
  | Node of  $\nu \times (\nu, \lambda) t$  list

let leaf n l = Leaf (n, l)

let cons n children = Node (n, children)

let rec leafs = function
  | Leaf (_, l)  $\rightarrow$  [l]
  | Node (_, ch)  $\rightarrow$  ThoList.flatmap leafs ch

let node = function
  | Leaf (n, _)  $\rightarrow$  n
  | Node (n, _)  $\rightarrow$  n

```

This guarantees that the root node can be stripped from the result by *List.tl*.

```

let rec nodes = function
  | Leaf _  $\rightarrow$  []
  | Node (n, ch)  $\rightarrow$  n :: ThoList.flatmap nodes ch

```

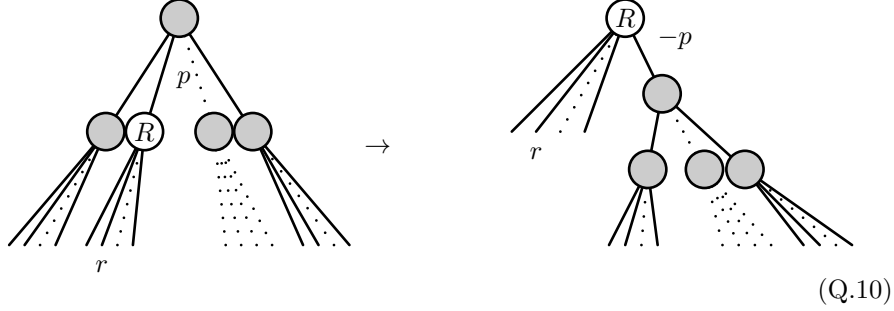
*first\_match p list* returns  $(x, list')$ , where  $x$  is the first element of *list* for which  $p\ x = \text{true}$  and *list'* is *list* sans  $x$ .

```

let first_match p list =
  let rec first_match' no_match = function
    | []  $\rightarrow$  invalid_arg "Tree.fuse: prospective root not found"
    | t :: rest when p t  $\rightarrow$  (t, List.rev_append no_match rest)
    | t :: rest  $\rightarrow$  first_match' (t :: no_match) rest in
  first_match' [] list

```

One recursion step in *fuse'* rotates the topmost tree node, moving the prospective root up:



```
let fuse conjg root contains_root trees =
  let rec fuse' subtrees =
    match first_match contains_root subtrees with
```

If the prospective root is contained in a leaf, we have either found the root—in which case we're done—or have failed catastrophically:

```
| Leaf (n, l), children →
  if l = root then
    Node (conjg n, children)
  else
    invalid_arg "Tree.fuse: root predicate inconsistent"
```

Otherwise, we perform a rotation as in (Q.10) and connect all nodes that do not contain the root to a new node. For efficiency, we append the new node at the end and prevent *first\_match* from searching for the root in it in vain again. Since *root\_children* is probably rather short, this should be a good strategy.

```
| Node (n, root_children), other_children →
  fuse' (root_children @ [Node (conjg n, other_children)]) in
  fuse' trees
```

Sorting is also straightforward, we only have to keep track of the suprema of the subtrees:

```
type (α, β) with_supremum = { sup : α; data : β }
```

Since the lists are rather short, *Sort.list* could be replaced by an optimized version, but we're not (yet) dealing with the most important speed bottleneck here:

```
let rec sort' lesseq = function
| Leaf (_, l) as e → { sup = l; data = e }
| Node (n, ch) →
  let ch' = Sort.list
    (fun x y → lesseq x.sup y.sup) (List.map (sort' lesseq) ch) in
  { sup = (List.hd (List.rev ch')).sup;
    data = Node (n, List.map (fun x → x.data) ch') }
```

finally, throw away the overall supremum:

```
let sort lesseq t = (sort' lesseq t).data
```

```

let rec canonicalize = function
| Leaf (_, _) as l → l
| Node (n, ch) →
  Node (n, List.sort compare (List.map canonicalize ch))

```

### Q.2.2 Homomorphisms

Isomorphisms are simple:

```

let rec map fn fl = function
| Leaf (n, l) → Leaf (fn n, fl l)
| Node (n, ch) → Node (fn n, List.map (map fn fl) ch)

```

homomorphisms are not more complicated:

```

let rec fold leaf node = function
| Leaf (n, l) → leaf n l
| Node (n, ch) → node n (List.map (fold leaf node) ch)

```

and tensor products are fun:

```

let rec fan leaf node = function
| Leaf (n, l) → leaf n l
| Node (n, ch) → Product.fold
  (fun ch' t → node n ch' @ t) (List.map (fan leaf node) ch) []

```

### Q.2.3 Output

```

let leaf_to_string n l =
  if n = "" then
    l
  else if l = "" then
    n
  else
    n ^ "(" ^ l ^ ")"
let node_to_string n ch =
  "(" ^ (if n = "" then "" else n ^ ":") ^ (String.concat "," ch) ^ ")"
let to_string t =
  fold leaf_to_string node_to_string t

```

### Feynmf

Add a value that is greater than all suprema

```

type α supremum_or_infinity = Infinity | Sup of α
type (α, β) with_supremum_or_infinity =
  { sup : α supremum_or_infinity; data : β }
let with_infinity lesseq x y =
  match x.sup, y.sup with

```

```

| Infinity, _ → false
| _, Infinity → true
| Sup x', Sup y' → lesseq x' y'

```

Using this, we can sort the tree in another way that guarantees that a particular leaf (*i2*) is moved as far to the end as possible. We can then flip this leaf from outgoing to incoming without introducing a crossing:

```

let rec sort_2i' lesseq i2 = function
| Leaf (_, l) as e →
  { sup = if l = i2 then Infinity else Sup l; data = e }
| Node (n, ch) →
  let ch' = Sort.list (with_infinity lesseq)
    (List.map (sort_2i' lesseq i2) ch) in
  { sup = (List.hd (List.rev ch')).sup;
    data = Node (n, List.map (fun x → x.data) ch') }

```

again, throw away the overall supremum:

```
let sort_2i lesseq i2 t = (sort_2i' lesseq i2 t).data
```

```

type feynmf =
{ style : (string × string) option;
  rev : bool;
  label : string option;
  tension : float option }

```

```
open Printf
```

```

let style prop =
  match prop.style with
  | None → ("plain","")
  | Some s → s

```

```
let species prop = fst (style prop)
```

```
let tex_lbl prop = snd (style prop)
```

```

let leaf_label tex io leaf lab = function
| None → fprintf tex "uuuu\\fmflabel{${%s}$}{%s%s}\\n" lab io leaf
| Some s →
  fprintf tex "uuuu\\fmflabel{${%s}{~{(%s)}}$}{%s%s}\\n" s lab io leaf

```

```

let leaf_label tex io leaf lab label =
()

```

We try to draw diagrams more symmetrically by reducing the tension on the outgoing external lines.



This is insufficient for asymmetrical cascade decays.

```

let rec leaf_node tex to_label i2 n prop leaf =
  let io, tension, rev =
    if leaf = i2 then
      ("i", "", ¬ prop.rev)
    else
      ("o", "", tension=0.5, prop.rev) in

```

---

```

leaf_label tex io (to_label leaf) (tex_lbl prop) prop.label ;
fprintf tex "\fmfdot{v%d}\n" n;
if rev then
  fprintf tex "\fmf{%s%s}{%s%s,v%d}\n"
    (species prop) tension io (to_label leaf) n
else
  fprintf tex "\fmf{%s%s}{v%d,%s%s}\n"
    (species prop) tension n io (to_label leaf)
and int_node tex to_label i2 n n' prop t =
  if prop.rev then
    fprintf tex
      "\fmf{%s,label=\begin{scriptsize}$\{s\}$\end{scriptsize}}{v%d,v%d}\n"
      (species prop) (tex_lbl prop) n' n
  else
    fprintf tex
      "\fmf{%s,label=\begin{scriptsize}$\{s\}$\end{scriptsize}}{v%d,v%d}\n"
      (species prop) (tex_lbl prop) n n';
    fprintf tex "\fmfdot{v%d,v%d}\n" n n';
    edges_feynmf' tex to_label i2 n' t
and leaf_or_int_node tex to_label i2 n n' = function
  | Leaf (prop, l) → leaf_node tex to_label i2 n prop l
  | Node (prop, _) as t → int_node tex to_label i2 n n' prop t
and edges_feynmf' tex to_label i2 n = function
  | Leaf (prop, l) → leaf_node tex to_label i2 n prop l
  | Node (_, ch) →
    ignore (List.fold_right
      (fun t' n' →
        leaf_or_int_node tex to_label i2 n n' t';
        succ n') ch (4 × n))
let edges_feynmf tex to_label i1 i2 t =
  let n = 1 in
  begin match t with
  | Leaf _ → ()
  | Node (prop, _) →
    leaf_label tex "i" "1" (tex_lbl prop) prop.label;
    if prop.rev then
      fprintf tex "\fmf{%s}{v%d,i%s}\n" (species prop) n (to_label i1)
    else
      fprintf tex "\fmf{%s}{i%s,v%d}\n" (species prop) (to_label i1) n
  end;
  fprintf tex "\fmfdot{v%d}\n" n;
  edges_feynmf' tex to_label i2 n t
let to_feynmf_channel tex to_TeX to_label incoming t =
  match incoming with
  | i1 :: i2 :: _ →
    let t' = sort_2i (≤) i2 t in
    let out = List.filter (fun a → i2 ≠ a) (leafs t') in
    fprintf tex "\fmfframe(8,7)(8,6){%%}\n";

```

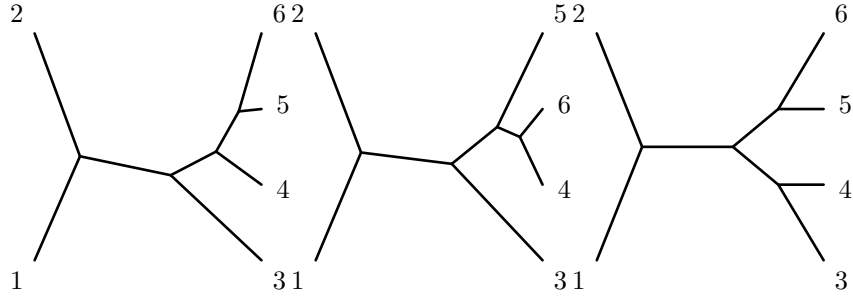


Figure Q.1: Note that this is subtly different ...

```

fprintf tex "\begin{fmfgraph*}(35,30)\n";
fprintf tex "\fmfpen{thin}\n";
fprintf tex "\fmfset{arrow_len}{2mm}\n";
fprintf tex "\fmfleft{i%s,i%s}\n" (to_label i1) (to_label i2);
fprintf tex "\fmfright{o%s}\n"
  (String.concat ",o" (List.map to_label out));
List.iter
  (fun s →
    fprintf tex "\fmflabel{${%s}$}{i%s}\n"
      (to_TeX s) (to_label s))
  [i1; i2];
List.iter
  (fun s →
    fprintf tex "\fmflabel{${%s}$}{o%s}\n"
      (to_TeX s) (to_label s))
  out;
edges_feynmf tex to_label i1 i2 t';
fprintf tex "\end{fmfgraph*}}\hfil\allowbreak\n"
| - → ()

```

```

let vanilla = { style = None; rev = false; label = None; tension = None }
let sty (s, r, l) = { vanilla with style = Some s; rev = r; label = Some l }
type λ feynmf_set =
  { header : string;
    incoming : λ list;
    diagrams : (feynmf, λ) t list }
type (λ, μ) feynmf_sets =
  { outer : λ feynmf_set;
    inner : μ feynmf_set list }
type λ feynmf_levels =
  { this : λ feynmf_set;
    lower : λ feynmf_levels list }
let latex_section = function

```





```

let feynmf_footer tex =
  fprintf tex "\n";
  fprintf tex "\\end{fmffile}\n";
  fprintf tex "\\end{document}\n"

let feynmf_sets_wrapped latex file
  to_TeX_outer to_label_outer to_TeX_inner to_label_inner sets =
  let tex = open_out (file ^ ".tex") in
  if latex then feynmf_header tex file;
  List.iter
    (feynmf_sets tex latex 1
     to_TeX_outer to_label_outer to_TeX_inner to_label_inner)
    sets;
  if latex then feynmf_footer tex;
  close_out tex

let rec feynmf_levels tex sections level to_TeX to_label set =
  fprintf tex "%s\\%s{%s}\n"
    (if sections then "" else "%%")
    (latex_section level)
    set.this.header;
  List.iter
    (to_feynmf_channel tex to_TeX to_label set.this.incoming)
    set.this.diagrams;
  List.iter (feynmf_levels tex sections (succ level) to_TeX to_label) set.lower

let feynmf_levels_plain sections level file to_TeX to_label sets =
  let tex = open_out (file ^ ".tex") in
  List.iter (feynmf_levels tex sections level to_TeX to_label) sets;
  close_out tex

let feynmf_levels_wrapped file to_TeX to_label sets =
  let tex = open_out (file ^ ".tex") in
  feynmf_header tex file;
  List.iter (feynmf_levels tex true 1 to_TeX to_label) sets;
  feynmf_footer tex;
  close_out tex

```

#### Q.2.4 Least Squares Layout

$$L = \frac{1}{2} \sum_{i' \neq i} T_{ii'} (x_i - x_{i'})^2 + \frac{1}{2} \sum_{i,j} T'_{ij} (x_i - e_j)^2 \quad (\text{Q.11})$$

and thus

$$0 = \frac{\partial L}{\partial x_i} = \sum_{i' \neq i} T_{ii'} (x_i - x_{i'}) + \sum_j T'_{ij} (x_i - e_j) \quad (\text{Q.12})$$

or

$$\left( \sum_{i' \neq i} T_{ii'} + \sum_j T'_{ij} \right) x_i - \sum_{i' \neq i} T_{ii'} x_{i'} = \sum_j T'_{ij} e_j \quad (\text{Q.13})$$

where we can assume that

$$T_{ii'} = T_{i'i} \quad (\text{Q.14a})$$

$$T_{ii} = 0 \quad (\text{Q.14b})$$

```

type  $\alpha$  node_with_tension = { node :  $\alpha$ ; tension : float }
let unit_tension t =
  map (fun n → { node = n; tension = 1.0 }) (fun l → l) t
let leafs_and_nodes i2 t =
  let t' = sort_2i ( $\leq$ ) i2 t in
  match nodes t' with
  | [] → failwith "Tree.nodes_and_leafs: impossible"
  | i1 :: _ as n → (i1, i2, List.filter (fun l → l  $\neq$  i2) (leafs t'), n)

```

Not tail recursive, but they're unlikely to meet any deep trees:

```

let rec internal_edges_from n = function
| Leaf _ → []
| Node (n', ch) → (n', n) :: (ThoList.flatmap (internal_edges_from n') ch)

```

The root node of the tree represents a vertex (node) and an external line (leaf) of the Feynman diagram simultaneously. Thus it requires special treatment:

```

let internal_edges = function
| Leaf _ → []
| Node (n, ch) → ThoList.flatmap (internal_edges_from n) ch
let rec external_edges_from n = function
| Leaf (n', _) → [(n', n)]
| Node (n', ch) → ThoList.flatmap (external_edges_from n') ch
let external_edges = function
| Leaf (n, _) → [(n, n)]
| Node (n, ch) → (n, n) :: ThoList.flatmap (external_edges_from n) ch
type ('edge, 'node, 'ext) graph =
{ int_nodes : 'node array;
  ext_nodes : 'ext array;
  int_edges : ('edge  $\times$  int  $\times$  int) list;
  ext_edges : ('edge  $\times$  int  $\times$  int) list }

```

```

module M = Pmap.Tree

```

Invert an array, viewed as a map from non-negative integers into a set. The result is a map from the set to the integers: `val invert_array :  $\alpha$  array  $\rightarrow$  ( $\alpha$ , int) M.t`

```

let invert_array_unsafe a =
  fst (Array.fold_left (fun (m, i) a_i →
    (M.add compare a_i i m, succ i)) (M.empty, 0) a)

```

```

exception Not_invertible

```

```

let add_unique key data map =
  if M.mem compare key map then

```

```

      raise Not_invertible
    else
      M.add compare key data map

let invert_array a =
  fst (Array.fold_left (fun (m, i) a_i →
    (add_unique a_i i m, succ i)) (M.empty, 0) a)

let graph_of_tree nodes2edge conjugate i2 t =
  let i1, i2, out, vertices = leafs_and_nodes i2 t in
  let int_nodes = Array.of_list vertices
  and ext_nodes = Array.of_list (conjugate i1 :: i2 :: out) in
  let int_nodes_index_table = invert_array int_nodes
  and ext_nodes_index_table = invert_array ext_nodes in
  let int_nodes_index n = M.find compare n int_nodes_index_table
  and ext_nodes_index n = M.find compare n ext_nodes_index_table in
  { int_nodes = int_nodes;
    ext_nodes = ext_nodes;
    int_edges = List.map
      (fun (n1, n2) →
        (nodes2edge n1 n2, int_nodes_index n1, int_nodes_index n2))
      (internal_edges t);
    ext_edges = List.map
      (fun (e, n) →
        let e' =
          if e = i1 then
            conjugate e
          else
            e in
        (nodes2edge e' n, ext_nodes_index e', int_nodes_index n))
      (external_edges t) }

let int_incidence f null g =
  let n = Array.length g.int_nodes in
  let incidence = Array.make_matrix n n null in
  List.iter (fun (edge, n1, n2) →
    if n1 ≠ n2 then begin
      let edge' = f edge g.int_nodes.(n1) g.int_nodes.(n2) in
      incidence.(n1).(n2) ← edge';
      incidence.(n2).(n1) ← edge'
    end)
    g.int_edges;
  incidence

let ext_incidence f null g =
  let n_int = Array.length g.int_nodes
  and n_ext = Array.length g.ext_nodes in
  let incidence = Array.make_matrix n_int n_ext null in
  List.iter (fun (edge, e, n) →
    incidence.(n).(e) ← f edge g.ext_nodes.(e) g.int_nodes.(n))
    g.ext_edges;
  incidence

```

```

let division n =
  if n < 0 then
    []
  else if n = 1 then
    [0.5]
  else
    let n' = pred n in
    let d = 1.0 /. (float n') in
    let rec division' i acc =
      if i < 0 then
        acc
      else
        division' (pred i) (float i *. d :: acc) in
    division' n' []

type (ε, ν, 'ext) ext_layout = (ε, ν, 'ext × float × float) graph
type (ε, ν, 'ext) layout = (ε, ν × float × float, 'ext) ext_layout

let left_to_right num_in g =
  if num_in < 1 then
    invalid_arg "left_to_right"
  else
    let num_out = Array.length g.ext_nodes - num_in in
    if num_out < 1 then
      invalid_arg "left_to_right"
    else
      let incoming =
        List.map2 (fun e y → (e, 0.0, y))
          (Array.to_list (Array.sub g.ext_nodes 0 num_in))
          (division num_in)
      and outgoing =
        List.map2 (fun e y → (e, 1.0, y))
          (Array.to_list (Array.sub g.ext_nodes num_in num_out))
          (division num_out) in
      { g with ext_nodes = Array.of_list (incoming @ outgoing) }

```

Reformulating (Q.13)

$$Ax = b_x \quad (\text{Q.15a})$$

$$Ay = b_y \quad (\text{Q.15b})$$

with

$$A_{ii'} = \left( \sum_{i'' \neq i} T_{ii''} + \sum_j T'_{ij} \right) \delta_{ii'} - T_{ii'} \quad (\text{Q.16a})$$

$$(b_{x/y})_i = \sum_j T'_{ij} (e_{x/y})_j \quad (\text{Q.16b})$$

```
let sum a = Array.fold_left (+.) 0.0 a
```

```
let tension_to_equation t t' e =
```

```

let xe, ye = List.split e in
let bx = Linalg.matmulv t' (Array.of_list xe)
and by = Linalg.matmulv t' (Array.of_list ye)
and a = Array.init (Array.length t)
  (fun i →
    let a_i = Array.map (~.) t.(i) in
    a_i.(i) ← a_i.(i) + . sum t.(i) + . sum t'.(i);
    a_i) in
(a, bx, by)

let layout g =
let ext_nodes =
  List.map (fun (_, x, y) → (x, y)) (Array.to_list g.ext_nodes) in
let a, bx, by =
  tension_to_equation
  (int_incidence (fun _ _ _ → 1.0) 0.0 g)
  (ext_incidence (fun _ _ _ → 1.0) 0.0 g) ext_nodes in
match Linalg.solve_many a [bx; by] with
| [x; y] → { g with int_nodes = Array.mapi
  (fun i n → (n, x.(i), y.(i))) g.int_nodes }
| _ → failwith "impossible"

let iter_edges f g =
  List.iter (fun (edge, n1, n2) →
    let _, x1, y1 = g.int_nodes.(n1)
    and _, x2, y2 = g.int_nodes.(n2) in
    f edge (x1, y1) (x2, y2)) g.int_edges;
  List.iter (fun (edge, e, n) →
    let _, x1, y1 = g.ext_nodes.(e)
    and _, x2, y2 = g.int_nodes.(n) in
    f edge (x1, y1) (x2, y2)) g.ext_edges

let iter_internal f g =
  Array.iter (fun (node, x, y) → f (x, y)) g.int_nodes

let iter_incoming f g =
  f g.ext_nodes.(0);
  f g.ext_nodes.(1)

let iter_outgoing f g =
  for i = 2 to pred (Array.length g.ext_nodes) do
    f g.ext_nodes.(i)
  done

let dump g =
  Array.iter (fun (_, x, y) → Printf.eprintf "(%g,%g)␣" x y) g.ext_nodes;
  Printf.eprintf "\n␣=>␣";
  Array.iter (fun (_, x, y) → Printf.eprintf "(%g,%g)␣" x y) g.int_nodes;
  Printf.eprintf "\n"

```

---

# —R—

## DEPENDENCY TREES

### *R.1 Interface of Tree2*

Dependency trees for wavefunctions.

```

type ( $\nu$ ,  $\varepsilon$ ) t
val cons : ( $\varepsilon \times \nu \times (\nu, \varepsilon) t$  list) list  $\rightarrow (\nu, \varepsilon) t$ 
val leaf :  $\nu \rightarrow (\nu, \varepsilon) t$ 
val to_string : ( $\nu \rightarrow string$ )  $\rightarrow (\varepsilon \rightarrow string) \rightarrow (\nu, \varepsilon) t \rightarrow string$ 

```

### *R.2 Implementation of Tree2*

Dependency trees for wavefunctions.

```

type ( $\nu$ ,  $\varepsilon$ ) t =
  | Node of ( $\varepsilon \times \nu \times (\nu, \varepsilon) t$  list) list
  | Leaf of  $\nu$ 

let leaf node = Leaf node

let sort_children (edge, node, children) =
  (edge, node, List.sort compare children)

let cons fusions = Node (List.sort compare (List.map sort_children fusions))

let rec to_string n2s e2s = function
  | Leaf n  $\rightarrow$  n2s n
  | Node children  $\rightarrow$ 
    "{" ^
    String.concat "," ^
    (List.map
      (fun (e, n, ch_list)  $\rightarrow$ 
        e2s e ^ ":" ^ n2s n ^
        "<(" ^ (String.concat ";" (List.map (to_string n2s e2s) ch_list)) ^ ")")
      children) ^
    "}"

```

---

—S—  
CONSISTENCY CHECKS



*Application count.ml unavailable!*



---

# —T—

## COMPLEX NUMBERS



*Interface `complex.mli` unavailable!*



*Implementation `complex.ml` unavailable!*

---

# —U—

## ALGEBRA

### *U.1 Interface of Algebra*

#### *U.1.1 Coefficients*

For our algebra, we need coefficient rings.

```
module type CRing =
sig
  type t
  val null : t
  val unit : t
  val mul : t → t → t
  val add : t → t → t
  val sub : t → t → t
  val neg : t → t
  val to_string : t → string
end
```

And rational numbers provide a particularly important example:

```
module type Rational =
sig
  include CRing
  val is_null : t → bool
  val is_unit : t → bool
  val make : int → int → t
  val to_ratio : t → int × int
  val to_float : t → float
end
```

#### *U.1.2 Naive Rational Arithmetic*



This *is* dangerous and will overflow even for simple applications. The production code will have to be linked to a library for large integer arithmetic.

```
module Small_Rational : Rational
```

### U.1.3 Expressions: Terms, Rings and Linear Combinations

The tensor algebra will be spanned by an abelian monoid:

```

module type Term =
sig
  type  $\alpha$  t
  val unit : unit  $\rightarrow$   $\alpha$  t
  val is_unit :  $\alpha$  t  $\rightarrow$  bool
  val atom :  $\alpha$   $\rightarrow$   $\alpha$  t
  val power : int  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\alpha$  t
  val mul :  $\alpha$  t  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\alpha$  t
  val map : ( $\alpha$   $\rightarrow$   $\beta$ )  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\beta$  t
  val to_string : ( $\alpha$   $\rightarrow$  string)  $\rightarrow$   $\alpha$  t  $\rightarrow$  string

```

The derivative of a term is *not* a term, but a sum of terms instead:

$$D(f_1^{p_1} f_2^{p_2} \dots f_n^{p_n}) = \sum_i (Df_i) p_i f_1^{p_1} f_2^{p_2} \dots f_i^{p_i-1} \dots f_n^{p_n} \quad (\text{U.1})$$

The function returns the sum as a list of triples  $(Df_i, p_i, f_1^{p_1} f_2^{p_2} \dots f_i^{p_i-1} \dots f_n^{p_n})$ . Summing the terms is left to the calling module and the  $Df_i$  are *not* guaranteed to be different. NB: The function implementating the inner derivative, is supposed to return *Some*  $Df_i$  and *None*, iff  $Df_i$  vanishes.

```

val derive : ( $\alpha$   $\rightarrow$   $\beta$  option)  $\rightarrow$   $\alpha$  t  $\rightarrow$  ( $\beta \times$  int  $\times$   $\alpha$  t) list

```

convenience function

```

val product :  $\alpha$  t list  $\rightarrow$   $\alpha$  t
val atoms :  $\alpha$  t  $\rightarrow$   $\alpha$  list

```

end

```

module type Ring =
sig
  module C : Rational
  type  $\alpha$  t
  val null : unit  $\rightarrow$   $\alpha$  t
  val unit : unit  $\rightarrow$   $\alpha$  t
  val is_null :  $\alpha$  t  $\rightarrow$  bool
  val is_unit :  $\alpha$  t  $\rightarrow$  bool
  val atom :  $\alpha$   $\rightarrow$   $\alpha$  t
  val scale : C.t  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\alpha$  t
  val add :  $\alpha$  t  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\alpha$  t
  val sub :  $\alpha$  t  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\alpha$  t
  val mul :  $\alpha$  t  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\alpha$  t
  val neg :  $\alpha$  t  $\rightarrow$   $\alpha$  t

```

Again

$$D(f_1^{p_1} f_2^{p_2} \dots f_n^{p_n}) = \sum_i (Df_i) p_i f_1^{p_1} f_2^{p_2} \dots f_i^{p_i-1} \dots f_n^{p_n} \quad (\text{U.2})$$

but, iff  $Df_i$  can be identified with a  $f'$ , we know how to perform the sum.

```

val derive_inner : ( $\alpha$   $\rightarrow$   $\alpha$  t)  $\rightarrow$   $\alpha$  t  $\rightarrow$   $\alpha$  t (* this? *)

```

val *derive\_inner'* : ( $\alpha \rightarrow \alpha \ t \ option$ )  $\rightarrow \alpha \ t \rightarrow \alpha \ t$  (\* or that? \*)

Below, we will need partial derivatives that lead out of the ring: *derive\_outer* *derive\_atom* *term* returns a list of partial derivatives  $\beta$  with non-zero coefficients  $\alpha \ t$ :

val *derive\_outer* : ( $\alpha \rightarrow \beta \ option$ )  $\rightarrow \alpha \ t \rightarrow (\beta \times \alpha \ t) \ list$

convenience functions

val *sum* :  $\alpha \ t \ list \rightarrow \alpha \ t$

val *product* :  $\alpha \ t \ list \rightarrow \alpha \ t$

The list of all generators appearing in an expression:

val *atoms* :  $\alpha \ t \rightarrow \alpha \ list$

val *to\_string* : ( $\alpha \rightarrow string$ )  $\rightarrow \alpha \ t \rightarrow string$

end

module type *Linear* =

sig

module *C* : *Ring*

type ( $\alpha, \gamma$ ) *t*

val *null* : *unit*  $\rightarrow (\alpha, \gamma) \ t$

val *atom* :  $\alpha \rightarrow (\alpha, \gamma) \ t$

val *singleton* :  $\gamma \ C.t \rightarrow \alpha \rightarrow (\alpha, \gamma) \ t$

val *scale* :  $\gamma \ C.t \rightarrow (\alpha, \gamma) \ t \rightarrow (\alpha, \gamma) \ t$

val *add* : ( $\alpha, \gamma$ ) *t*  $\rightarrow (\alpha, \gamma) \ t \rightarrow (\alpha, \gamma) \ t$

val *sub* : ( $\alpha, \gamma$ ) *t*  $\rightarrow (\alpha, \gamma) \ t \rightarrow (\alpha, \gamma) \ t$

A partial derivative w.r.t. a vector maps from a coefficient ring to the dual vector space.

val *partial* : ( $\gamma \rightarrow (\alpha, \gamma) \ t$ )  $\rightarrow \gamma \ C.t \rightarrow (\alpha, \gamma) \ t$

A linear combination of vectors

$$linear[(v_1, c_1); (v_2, c_2); \dots; (v_n, c_n)] = \sum_{i=1}^n c_i \cdot v_i \quad (U.3)$$

val *linear* : (( $\alpha, \gamma$ ) *t*  $\times \gamma \ C.t$ ) *list*  $\rightarrow (\alpha, \gamma) \ t$

Some convenience functions

val *map* : ( $\alpha \rightarrow \gamma \ C.t \rightarrow (\beta, \delta) \ t$ )  $\rightarrow (\alpha, \gamma) \ t \rightarrow (\beta, \delta) \ t$

val *sum* : ( $\alpha, \gamma$ ) *t list*  $\rightarrow (\alpha, \gamma) \ t$

The list of all generators and the list of all generators of coefficients appearing in an expression:

val *atoms* : ( $\alpha, \gamma$ ) *t*  $\rightarrow \alpha \ list \times \gamma \ list$

val *to\_string* : ( $\alpha \rightarrow string$ )  $\rightarrow (\gamma \rightarrow string) \rightarrow (\alpha, \gamma) \ t \rightarrow string$

end

module *Term* : *Term*

module *Make\_Ring* (*C* : *Rational*) (*T* : *Term*) : *Ring*

module *Make\_Linear* (*C* : *Ring*) : *Linear* with module *C* = *C*

## U.2 Implementation of Algebra

The terms will be small and there's no need to be fancy and/or efficient. It's more important to have a unique representation.

```
module PM = Pmap.List
```

### U.2.1 Coefficients

For our algebra, we need coefficient rings.

```
module type CRing =
sig
  type t
  val null : t
  val unit : t
  val mul : t → t → t
  val add : t → t → t
  val sub : t → t → t
  val neg : t → t
  val to_string : t → string
end
```

And rational numbers provide a particularly important example:

```
module type Rational =
sig
  include CRing
  val is_null : t → bool
  val is_unit : t → bool
  val make : int → int → t
  val to_ratio : t → int × int
  val to_float : t → float
end
```

### U.2.2 Naive Rational Arithmetic



This *is* dangerous and will overflow even for simple applications. The production code will have to be linked to a library for large integer arithmetic.

Anyway, here's Euclid's algorithm:

```
let rec gcd i1 i2 =
  if i2 = 0 then
    abs i1
  else
    gcd i2 (i1 mod i2)
let lcm i1 i2 = (i1 / gcd i1 i2) × i2
module Small_Rational : Rational =
struct
  type t = int × int
```

```

let is_null (n, _) = (n = 0)
let is_unit (n, d) = (n ≠ 0) ∧ (n = d)
let null = (0, 1)
let unit = (1, 1)
let make n d =
  let c = gcd n d in
  (n / c, d / c)
let mul (n1, d1) (n2, d2) = make (n1 × n2) (d1 × d2)
let add (n1, d1) (n2, d2) = make (n1 × d2 + n2 × d1) (d1 × d2)
let sub (n1, d1) (n2, d2) = make (n1 × d2 - n2 × d1) (d1 × d2)
let neg (n, d) = (-n, d)
let to_ratio (n, d) =
  if d < 0 then
    (-n, -d)
  else
    (n, d)
let to_float (n, d) = float n /. float d
let to_string (n, d) =
  if d = 1 then
    Printf.sprintf "%d" n
  else
    Printf.sprintf "(%d/%d)" n d
end

```

### U.2.3 Expressions: Terms, Rings and Linear Combinations

The tensor algebra will be spanned by an abelian monoid:

```

module type Term =
sig
  type α t
  val unit : unit → α t
  val is_unit : α t → bool
  val atom : α → α t
  val power : int → α t → α t
  val mul : α t → α t → α t
  val map : (α → β) → α t → β t
  val to_string : (α → string) → α t → string
  val derive : (α → β option) → α t → (β × int × α t) list
  val product : α t list → α t
  val atoms : α t → α list
end

module type Ring =
sig
  module C : Rational
  type α t
  val null : unit → α t
  val unit : unit → α t
  val is_null : α t → bool
  val is_unit : α t → bool

```

```

val atom :  $\alpha \rightarrow \alpha\ t$ 
val scale :  $C.t \rightarrow \alpha\ t \rightarrow \alpha\ t$ 
val add :  $\alpha\ t \rightarrow \alpha\ t \rightarrow \alpha\ t$ 
val sub :  $\alpha\ t \rightarrow \alpha\ t \rightarrow \alpha\ t$ 
val mul :  $\alpha\ t \rightarrow \alpha\ t \rightarrow \alpha\ t$ 
val neg :  $\alpha\ t \rightarrow \alpha\ t$ 
val derive_inner :  $(\alpha \rightarrow \alpha\ t) \rightarrow \alpha\ t \rightarrow \alpha\ t$  (* this? *)
val derive_inner' :  $(\alpha \rightarrow \alpha\ t\ option) \rightarrow \alpha\ t \rightarrow \alpha\ t$  (* or that? *)
val derive_outer :  $(\alpha \rightarrow \beta\ option) \rightarrow \alpha\ t \rightarrow (\beta \times \alpha\ t)\ list$ 
val sum :  $\alpha\ t\ list \rightarrow \alpha\ t$ 
val product :  $\alpha\ t\ list \rightarrow \alpha\ t$ 
val atoms :  $\alpha\ t \rightarrow \alpha\ list$ 
val to_string :  $(\alpha \rightarrow string) \rightarrow \alpha\ t \rightarrow string$ 
end

module type Linear =
sig
  module C : Ring
  type  $(\alpha, \gamma)\ t$ 
  val null :  $unit \rightarrow (\alpha, \gamma)\ t$ 
  val atom :  $\alpha \rightarrow (\alpha, \gamma)\ t$ 
  val singleton :  $\gamma\ C.t \rightarrow \alpha \rightarrow (\alpha, \gamma)\ t$ 
  val scale :  $\gamma\ C.t \rightarrow (\alpha, \gamma)\ t \rightarrow (\alpha, \gamma)\ t$ 
  val add :  $(\alpha, \gamma)\ t \rightarrow (\alpha, \gamma)\ t \rightarrow (\alpha, \gamma)\ t$ 
  val sub :  $(\alpha, \gamma)\ t \rightarrow (\alpha, \gamma)\ t \rightarrow (\alpha, \gamma)\ t$ 
  val partial :  $(\gamma \rightarrow (\alpha, \gamma)\ t) \rightarrow \gamma\ C.t \rightarrow (\alpha, \gamma)\ t$ 
  val linear :  $((\alpha, \gamma)\ t \times \gamma\ C.t)\ list \rightarrow (\alpha, \gamma)\ t$ 
  val map :  $(\alpha \rightarrow \gamma\ C.t \rightarrow (\beta, \delta)\ t) \rightarrow (\alpha, \gamma)\ t \rightarrow (\beta, \delta)\ t$ 
  val sum :  $(\alpha, \gamma)\ t\ list \rightarrow (\alpha, \gamma)\ t$ 
  val atoms :  $(\alpha, \gamma)\ t \rightarrow \alpha\ list \times \gamma\ list$ 
  val to_string :  $(\alpha \rightarrow string) \rightarrow (\gamma \rightarrow string) \rightarrow (\alpha, \gamma)\ t \rightarrow string$ 
end

module Term : Term =
struct
  module M = PM
  type  $\alpha\ t = (\alpha, int)\ M.t$ 
  let unit () = M.empty
  let is_unit = M.is_empty
  let atom f = M.singleton f 1
  let power p x = M.map (( $\times$ ) p) x
  let insert1 binop f p term =
    let p' = binop (try M.find compare f term with Not_found  $\rightarrow$  0) p in
    if p' = 0 then
      M.remove compare f term
    else
      M.add compare f p' term

```

```

let mul1 f p term = insert1 (+) f p term
let mul x y = M.fold mul1 x y

let map f term = M.fold (fun t → mul1 (f t)) term M.empty

let to_string fmt term =
  String.concat "*"
    (M.fold (fun f p acc →
      (if p = 0 then
        "1"
      else if p = 1 then
        fmt f
      else
        "[" ^ fmt f ^ "]" ^ string_of_int p) :: acc) term [])

let derive derive1 x =
  M.fold (fun f p dx →
    if p ≠ 0 then
      match derive1 f with
      | Some df → (df, p, mul1 f (pred p) (M.remove compare f x)) :: dx
      | None → dx
    else
      dx) x []

let product factors =
  List.fold_left mul (unit ()) factors

let atoms t =
  List.map fst (PM.elements t)

end

module Make_Ring (C : Rational) (T : Term) : Ring =
struct

  module C = C
  let one = C.unit

  module M = PM

  type α t = (α T.t, C.t) M.t

  let null () = M.empty
  let is_null = M.is_empty

  let power t p = M.singleton t p
  let unit () = power (T.unit ()) one

  let is_unit t = unit () = t

```



The following should be correct too, but produces too many false positives instead! What's going on?

```

let broken_is_unit t =
  match M.elements t with
  | [(t, p)] → T.is_unit t ∨ C.is_null p

```



```

| _ → false
let atom t = power (T.atom t) one
let scale c x = M.map (C.mul c) x
let insert1 binop t c sum =
  let c' = binop (try M.find compare t sum with Not_found → C.null) c in
  if C.is_null c' then
    M.remove compare t sum
  else
    M.add compare t c' sum
let add x y = M.fold (insert1 C.add) x y
let sub x y = M.fold (insert1 C.sub) y x

```

One might be tempted to use *Product.outer\_self* *M.fold* instead, but this would require us to combine *tx* and *cx* to *(tx, cx)*.

```

let fold2 f x y =
  M.fold (fun tx cx → M.fold (f tx cx) y) x
let mul x y =
  fold2 (fun tx cx ty cy → insert1 C.add (T.mul tx ty) (C.mul cx cy))
    x y (null ())
let neg x =
  sub (null ()) x
let neg x =
  scale (C.neg C.unit) x

```

Multiply the *derivatives* by *c* and add the result to *dx*.

```

let add_derivatives derivatives c dx =
  List.fold_left (fun acc (df, dt_c, dt_t) →
    add (mul df (power dt_t (C.mul c (C.make dt_c 1)))) acc) dx derivatives
let derive_inner derive1 x =
  M.fold (fun t →
    add_derivatives (T.derive (fun f → Some (derive1 f)) t)) x (null ())
let derive_inner' derive1 x =
  M.fold (fun t → add_derivatives (T.derive derive1 t)) x (null ())
let collect_derivatives derivatives c dx =
  List.fold_left (fun acc (df, dt_c, dt_t) →
    (df, power dt_t (C.mul c (C.make dt_c 1))) :: acc) dx derivatives
let derive_outer derive1 x =
  M.fold (fun t → collect_derivatives (T.derive derive1 t)) x []
let sum terms =
  List.fold_left add (null ()) terms
let product factors =
  List.fold_left mul (unit ()) factors
let atoms t =

```

```

    ThoList.uniq (List.sort compare
      (ThoList.flatmap (fun (t, _) → T.atoms t) (PM.elements t)))

let to_string fmt sum =
  "(" ^ String.concat "□+□"
    (M.fold (fun t c acc →
      if C.is_null c then
        acc
      else if C.is_unit c then
        T.to_string fmt t :: acc
      else if C.is_unit (C.neg c) then
        ("(-" ^ T.to_string fmt t ^ ")") :: acc
      else
        (C.to_string c ^ "*" ^ T.to_string fmt t ^ ")") :: acc) sum []) ^ ")"

end

module Make_Linear (C : Ring) : Linear with module C = C =
struct
  module C = C
  module M = PM

  type (α, γ) t = (α, γ C.t) M.t

  let null () = M.empty
  let is_null = M.is_empty
  let atom a = M.singleton a (C.unit ())
  let singleton c a = M.singleton a c

  let scale c x = M.map (C.mul c) x

  let insert1 binop t c sum =
    let c' = binop (try M.find compare t sum with Not_found → C.null ()) c in
    if C.is_null c' then
      M.remove compare t sum
    else
      M.add compare t c' sum

  let add x y = M.fold (insert1 C.add) x y
  let sub x y = M.fold (insert1 C.sub) y x

  let map f t =
    M.fold (fun a c → add (f a c)) t M.empty

  let sum terms =
    List.fold_left add (null ()) terms

  let linear terms =
    List.fold_left (fun acc (a, c) → add (scale c a) acc) (null ()) terms

  let partial derive t =
    let d t' =
      let dt' = derive t' in
      if is_null dt' then
        None

```

```

      else
        Some dt' in
          linear (C.derive_outer d t)

let atoms t =
  let a, c = List.split (PM.elements t) in
  (a, ThoList.uniq (List.sort compare (ThoList.flatmap C.atoms c)))

let to_string fmt cfmt sum =
  "(" ^ String.concat " + "
    (M.fold (fun t c acc →
      if C.is_null c then
        acc
      else if C.is_unit c then
        fmt t :: acc
      else if C.is_unit (C.neg c) then
        (" - " ^ fmt t ^ ") " :: acc
      else
        (C.to_string cfmt c ^ "*" ^ fmt t) :: acc)
      sum []) ^ ") "
end

```

---

# —V—

## SIMPLE LINEAR ALGEBRA

### *V.1 Interface of Linalg*

```
exception Singular
exception Not_Square

val copy_matrix : float array array → float array array
val matmul : float array array → float array array → float array array
val matmulv : float array array → float array → float array
val lu_decompose : float array array → float array array × float array array
val solve : float array array → float array → float array
val solve_many : float array array → float array list → float array list
```

### *V.2 Implementation of Linalg*

This is not a functional implementations, but uses imperative array in Fortran style for maximum speed.

```
exception Singular
exception Not_Square

let copy_matrix a =
  Array.init (Array.length a)
    (fun i → Array.copy a.(i))

let matmul a b =
  let ni = Array.length a
  and nj = Array.length b.(0)
  and n = Array.length b in
  let ab = Array.make_matrix ni nj 0.0 in
  for i = 0 to pred ni do
    for j = 0 to pred nj do
      for k = 0 to pred n do
        ab.(i).(j) ← ab.(i).(j) + . a.(i).(k) * . b.(k).(j)
      done
    done
  done;
  ab
```

```

let matmulv a v =
  let na = Array.length a in
  let nv = Array.length v in
  let v' = Array.make na 0.0 in
  for i = 0 to pred na do
    for j = 0 to pred nv do
      v'.(i) ← v'.(i) + . a.(i).(j) *. v.(j)
    done
  done;
  v'

let maxabsval a : float =
  let x = ref (abs_float a.(0)) in
  for i = 1 to Array.length a - 1 do
    x := max !x (abs_float a.(i))
  done;
  !x

```

### V.2.1 LU Decomposition

$$A = LU \quad (\text{V.1a})$$

In more detail

$$\begin{pmatrix} a_{00} & a_{01} & \dots & a_{0(n-1)} \\ a_{10} & a_{11} & \dots & a_{1(n-1)} \\ \vdots & \vdots & \vdots & \vdots \\ a_{(n-1)0} & a_{(n-1)1} & \dots & a_{(n-1)(n-1)} \end{pmatrix} = \begin{pmatrix} 1 & 0 & \dots & 0 \\ l_{10} & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ l_{(n-1)0} & l_{(n-1)1} & \dots & 1 \end{pmatrix} \begin{pmatrix} u_{00} & u_{01} & \dots & u_{0(n-1)} \\ 0 & u_{11} & \dots & u_{1(n-1)} \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & u_{(n-1)(n-1)} \end{pmatrix} \quad (\text{V.1b})$$

Rewriting (V.1) in block matrix notation

$$\begin{pmatrix} a_{00} & a_{0\cdot} \\ a_{\cdot 0} & A \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ l_{\cdot 0} & L \end{pmatrix} \begin{pmatrix} u_{00} & u_{0\cdot} \\ 0 & U \end{pmatrix} = \begin{pmatrix} u_{00} & u_{0\cdot} \\ l_{\cdot 0} u_{00} & l_{\cdot 0} \otimes u_{0\cdot} + LU \end{pmatrix} \quad (\text{V.2})$$

we can solve it easily

$$u_{00} = a_{00} \quad (\text{V.3a})$$

$$u_{0\cdot} = a_{0\cdot} \quad (\text{V.3b})$$

$$l_{\cdot 0} = \frac{a_{\cdot 0}}{a_{00}} \quad (\text{V.3c})$$

$$LU = A - \frac{a_{\cdot 0} \otimes a_{0\cdot}}{a_{00}} \quad (\text{V.3d})$$

and (V.3c) and (V.3d) define a simple iterative algorithm if we work from the outside in. It just remains to add pivoting.

```

let swap a i j =

```

```

    let a_i = a.(i) in
    a.(i) ← a.(j);
    a.(j) ← a_i
  let pivot_column v a n =
    let n' = ref n
    and max_va = ref (v.(n) *. (abs_float a.(n).(n))) in
    for i = succ n to Array.length v - 1 do
      let va_i = v.(i) *. (abs_float a.(i).(n)) in
      if va_i > !max_va then begin
        n' := i;
        max_va := va_i
      end
    end;
    done;
    !n'
  let lu_decompose_in_place a =
    let n = Array.length a in
    let eps = ref 1
    and pivots = Array.make n 0
    and v =
      try
        Array.init n (fun i →
          let a_i = a.(i) in
          if Array.length a_i ≠ n then
            raise Not_Square;
          1.0 /. (maxabsval a_i))
      with
        | Division_by_zero → raise Singular in
    for i = 0 to pred n do
      let pivot = pivot_column v a i in
      if pivot ≠ i then begin
        swap a pivot i;
        eps := - !eps;
        v.(pivot) ← v.(i)
      end;
      pivots.(i) ← pivot;
      let inv_a_ii =
        try 1.0 /. a.(i).(i) with Division_by_zero → raise Singular in
      for j = succ i to pred n do
        a.(j).(i) ← inv_a_ii *. a.(j).(i)
      done;
      for j = succ i to pred n do
        for k = succ i to pred n do
          a.(j).(k) ← a.(j).(k) - a.(j).(i) *. a.(i).(k)
        done
      done
    done;
    (pivots, !eps)
  let lu_decompose_split a pivots =
    let n = Array.length pivots in

```

```

let l = Array.make_matrix n n 0.0 in
let u = Array.make_matrix n n 0.0 in
for i = 0 to pred n do
  l.(i).(i) ← 1.0;
  for j = succ i to pred n do
    l.(j).(i) ← a.(j).(i)
  done
done;
for i = pred n downto 0 do
  swap l i pivots.(i)
done;
for i = 0 to pred n do
  for j = 0 to i do
    u.(j).(i) ← a.(j).(i)
  done
done;
(l, u)

let lu_decompose a =
  let a = copy_matrix a in
  let pivots, _ = lu_decompose_in_place a in
  lu_decompose_split a pivots

let lu_backsubstitute a pivots b =
  let n = Array.length a in
  let nonzero = ref (-1) in
  let b = Array.copy b in
  for i = 0 to pred n do
    let ll = pivots.(i) in
    let b_i = ref (b.(ll)) in
    b.(ll) ← b.(i);
    if !nonzero ≥ 0 then
      for j = !nonzero to pred i do
        b_i := !b_i - . a.(i).(j) * . b.(j)
      done
    else if !b_i ≠ 0.0 then
      nonzero := i;
      b.(i) ← !b_i
    done;
  for i = pred n downto 0 do
    let b_i = ref (b.(i)) in
    for j = succ i to pred n do
      b_i := !b_i - . a.(i).(j) * . b.(j)
    done;
    b.(i) ← !b_i / . a.(i).(i)
  done;
  b

let solve_destructive a b =
  let pivot, _ = lu_decompose_in_place a in
  lu_backsubstitute a pivot b

```

```
let solve_many_destructive a bs =  
  let pivot, _ = lu_decompose_in_place a in  
  List.map (lu_backsubstitute a pivot) bs  
  
let solve a b =  
  solve_destructive (copy_matrix a) b  
  
let solve_many a bs =  
  solve_many_destructive (copy_matrix a) bs
```



---

—W—  
TALK TO THE WHIZARD . . .

Talk to [\[11\]](#).



Temporarily disabled, until, we implement some conditional weaving . . .

---

# —X—

## FORTRAN LIBRARIES

### *X.1 Trivia*

```
<omega_spinors.f90>≡  
  <Cotypeleft>  
  module omega_spinors  
    use kinds  
    use constants  
    implicit none  
    private  
    public :: operator (*), operator (+), operator (-)  
    public :: abs  
    <intrinsic :: abs>  
    type, public :: conjspinor  
      ! private (omegalib needs access, but DON'T TOUCH IT!)  
      complex(kind=default), dimension(4) :: a  
    end type conjspinor  
    type, public :: spinor  
      ! private (omegalib needs access, but DON'T TOUCH IT!)  
      complex(kind=default), dimension(4) :: a  
    end type spinor  
    <Declaration of operations for spinors>  
    integer, parameter, public :: omega_spinors_2010_01_A = 0  
  contains  
    <Implementation of operations for spinors>  
  end module omega_spinors
```

```
<intrinsic :: abs (if working)>≡  
  intrinsic :: abs
```

```
<intrinsic :: conjg (if working)>≡  
  intrinsic :: conjg
```

well, the Intel Fortran Compiler chokes on these with an internal error:

```
<intrinsic :: abs>≡
```

```
<intrinsic :: conjg>≡
```

To reenable the pure functions that have been removed for OpenMP, one should set this chunk to pure &

```
<pure unless OpenMP>≡
```

### X.1.1 Inner Product

*(Declaration of operations for spinors)*≡

```
interface operator (*)
  module procedure conjspinor_spinor
end interface
private :: conjspinor_spinor
```

$$\bar{\psi}\psi' \quad (X.1)$$

NB: dot\_product conjugates its first argument, we can either cancel this or inline dot\_product:

*(Implementation of operations for spinors)*≡

```
pure function conjspinor_spinor (psibar, psi) result (psibarpsi)
  complex(kind=default) :: psibarpsi
  type(conjspinor), intent(in) :: psibar
  type(spinor), intent(in) :: psi
  psibarpsi = psibar%a(1)*psi%a(1) + psibar%a(2)*psi%a(2) &
    + psibar%a(3)*psi%a(3) + psibar%a(4)*psi%a(4)
end function conjspinor_spinor
```

### X.1.2 Spinor Vector Space

#### Scalar Multiplication

*(Declaration of operations for spinors)*+≡

```
interface operator (*)
  module procedure integer_spinor, spinor_integer, &
    real_spinor, double_spinor, &
    complex_spinor, dcomplex_spinor, &
    spinor_real, spinor_double, &
    spinor_complex, spinor_dcomplex
end interface
private :: integer_spinor, spinor_integer, real_spinor, &
  double_spinor, complex_spinor, dcomplex_spinor, &
  spinor_real, spinor_double, spinor_complex, spinor_dcomplex
```

*(Implementation of operations for spinors)*+≡

```
pure function integer_spinor (x, y) result (xy)
  integer, intent(in) :: x
  type(spinor), intent(in) :: y
  type(spinor) :: xy
  xy%a = x * y%a
end function integer_spinor
```

*(Implementation of operations for spinors)*+≡

```
pure function real_spinor (x, y) result (xy)
  real(kind=single), intent(in) :: x
  type(spinor), intent(in) :: y
  type(spinor) :: xy
  xy%a = x * y%a
end function real_spinor
pure function double_spinor (x, y) result (xy)
  real(kind=default), intent(in) :: x
  type(spinor), intent(in) :: y
```

---

```

    type(spinor) :: xy
    xy%a = x * y%a
end function double_spinor
pure function complex_spinor (x, y) result (xy)
    complex(kind=single), intent(in) :: x
    type(spinor), intent(in) :: y
    type(spinor) :: xy
    xy%a = x * y%a
end function complex_spinor
pure function dcomplex_spinor (x, y) result (xy)
    complex(kind=default), intent(in) :: x
    type(spinor), intent(in) :: y
    type(spinor) :: xy
    xy%a = x * y%a
end function dcomplex_spinor
pure function spinor_integer (y, x) result (xy)
    integer, intent(in) :: x
    type(spinor), intent(in) :: y
    type(spinor) :: xy
    xy%a = x * y%a
end function spinor_integer
pure function spinor_real (y, x) result (xy)
    real(kind=single), intent(in) :: x
    type(spinor), intent(in) :: y
    type(spinor) :: xy
    xy%a = x * y%a
end function spinor_real
pure function spinor_double (y, x) result (xy)
    real(kind=default), intent(in) :: x
    type(spinor), intent(in) :: y
    type(spinor) :: xy
    xy%a = x * y%a
end function spinor_double
pure function spinor_complex (y, x) result (xy)
    complex(kind=single), intent(in) :: x
    type(spinor), intent(in) :: y
    type(spinor) :: xy
    xy%a = x * y%a
end function spinor_complex
pure function spinor_dcomplex (y, x) result (xy)
    complex(kind=default), intent(in) :: x
    type(spinor), intent(in) :: y
    type(spinor) :: xy
    xy%a = x * y%a
end function spinor_dcomplex
<Declaration of operations for spinors>+≡
interface operator (*)
    module procedure integer_conjspinor, conjspinor_integer, &
        real_conjspinor, double_conjspinor, &
        complex_conjspinor, dcomplex_conjspinor, &
        conjspinor_real, conjspinor_double, &
        conjspinor_complex, conjspinor_dcomplex
end interface
private :: integer_conjspinor, conjspinor_integer, real_conjspinor, &

```

```

double_conjspinor, complex_conjspinor, dcomplex_conjspinor, &
conjspinor_real, conjspinor_double, conjspinor_complex, &
conjspinor_dcomplex

<Implementation of operations for spinors>+≡
pure function integer_conjspinor (x, y) result (xy)
  integer, intent(in) :: x
  type(conjspinor), intent(in) :: y
  type(conjspinor) :: xy
  xy%a = x * y%a
end function integer_conjspinor
pure function real_conjspinor (x, y) result (xy)
  real(kind=single), intent(in) :: x
  type(conjspinor), intent(in) :: y
  type(conjspinor) :: xy
  xy%a = x * y%a
end function real_conjspinor
pure function double_conjspinor (x, y) result (xy)
  real(kind=default), intent(in) :: x
  type(conjspinor), intent(in) :: y
  type(conjspinor) :: xy
  xy%a = x * y%a
end function double_conjspinor
pure function complex_conjspinor (x, y) result (xy)
  complex(kind=single), intent(in) :: x
  type(conjspinor), intent(in) :: y
  type(conjspinor) :: xy
  xy%a = x * y%a
end function complex_conjspinor
pure function dcomplex_conjspinor (x, y) result (xy)
  complex(kind=default), intent(in) :: x
  type(conjspinor), intent(in) :: y
  type(conjspinor) :: xy
  xy%a = x * y%a
end function dcomplex_conjspinor
pure function conjspinor_integer (y, x) result (xy)
  integer, intent(in) :: x
  type(conjspinor), intent(in) :: y
  type(conjspinor) :: xy
  xy%a = x * y%a
end function conjspinor_integer
pure function conjspinor_real (y, x) result (xy)
  real(kind=single), intent(in) :: x
  type(conjspinor), intent(in) :: y
  type(conjspinor) :: xy
  xy%a = x * y%a
end function conjspinor_real
pure function conjspinor_double (y, x) result (xy)
  real(kind=default), intent(in) :: x
  type(conjspinor), intent(in) :: y
  type(conjspinor) :: xy
  xy%a = x * y%a
end function conjspinor_double
pure function conjspinor_complex (y, x) result (xy)
  complex(kind=single), intent(in) :: x

```

```

    type(conjspinor), intent(in) :: y
    type(conjspinor) :: xy
    xy%a = x * y%a
end function conjspinor_complex
pure function conjspinor_dcomplex (y, x) result (xy)
    complex(kind=default), intent(in) :: x
    type(conjspinor), intent(in) :: y
    type(conjspinor) :: xy
    xy%a = x * y%a
end function conjspinor_dcomplex

```

### *Unary Plus and Minus*

```

<Declaration of operations for spinors>+≡
interface operator (+)
    module procedure plus_spinor, plus_conjspinor
end interface
private :: plus_spinor, plus_conjspinor
interface operator (-)
    module procedure neg_spinor, neg_conjspinor
end interface
private :: neg_spinor, neg_conjspinor

<Implementation of operations for spinors>+≡
pure function plus_spinor (x) result (plus_x)
    type(spinor), intent(in) :: x
    type(spinor) :: plus_x
    plus_x%a = x%a
end function plus_spinor
pure function neg_spinor (x) result (neg_x)
    type(spinor), intent(in) :: x
    type(spinor) :: neg_x
    neg_x%a = - x%a
end function neg_spinor

<Implementation of operations for spinors>+≡
pure function plus_conjspinor (x) result (plus_x)
    type(conjspinor), intent(in) :: x
    type(conjspinor) :: plus_x
    plus_x%a = x%a
end function plus_conjspinor
pure function neg_conjspinor (x) result (neg_x)
    type(conjspinor), intent(in) :: x
    type(conjspinor) :: neg_x
    neg_x%a = - x%a
end function neg_conjspinor

```

### *Addition and Subtraction*

```

<Declaration of operations for spinors>+≡
interface operator (+)
    module procedure add_spinor, add_conjspinor
end interface
private :: add_spinor, add_conjspinor
interface operator (-)

```

```

    module procedure sub_spinor, sub_conjspinor
end interface
private :: sub_spinor, sub_conjspinor

<Implementation of operations for spinors>+≡
pure function add_spinor (x, y) result (xy)
    type(spinor), intent(in) :: x, y
    type(spinor) :: xy
    xy%a = x%a + y%a
end function add_spinor
pure function sub_spinor (x, y) result (xy)
    type(spinor), intent(in) :: x, y
    type(spinor) :: xy
    xy%a = x%a - y%a
end function sub_spinor

<Implementation of operations for spinors>+≡
pure function add_conjspinor (x, y) result (xy)
    type(conjspinor), intent(in) :: x, y
    type(conjspinor) :: xy
    xy%a = x%a + y%a
end function add_conjspinor
pure function sub_conjspinor (x, y) result (xy)
    type(conjspinor), intent(in) :: x, y
    type(conjspinor) :: xy
    xy%a = x%a - y%a
end function sub_conjspinor

```

### X.1.3 Norm

```

<Declaration of operations for spinors>+≡
interface abs
    module procedure abs_spinor, abs_conjspinor
end interface
private :: abs_spinor, abs_conjspinor

<Implementation of operations for spinors>+≡
pure function abs_spinor (psi) result (x)
    type(spinor), intent(in) :: psi
    real(kind=default) :: x
    x = sqrt (real (dot_product (psi%a, psi%a)))
end function abs_spinor

<Implementation of operations for spinors>+≡
pure function abs_conjspinor (psibar) result (x)
    real(kind=default) :: x
    type(conjspinor), intent(in) :: psibar
    x = sqrt (real (dot_product (psibar%a, psibar%a)))
end function abs_conjspinor

```

## X.2 Spinors Revisited

```

<omega_bispinors.f90>≡
<Copleft>

```

```

module omega_bispinors
  use kinds
  use constants
  implicit none
  private
  public :: operator (*), operator (+), operator (-)
  public :: abs
  type, public :: bispinor
    ! private (omegalib needs access, but DON'T TOUCH IT!)
    complex(kind=default), dimension(4) :: a
  end type bispinor
  <Declaration of operations for bispinors>
  integer, parameter, public :: omega_bispinors_2010_01_A = 0
contains
  <Implementation of operations for bispinors>
end module omega_bispinors

<Declaration of operations for bispinors>≡
interface operator (*)
  module procedure spinor_product
end interface
private :: spinor_product

```

$$\bar{\psi}\psi' \quad (X.2)$$

NB: dot\_product conjugates its first argument, we have to cancel this.

```

<Implementation of operations for bispinors>≡
pure function spinor_product (psil, psir) result (psilpsir)
  complex(kind=default) :: psilpsir
  type(bispinor), intent(in) :: psil, psir
  type(bispinor) :: psidum
  psidum%a(1) = psir%a(2)
  psidum%a(2) = - psir%a(1)
  psidum%a(3) = - psir%a(4)
  psidum%a(4) = psir%a(3)
  psilpsir = dot_product (conjg (psil%a), psidum%a)
end function spinor_product

```

### X.2.1 Spinor Vector Space

#### Scalar Multiplication

```

<Declaration of operations for bispinors>+≡
interface operator (*)
  module procedure integer_bispinor, bispinor_integer, &
    real_bispinor, double_bispinor, &
    complex_bispinor, dcomplex_bispinor, &
    bispinor_real, bispinor_double, &
    bispinor_complex, bispinor_dcomplex
end interface
private :: integer_bispinor, bispinor_integer, real_bispinor, &
  double_bispinor, complex_bispinor, dcomplex_bispinor, &
  bispinor_real, bispinor_double, bispinor_complex, bispinor_dcomplex

```



---

```

<Implementation of operations for bispinors>+≡
pure function integer_bispinor (x, y) result (xy)
  type(bispinor) :: xy
  integer, intent(in) :: x
  type(bispinor), intent(in) :: y
  xy%a = x * y%a
end function integer_bispinor

```

```

<Implementation of operations for bispinors>+≡
pure function real_bispinor (x, y) result (xy)
  type(bispinor) :: xy
  real(kind=single), intent(in) :: x
  type(bispinor), intent(in) :: y
  xy%a = x * y%a
end function real_bispinor

```

```

<Implementation of operations for bispinors>+≡
pure function double_bispinor (x, y) result (xy)
  type(bispinor) :: xy
  real(kind=default), intent(in) :: x
  type(bispinor), intent(in) :: y
  xy%a = x * y%a
end function double_bispinor

```

```

<Implementation of operations for bispinors>+≡
pure function complex_bispinor (x, y) result (xy)
  type(bispinor) :: xy
  complex(kind=single), intent(in) :: x
  type(bispinor), intent(in) :: y
  xy%a = x * y%a
end function complex_bispinor

```

```

<Implementation of operations for bispinors>+≡
pure function dcomplex_bispinor (x, y) result (xy)
  type(bispinor) :: xy
  complex(kind=default), intent(in) :: x
  type(bispinor), intent(in) :: y
  xy%a = x * y%a
end function dcomplex_bispinor

```

```

<Implementation of operations for bispinors>+≡
pure function bispinor_integer (y, x) result (xy)
  type(bispinor) :: xy
  integer, intent(in) :: x
  type(bispinor), intent(in) :: y
  xy%a = x * y%a
end function bispinor_integer

```

```

<Implementation of operations for bispinors>+≡
pure function bispinor_real (y, x) result (xy)
  type(bispinor) :: xy
  real(kind=single), intent(in) :: x
  type(bispinor), intent(in) :: y
  xy%a = x * y%a
end function bispinor_real

```

```

<Implementation of operations for bispinors>+≡
pure function bispinor_double (y, x) result (xy)

```

```

    type(bispinor) :: xy
    real(kind=default), intent(in) :: x
    type(bispinor), intent(in) :: y
    xy%a = x * y%a
end function bispinor_double

<Implementation of operations for bispinors>+≡
pure function bispinor_complex (y, x) result (xy)
    type(bispinor) :: xy
    complex(kind=single), intent(in) :: x
    type(bispinor), intent(in) :: y
    xy%a = x * y%a
end function bispinor_complex

<Implementation of operations for bispinors>+≡
pure function bispinor_dcomplex (y, x) result (xy)
    type(bispinor) :: xy
    complex(kind=default), intent(in) :: x
    type(bispinor), intent(in) :: y
    xy%a = x * y%a
end function bispinor_dcomplex

```

#### Unary Plus and Minus

```

<Declaration of operations for bispinors>+≡
interface operator (+)
    module procedure plus_bispinor
end interface
private :: plus_bispinor
interface operator (-)
    module procedure neg_bispinor
end interface
private :: neg_bispinor

<Implementation of operations for bispinors>+≡
pure function plus_bispinor (x) result (plus_x)
    type(bispinor) :: plus_x
    type(bispinor), intent(in) :: x
    plus_x%a = x%a
end function plus_bispinor

<Implementation of operations for bispinors>+≡
pure function neg_bispinor (x) result (neg_x)
    type(bispinor) :: neg_x
    type(bispinor), intent(in) :: x
    neg_x%a = - x%a
end function neg_bispinor

```

#### Addition and Subtraction

```

<Declaration of operations for bispinors>+≡
interface operator (+)
    module procedure add_bispinor
end interface
private :: add_bispinor
interface operator (-)

```

```

    module procedure sub_bispinor
  end interface
  private :: sub_bispinor

  (Implementation of operations for bispinors)+≡
  pure function add_bispinor (x, y) result (xy)
    type(bispinor) :: xy
    type(bispinor), intent(in) :: x, y
    xy%a = x%a + y%a
  end function add_bispinor

  (Implementation of operations for bispinors)+≡
  pure function sub_bispinor (x, y) result (xy)
    type(bispinor) :: xy
    type(bispinor), intent(in) :: x, y
    xy%a = x%a - y%a
  end function sub_bispinor

```

### X.2.2 Norm

```

  (Declaration of operations for bispinors)+≡
  interface abs
    module procedure abs_bispinor
  end interface
  private :: abs_bispinor

  (Implementation of operations for bispinors)+≡
  pure function abs_bispinor (psi) result (x)
    real(kind=default) :: x
    type(bispinor), intent(in) :: psi
    x = sqrt (real (dot_product (psi%a, psi%a)))
  end function abs_bispinor

```

## X.3 Vectorspinors

```

  (omega_vectorspinors.f90)≡
  (Copyleft)
  module omega_vectorspinors
    use kinds
    use constants
    use omega_bispinors
    use omega_vectors
    implicit none
    private
    public :: operator (*), operator (+), operator (-)
    public :: abs
    type, public :: vectorspinor
      ! private (omegalib needs access, but DON'T TOUCH IT!)
      type(bispinor), dimension(4) :: psi
    end type vectorspinor
    (Declaration of operations for vectorspinors)
    integer, parameter, public :: omega_vectorspinors_2010_01_A = 0
  contains
    (Implementation of operations for vectorspinors)

```

```

end module omega_vectorspinors

<Declaration of operations for vectorspinors>≡
interface operator (*)
  module procedure vspinor_product
end interface
private :: vspinor_product


$$\bar{\psi}^\mu \psi'_\mu \quad (X.3)$$


<Implementation of operations for vectorspinors>≡
pure function vspinor_product (psil, psir) result (psilpsir)
  complex(kind=default) :: psilpsir
  type(vectorspinor), intent(in) :: psil, psir
  psilpsir = psil%psi(1) * psir%psi(1) &
    - psil%psi(2) * psir%psi(2) &
    - psil%psi(3) * psir%psi(3) &
    - psil%psi(4) * psir%psi(4)
end function vspinor_product

```

### X.3.1 Vectorspinor Vector Space

#### Scalar Multiplication

```

<Declaration of operations for vectorspinors>+≡
interface operator (*)
  module procedure integer_vectorspinor, vectorspinor_integer, &
    real_vectorspinor, double_vectorspinor, &
    complex_vectorspinor, dcomplex_vectorspinor, &
    vectorspinor_real, vectorspinor_double, &
    vectorspinor_complex, vectorspinor_dcomplex, &
    momentum_vectorspinor, vectorspinor_momentum
end interface
private :: integer_vectorspinor, vectorspinor_integer, real_vectorspinor, &
  double_vectorspinor, complex_vectorspinor, dcomplex_vectorspinor, &
  vectorspinor_real, vectorspinor_double, vectorspinor_complex, &
  vectorspinor_dcomplex

<Implementation of operations for vectorspinors>+≡
pure function integer_vectorspinor (x, y) result (xy)
  type(vectorspinor) :: xy
  integer, intent(in) :: x
  type(vectorspinor), intent(in) :: y
  integer :: k
  do k = 1,4
    xy%psi(k) = x * y%psi(k)
  end do
end function integer_vectorspinor

<Implementation of operations for vectorspinors>+≡
pure function real_vectorspinor (x, y) result (xy)
  type(vectorspinor) :: xy
  real(kind=single), intent(in) :: x
  type(vectorspinor), intent(in) :: y
  integer :: k

```

```

    do k = 1,4
      xy%psi(k) = x * y%psi(k)
    end do
  end function real_vectorspinor

(Implementation of operations for vectorspinors)+≡
  pure function double_vectorspinor (x, y) result (xy)
    type(vectorspinor) :: xy
    real(kind=default), intent(in) :: x
    type(vectorspinor), intent(in) :: y
    integer :: k
    do k = 1,4
      xy%psi(k) = x * y%psi(k)
    end do
  end function double_vectorspinor

(Implementation of operations for vectorspinors)+≡
  pure function complex_vectorspinor (x, y) result (xy)
    type(vectorspinor) :: xy
    complex(kind=single), intent(in) :: x
    type(vectorspinor), intent(in) :: y
    integer :: k
    do k = 1,4
      xy%psi(k) = x * y%psi(k)
    end do
  end function complex_vectorspinor

(Implementation of operations for vectorspinors)+≡
  pure function dcomplex_vectorspinor (x, y) result (xy)
    type(vectorspinor) :: xy
    complex(kind=default), intent(in) :: x
    type(vectorspinor), intent(in) :: y
    integer :: k
    do k = 1,4
      xy%psi(k) = x * y%psi(k)
    end do
  end function dcomplex_vectorspinor

(Implementation of operations for vectorspinors)+≡
  pure function vectorspinor_integer (y, x) result (xy)
    type(vectorspinor) :: xy
    integer, intent(in) :: x
    type(vectorspinor), intent(in) :: y
    integer :: k
    do k = 1,4
      xy%psi(k) = y%psi(k) * x
    end do
  end function vectorspinor_integer

(Implementation of operations for vectorspinors)+≡
  pure function vectorspinor_real (y, x) result (xy)
    type(vectorspinor) :: xy
    real(kind=single), intent(in) :: x
    type(vectorspinor), intent(in) :: y
    integer :: k
    do k = 1,4
      xy%psi(k) = y%psi(k) * x
    end do
  end function vectorspinor_real

```

```

        end do
    end function vectorspinor_real

(Implementation of operations for vectorspinors)+≡
    pure function vectorspinor_double (y, x) result (xy)
        type(vectorspinor) :: xy
        real(kind=default), intent(in) :: x
        type(vectorspinor), intent(in) :: y
        integer :: k
        do k = 1,4
            xy%psi(k) = y%psi(k) * x
        end do
    end function vectorspinor_double

(Implementation of operations for vectorspinors)+≡
    pure function vectorspinor_complex (y, x) result (xy)
        type(vectorspinor) :: xy
        complex(kind=single), intent(in) :: x
        type(vectorspinor), intent(in) :: y
        integer :: k
        do k = 1,4
            xy%psi(k) = y%psi(k) * x
        end do
    end function vectorspinor_complex

(Implementation of operations for vectorspinors)+≡
    pure function vectorspinor_dcomplex (y, x) result (xy)
        type(vectorspinor) :: xy
        complex(kind=default), intent(in) :: x
        type(vectorspinor), intent(in) :: y
        integer :: k
        do k = 1,4
            xy%psi(k) = y%psi(k) * x
        end do
    end function vectorspinor_dcomplex

(Implementation of operations for vectorspinors)+≡
    pure function momentum_vectorspinor (y, x) result (xy)
        type(bispinor) :: xy
        type(momentum), intent(in) :: y
        type(vectorspinor), intent(in) :: x
        integer :: k
        do k = 1,4
            xy%a(k) = y%t      * x%psi(1)%a(k) - y%x(1) * x%psi(2)%a(k) - &
                    y%x(2) * x%psi(3)%a(k) - y%x(3) * x%psi(4)%a(k)
        end do
    end function momentum_vectorspinor

(Implementation of operations for vectorspinors)+≡
    pure function vectorspinor_momentum (y, x) result (xy)
        type(bispinor) :: xy
        type(momentum), intent(in) :: x
        type(vectorspinor), intent(in) :: y
        integer :: k
        do k = 1,4
            xy%a(k) = x%t      * y%psi(1)%a(k) - x%x(1) * y%psi(2)%a(k) - &
                    x%x(2) * y%psi(3)%a(k) - x%x(3) * y%psi(4)%a(k)
        end do
    end function vectorspinor_momentum

```

```

    end do
end function vectorspinor_momentum

```

### *Unary Plus and Minus*

```

<Declaration of operations for vectorspinors>+≡
  interface operator (+)
    module procedure plus_vectorspinor
  end interface
  private :: plus_vectorspinor
  interface operator (-)
    module procedure neg_vectorspinor
  end interface
  private :: neg_vectorspinor

<Implementation of operations for vectorspinors>+≡
  pure function plus_vectorspinor (x) result (plus_x)
    type(vectorspinor) :: plus_x
    type(vectorspinor), intent(in) :: x
    integer :: k
    do k = 1,4
      plus_x%psi(k) = + x%psi(k)
    end do
  end function plus_vectorspinor

<Implementation of operations for vectorspinors>+≡
  pure function neg_vectorspinor (x) result (neg_x)
    type(vectorspinor) :: neg_x
    type(vectorspinor), intent(in) :: x
    integer :: k
    do k = 1,4
      neg_x%psi(k) = - x%psi(k)
    end do
  end function neg_vectorspinor

```

### *Addition and Subtraction*

```

<Declaration of operations for vectorspinors>+≡
  interface operator (+)
    module procedure add_vectorspinor
  end interface
  private :: add_vectorspinor
  interface operator (-)
    module procedure sub_vectorspinor
  end interface
  private :: sub_vectorspinor

<Implementation of operations for vectorspinors>+≡
  pure function add_vectorspinor (x, y) result (xy)
    type(vectorspinor) :: xy
    type(vectorspinor), intent(in) :: x, y
    integer :: k
    do k = 1,4
      xy%psi(k) = x%psi(k) + y%psi(k)
    end do
  end function add_vectorspinor

```

```

<Implementation of operations for vectorspinors>+=
pure function sub_vectorspinor (x, y) result (xy)
  type(vectorspinor) :: xy
  type(vectorspinor), intent(in) :: x, y
  integer :: k
  do k = 1,4
    xy%psi(k) = x%psi(k) - y%psi(k)
  end do
end function sub_vectorspinor

```

### X.3.2 Norm

```

<Declaration of operations for vectorspinors>+=
interface abs
  module procedure abs_vectorspinor
end interface
private :: abs_vectorspinor

<Implementation of operations for vectorspinors>+=
pure function abs_vectorspinor (psi) result (x)
  real(kind=default) :: x
  type(vectorspinor), intent(in) :: psi
  x = sqrt (real (dot_product (psi%psi(1)%a, psi%psi(1)%a) &
    - dot_product (psi%psi(2)%a, psi%psi(2)%a) &
    - dot_product (psi%psi(3)%a, psi%psi(3)%a) &
    - dot_product (psi%psi(4)%a, psi%psi(4)%a)))
end function abs_vectorspinor

```

## X.4 Vectors and Tensors

Condensed representation of antisymmetric rank-2 tensors:

$$\begin{pmatrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{pmatrix} = \begin{pmatrix} 0 & T_e^1 & T_e^2 & T_e^3 \\ -T_e^1 & 0 & T_b^3 & -T_b^2 \\ -T_e^2 & -T_b^3 & 0 & T_b^1 \\ -T_e^3 & T_b^2 & -T_b^1 & 0 \end{pmatrix} \quad (X.4)$$

```

<omega_vectors.f90>=
<Cotypeleft>
module omega_vectors
  use kinds
  use constants
  implicit none
  private
  public :: assignment (=)
  public :: operator (*), operator (+), operator (-), operator (.wedge.)
  public :: abs, conjg
  public :: random_momentum
  <intrinsic :: abs>
  <intrinsic :: conjg>
  type, public :: momentum
  ! private (omegalib needs access, but DON'T TOUCH IT!)
  real(kind=default) :: t

```



```

        real(kind=default), dimension(3) :: x
    end type momentum
    type, public :: vector
        ! private (omegalib needs access, but DON'T TOUCH IT!)
        complex(kind=default) :: t
        complex(kind=default), dimension(3) :: x
    end type vector
    type, public :: tensor2odd
        ! private (omegalib needs access, but DON'T TOUCH IT!)
        complex(kind=default), dimension(3) :: e
        complex(kind=default), dimension(3) :: b
    end type tensor2odd
    <Declaration of operations for vectors>
    integer, parameter, public :: omega_vectors_2010_01_A = 0
contains
    <Implementation of operations for vectors>
end module omega_vectors

```

### X.4.1 Constructors

```

<Declaration of operations for vectors>≡
    interface assignment (=)
        module procedure momentum_of_array, vector_of_momentum, &
            vector_of_array, vector_of_double_array, &
            array_of_momentum, array_of_vector
    end interface
    private :: momentum_of_array, vector_of_momentum, vector_of_array, &
        vector_of_double_array, array_of_momentum, array_of_vector

<Implementation of operations for vectors>≡
    pure subroutine momentum_of_array (m, p)
        type(momentum), intent(out) :: m
        real(kind=default), dimension(0:), intent(in) :: p
        m%t = p(0)
        m%x = p(1:3)
    end subroutine momentum_of_array
    pure subroutine array_of_momentum (p, v)
        real(kind=default), dimension(0:), intent(out) :: p
        type(momentum), intent(in) :: v
        p(0) = v%t
        p(1:3) = v%x
    end subroutine array_of_momentum

<Implementation of operations for vectors>+≡
    pure subroutine vector_of_array (v, p)
        type(vector), intent(out) :: v
        complex(kind=default), dimension(0:), intent(in) :: p
        v%t = p(0)
        v%x = p(1:3)
    end subroutine vector_of_array
    pure subroutine vector_of_double_array (v, p)
        type(vector), intent(out) :: v
        real(kind=default), dimension(0:), intent(in) :: p
        v%t = p(0)
        v%x = p(1:3)
    end subroutine vector_of_double_array

```

```

end subroutine vector_of_double_array
pure subroutine array_of_vector (p, v)
  complex(kind=default), dimension(0:), intent(out) :: p
  type(vector), intent(in) :: v
  p(0) = v%t
  p(1:3) = v%x
end subroutine array_of_vector
<Implementation of operations for vectors>+≡
pure subroutine vector_of_momentum (v, p)
  type(vector), intent(out) :: v
  type(momentum), intent(in) :: p
  v%t = p%t
  v%x = p%x
end subroutine vector_of_momentum

```

#### X.4.2 Inner Products

```

<Declaration of operations for vectors>+≡
interface operator (*)
  module procedure momentum_momentum, vector_vector, &
    vector_momentum, momentum_vector, tensor2odd_tensor2odd
end interface
private :: momentum_momentum, vector_vector, vector_momentum, &
  momentum_vector, tensor2odd_tensor2odd

<Implementation of operations for vectors>+≡
pure function momentum_momentum (x, y) result (xy)
  type(momentum), intent(in) :: x
  type(momentum), intent(in) :: y
  real(kind=default) :: xy
  xy = x%t*y%t - x%x(1)*y%x(1) - x%x(2)*y%x(2) - x%x(3)*y%x(3)
end function momentum_momentum
pure function momentum_vector (x, y) result (xy)
  type(momentum), intent(in) :: x
  type(vector), intent(in) :: y
  complex(kind=default) :: xy
  xy = x%t*y%t - x%x(1)*y%x(1) - x%x(2)*y%x(2) - x%x(3)*y%x(3)
end function momentum_vector
pure function vector_momentum (x, y) result (xy)
  type(vector), intent(in) :: x
  type(momentum), intent(in) :: y
  complex(kind=default) :: xy
  xy = x%t*y%t - x%x(1)*y%x(1) - x%x(2)*y%x(2) - x%x(3)*y%x(3)
end function vector_momentum
pure function vector_vector (x, y) result (xy)
  type(vector), intent(in) :: x
  type(vector), intent(in) :: y
  complex(kind=default) :: xy
  xy = x%t*y%t - x%x(1)*y%x(1) - x%x(2)*y%x(2) - x%x(3)*y%x(3)
end function vector_vector

```

Just like classical electrodynamics:

$$\frac{1}{2}T_{\mu\nu}U^{\mu\nu} = \frac{1}{2}(-T^{0i}U^{0i} - T^{i0}U^{i0} + T^{ij}U^{ij}) = T_b^k U_b^k - T_e^k U_e^k \quad (\text{X.5})$$

```

<Implementation of operations for vectors>+≡
pure function tensor2odd_tensor2odd (x, y) result (xy)
  type(tensor2odd), intent(in) :: x
  type(tensor2odd), intent(in) :: y
  complex(kind=default) :: xy
  xy = x%b(1)*y%b(1) + x%b(2)*y%b(2) + x%b(3)*y%b(3) &
    - x%e(1)*y%e(1) - x%e(2)*y%e(2) - x%e(3)*y%e(3)
end function tensor2odd_tensor2odd

```

### X.4.3 Not Entirely Inner Products

```

<Declaration of operations for vectors>+≡
interface operator (*)
  module procedure momentum_tensor2odd, tensor2odd_momentum, &
    vector_tensor2odd, tensor2odd_vector
end interface
private :: momentum_tensor2odd, tensor2odd_momentum, vector_tensor2odd, &
  tensor2odd_vector

```

$$y^\nu = x_\mu T^{\mu\nu} : y^0 = -x^i T^{i0} = x^i T^{0i} \quad (\text{X.6a})$$

$$y^1 = x^0 T^{01} - x^2 T^{21} - x^3 T^{31} \quad (\text{X.6b})$$

$$y^2 = x^0 T^{02} - x^1 T^{12} - x^3 T^{32} \quad (\text{X.6c})$$

$$y^3 = x^0 T^{03} - x^1 T^{13} - x^2 T^{23} \quad (\text{X.6d})$$

```

<Implementation of operations for vectors>+≡
pure function vector_tensor2odd (x, t2) result (xt2)
  type(vector), intent(in) :: x
  type(tensor2odd), intent(in) :: t2
  type(vector) :: xt2
  xt2%t = x%x(1)*t2%e(1) + x%x(2)*t2%e(2) + x%x(3)*t2%e(3)
  xt2%x(1) = x%t*t2%e(1) + x%x(2)*t2%b(3) - x%x(3)*t2%b(2)
  xt2%x(2) = x%t*t2%e(2) + x%x(3)*t2%b(1) - x%x(1)*t2%b(3)
  xt2%x(3) = x%t*t2%e(3) + x%x(1)*t2%b(2) - x%x(2)*t2%b(1)
end function vector_tensor2odd
pure function momentum_tensor2odd (x, t2) result (xt2)
  type(momentum), intent(in) :: x
  type(tensor2odd), intent(in) :: t2
  type(vector) :: xt2
  xt2%t = x%x(1)*t2%e(1) + x%x(2)*t2%e(2) + x%x(3)*t2%e(3)
  xt2%x(1) = x%t*t2%e(1) + x%x(2)*t2%b(3) - x%x(3)*t2%b(2)
  xt2%x(2) = x%t*t2%e(2) + x%x(3)*t2%b(1) - x%x(1)*t2%b(3)
  xt2%x(3) = x%t*t2%e(3) + x%x(1)*t2%b(2) - x%x(2)*t2%b(1)
end function momentum_tensor2odd

```

$$y^\mu = T^{\mu\nu} x_\nu : y^0 = -T^{0i} x^i \quad (\text{X.7a})$$

$$y^1 = T^{10} x^0 - T^{12} x^2 - T^{13} x^3 \quad (\text{X.7b})$$

$$y^2 = T^{20} x^0 - T^{21} x^1 - T^{23} x^3 \quad (\text{X.7c})$$

$$y^3 = T^{30} x^0 - T^{31} x^1 - T^{32} x^2 \quad (\text{X.7d})$$

```

<Implementation of operations for vectors>+≡
pure function tensor2odd_vector (t2, x) result (t2x)
  type(tensor2odd), intent(in) :: t2
  type(vector), intent(in) :: x
  type(vector) :: t2x
  t2x%t = - t2%e(1)*x%x(1) - t2%e(2)*x%x(2) - t2%e(3)*x%x(3)
  t2x%x(1) = - t2%e(1)*x%t + t2%b(2)*x%x(3) - t2%b(3)*x%x(2)
  t2x%x(2) = - t2%e(2)*x%t + t2%b(3)*x%x(1) - t2%b(1)*x%x(3)
  t2x%x(3) = - t2%e(3)*x%t + t2%b(1)*x%x(2) - t2%b(2)*x%x(1)
end function tensor2odd_vector
pure function tensor2odd_momentum (t2, x) result (t2x)
  type(tensor2odd), intent(in) :: t2
  type(momentum), intent(in) :: x
  type(vector) :: t2x
  t2x%t = - t2%e(1)*x%x(1) - t2%e(2)*x%x(2) - t2%e(3)*x%x(3)
  t2x%x(1) = - t2%e(1)*x%t + t2%b(2)*x%x(3) - t2%b(3)*x%x(2)
  t2x%x(2) = - t2%e(2)*x%t + t2%b(3)*x%x(1) - t2%b(1)*x%x(3)
  t2x%x(3) = - t2%e(3)*x%t + t2%b(1)*x%x(2) - t2%b(2)*x%x(1)
end function tensor2odd_momentum

```

#### X.4.4 Outer Products

```

<Declaration of operations for vectors>+≡
interface operator (.wedge.)
  module procedure momentum_wedge_momentum, &
    momentum_wedge_vector, vector_wedge_momentum, vector_wedge_vector
end interface
private :: momentum_wedge_momentum, momentum_wedge_vector, &
  vector_wedge_momentum, vector_wedge_vector

```

```

<Implementation of operations for vectors>+≡
pure function momentum_wedge_momentum (x, y) result (t2)
  type(momentum), intent(in) :: x
  type(momentum), intent(in) :: y
  type(tensor2odd) :: t2
  t2%e = x%t * y%x - x%x * y%t
  t2%b(1) = x%x(2) * y%x(3) - x%x(3) * y%x(2)
  t2%b(2) = x%x(3) * y%x(1) - x%x(1) * y%x(3)
  t2%b(3) = x%x(1) * y%x(2) - x%x(2) * y%x(1)
end function momentum_wedge_momentum
pure function momentum_wedge_vector (x, y) result (t2)
  type(momentum), intent(in) :: x
  type(vector), intent(in) :: y
  type(tensor2odd) :: t2
  t2%e = x%t * y%x - x%x * y%t
  t2%b(1) = x%x(2) * y%x(3) - x%x(3) * y%x(2)
  t2%b(2) = x%x(3) * y%x(1) - x%x(1) * y%x(3)
  t2%b(3) = x%x(1) * y%x(2) - x%x(2) * y%x(1)
end function momentum_wedge_vector
pure function vector_wedge_momentum (x, y) result (t2)
  type(vector), intent(in) :: x
  type(momentum), intent(in) :: y
  type(tensor2odd) :: t2
  t2%e = x%t * y%x - x%x * y%t

```

```

t2%b(1) = x%x(2) * y%x(3) - x%x(3) * y%x(2)
t2%b(2) = x%x(3) * y%x(1) - x%x(1) * y%x(3)
t2%b(3) = x%x(1) * y%x(2) - x%x(2) * y%x(1)
end function vector_wedge_momentum
pure function vector_wedge_vector (x, y) result (t2)
  type(vector), intent(in) :: x
  type(vector), intent(in) :: y
  type(tensor2odd) :: t2
  t2%e = x%t * y%x - x%x * y%t
  t2%b(1) = x%x(2) * y%x(3) - x%x(3) * y%x(2)
  t2%b(2) = x%x(3) * y%x(1) - x%x(1) * y%x(3)
  t2%b(3) = x%x(1) * y%x(2) - x%x(2) * y%x(1)
end function vector_wedge_vector

```

### X.4.5 Vector Space

#### Scalar Multiplication

*(Declaration of operations for vectors)*+≡

```

interface operator (*)
  module procedure integer_momentum, real_momentum, double_momentum, &
    complex_momentum, dcomplex_momentum, &
    integer_vector, real_vector, double_vector, &
    complex_vector, dcomplex_vector, &
    integer_tensor2odd, real_tensor2odd, double_tensor2odd, &
    complex_tensor2odd, dcomplex_tensor2odd, &
    momentum_integer, momentum_real, momentum_double, &
    momentum_complex, momentum_dcomplex, &
    vector_integer, vector_real, vector_double, &
    vector_complex, vector_dcomplex, &
    tensor2odd_integer, tensor2odd_real, tensor2odd_double, &
    tensor2odd_complex, tensor2odd_dcomplex
end interface
private :: integer_momentum, real_momentum, double_momentum, &
  complex_momentum, dcomplex_momentum, integer_vector, real_vector, &
  double_vector, complex_vector, dcomplex_vector, &
  integer_tensor2odd, real_tensor2odd, double_tensor2odd, &
  complex_tensor2odd, dcomplex_tensor2odd, momentum_integer, &
  momentum_real, momentum_double, momentum_complex, &
  momentum_dcomplex, vector_integer, vector_real, vector_double, &
  vector_complex, vector_dcomplex, tensor2odd_integer, &
  tensor2odd_real, tensor2odd_double, tensor2odd_complex, &
  tensor2odd_dcomplex

```

*(Implementation of operations for vectors)*+≡

```

pure function integer_momentum (x, y) result (xy)
  integer, intent(in) :: x
  type(momentum), intent(in) :: y
  type(momentum) :: xy
  xy%t = x * y%t
  xy%x = x * y%x
end function integer_momentum
pure function real_momentum (x, y) result (xy)
  real(kind=single), intent(in) :: x

```

```

    type(momentum), intent(in) :: y
    type(momentum) :: xy
    xy%t = x * y%t
    xy%x = x * y%x
end function real_momentum
pure function double_momentum (x, y) result (xy)
    real(kind=default), intent(in) :: x
    type(momentum), intent(in) :: y
    type(momentum) :: xy
    xy%t = x * y%t
    xy%x = x * y%x
end function double_momentum
pure function complex_momentum (x, y) result (xy)
    complex(kind=single), intent(in) :: x
    type(momentum), intent(in) :: y
    type(vector) :: xy
    xy%t = x * y%t
    xy%x = x * y%x
end function complex_momentum
pure function dcomplex_momentum (x, y) result (xy)
    complex(kind=default), intent(in) :: x
    type(momentum), intent(in) :: y
    type(vector) :: xy
    xy%t = x * y%t
    xy%x = x * y%x
end function dcomplex_momentum

<Implementation of operations for vectors>+≡
pure function integer_vector (x, y) result (xy)
    integer, intent(in) :: x
    type(vector), intent(in) :: y
    type(vector) :: xy
    xy%t = x * y%t
    xy%x = x * y%x
end function integer_vector
pure function real_vector (x, y) result (xy)
    real(kind=single), intent(in) :: x
    type(vector), intent(in) :: y
    type(vector) :: xy
    xy%t = x * y%t
    xy%x = x * y%x
end function real_vector
pure function double_vector (x, y) result (xy)
    real(kind=default), intent(in) :: x
    type(vector), intent(in) :: y
    type(vector) :: xy
    xy%t = x * y%t
    xy%x = x * y%x
end function double_vector
pure function complex_vector (x, y) result (xy)
    complex(kind=single), intent(in) :: x
    type(vector), intent(in) :: y
    type(vector) :: xy
    xy%t = x * y%t
    xy%x = x * y%x

```

```

end function complex_vector
pure function dcomplex_vector (x, y) result (xy)
  complex(kind=default), intent(in) :: x
  type(vector), intent(in) :: y
  type(vector) :: xy
  xy%t = x * y%t
  xy%x = x * y%x
end function dcomplex_vector

<Implementation of operations for vectors>+≡
pure function integer_tensor2odd (x, t2) result (xt2)
  integer, intent(in) :: x
  type(tensor2odd), intent(in) :: t2
  type(tensor2odd) :: xt2
  xt2%e = x * t2%e
  xt2%b = x * t2%b
end function integer_tensor2odd
pure function real_tensor2odd (x, t2) result (xt2)
  real(kind=single), intent(in) :: x
  type(tensor2odd), intent(in) :: t2
  type(tensor2odd) :: xt2
  xt2%e = x * t2%e
  xt2%b = x * t2%b
end function real_tensor2odd
pure function double_tensor2odd (x, t2) result (xt2)
  real(kind=default), intent(in) :: x
  type(tensor2odd), intent(in) :: t2
  type(tensor2odd) :: xt2
  xt2%e = x * t2%e
  xt2%b = x * t2%b
end function double_tensor2odd
pure function complex_tensor2odd (x, t2) result (xt2)
  complex(kind=single), intent(in) :: x
  type(tensor2odd), intent(in) :: t2
  type(tensor2odd) :: xt2
  xt2%e = x * t2%e
  xt2%b = x * t2%b
end function complex_tensor2odd
pure function dcomplex_tensor2odd (x, t2) result (xt2)
  complex(kind=default), intent(in) :: x
  type(tensor2odd), intent(in) :: t2
  type(tensor2odd) :: xt2
  xt2%e = x * t2%e
  xt2%b = x * t2%b
end function dcomplex_tensor2odd

<Implementation of operations for vectors>+≡
pure function momentum_integer (y, x) result (xy)
  integer, intent(in) :: x
  type(momentum), intent(in) :: y
  type(momentum) :: xy
  xy%t = x * y%t
  xy%x = x * y%x
end function momentum_integer
pure function momentum_real (y, x) result (xy)

```

```

    real(kind=single), intent(in) :: x
    type(momentum), intent(in) :: y
    type(momentum) :: xy
    xy%t = x * y%t
    xy%x = x * y%x
end function momentum_real
pure function momentum_double (y, x) result (xy)
    real(kind=default), intent(in) :: x
    type(momentum), intent(in) :: y
    type(momentum) :: xy
    xy%t = x * y%t
    xy%x = x * y%x
end function momentum_double
pure function momentum_complex (y, x) result (xy)
    complex(kind=single), intent(in) :: x
    type(momentum), intent(in) :: y
    type(vector) :: xy
    xy%t = x * y%t
    xy%x = x * y%x
end function momentum_complex
pure function momentum_dcomplex (y, x) result (xy)
    complex(kind=default), intent(in) :: x
    type(momentum), intent(in) :: y
    type(vector) :: xy
    xy%t = x * y%t
    xy%x = x * y%x
end function momentum_dcomplex

(Implementation of operations for vectors)+≡
pure function vector_integer (y, x) result (xy)
    integer, intent(in) :: x
    type(vector), intent(in) :: y
    type(vector) :: xy
    xy%t = x * y%t
    xy%x = x * y%x
end function vector_integer
pure function vector_real (y, x) result (xy)
    real(kind=single), intent(in) :: x
    type(vector), intent(in) :: y
    type(vector) :: xy
    xy%t = x * y%t
    xy%x = x * y%x
end function vector_real
pure function vector_double (y, x) result (xy)
    real(kind=default), intent(in) :: x
    type(vector), intent(in) :: y
    type(vector) :: xy
    xy%t = x * y%t
    xy%x = x * y%x
end function vector_double
pure function vector_complex (y, x) result (xy)
    complex(kind=single), intent(in) :: x
    type(vector), intent(in) :: y
    type(vector) :: xy
    xy%t = x * y%t

```



```

    xy%x = x * y%x
end function vector_complex
pure function vector_dcomplex (y, x) result (xy)
    complex(kind=default), intent(in) :: x
    type(vector), intent(in) :: y
    type(vector) :: xy
    xy%t = x * y%t
    xy%x = x * y%x
end function vector_dcomplex

(Implementation of operations for vectors)+≡
pure function tensor2odd_integer (t2, x) result (t2x)
    type(tensor2odd), intent(in) :: t2
    integer, intent(in) :: x
    type(tensor2odd) :: t2x
    t2x%e = x * t2%e
    t2x%b = x * t2%b
end function tensor2odd_integer
pure function tensor2odd_real (t2, x) result (t2x)
    type(tensor2odd), intent(in) :: t2
    real(kind=single), intent(in) :: x
    type(tensor2odd) :: t2x
    t2x%e = x * t2%e
    t2x%b = x * t2%b
end function tensor2odd_real
pure function tensor2odd_double (t2, x) result (t2x)
    type(tensor2odd), intent(in) :: t2
    real(kind=default), intent(in) :: x
    type(tensor2odd) :: t2x
    t2x%e = x * t2%e
    t2x%b = x * t2%b
end function tensor2odd_double
pure function tensor2odd_complex (t2, x) result (t2x)
    type(tensor2odd), intent(in) :: t2
    complex(kind=single), intent(in) :: x
    type(tensor2odd) :: t2x
    t2x%e = x * t2%e
    t2x%b = x * t2%b
end function tensor2odd_complex
pure function tensor2odd_dcomplex (t2, x) result (t2x)
    type(tensor2odd), intent(in) :: t2
    complex(kind=default), intent(in) :: x
    type(tensor2odd) :: t2x
    t2x%e = x * t2%e
    t2x%b = x * t2%b
end function tensor2odd_dcomplex

```

### *Unary Plus and Minus*

```

(Declaration of operations for vectors)+≡
interface operator (+)
    module procedure plus_momentum, plus_vector, plus_tensor2odd
end interface
private :: plus_momentum, plus_vector, plus_tensor2odd

```

```

interface operator (-)
  module procedure neg_momentum, neg_vector, neg_tensor2odd
end interface
private :: neg_momentum, neg_vector, neg_tensor2odd

<Implementation of operations for vectors>+≡
pure function plus_momentum (x) result (plus_x)
  type(momentum), intent(in) :: x
  type(momentum) :: plus_x
  plus_x = x
end function plus_momentum
pure function neg_momentum (x) result (neg_x)
  type(momentum), intent(in) :: x
  type(momentum) :: neg_x
  neg_x%t = - x%t
  neg_x%x = - x%x
end function neg_momentum

<Implementation of operations for vectors>+≡
pure function plus_vector (x) result (plus_x)
  type(vector), intent(in) :: x
  type(vector) :: plus_x
  plus_x = x
end function plus_vector
pure function neg_vector (x) result (neg_x)
  type(vector), intent(in) :: x
  type(vector) :: neg_x
  neg_x%t = - x%t
  neg_x%x = - x%x
end function neg_vector

<Implementation of operations for vectors>+≡
pure function plus_tensor2odd (x) result (plus_x)
  type(tensor2odd), intent(in) :: x
  type(tensor2odd) :: plus_x
  plus_x = x
end function plus_tensor2odd
pure function neg_tensor2odd (x) result (neg_x)
  type(tensor2odd), intent(in) :: x
  type(tensor2odd) :: neg_x
  neg_x%e = - x%e
  neg_x%b = - x%b
end function neg_tensor2odd

```

### *Addition and Subtraction*

```

<Declaration of operations for vectors>+≡
interface operator (+)
  module procedure add_momentum, add_vector, &
    add_vector_momentum, add_momentum_vector, add_tensor2odd
end interface
private :: add_momentum, add_vector, add_vector_momentum, &
  add_momentum_vector, add_tensor2odd
interface operator (-)
  module procedure sub_momentum, sub_vector, &

```

```

        sub_vector_momentum, sub_momentum_vector, sub_tensor2odd
end interface
private :: sub_momentum, sub_vector, sub_vector_momentum, &
        sub_momentum_vector, sub_tensor2odd

<Implementation of operations for vectors>+≡
pure function add_momentum (x, y) result (xy)
    type(momentum), intent(in) :: x, y
    type(momentum) :: xy
    xy%t = x%t + y%t
    xy%x = x%x + y%x
end function add_momentum
pure function add_vector (x, y) result (xy)
    type(vector), intent(in) :: x, y
    type(vector) :: xy
    xy%t = x%t + y%t
    xy%x = x%x + y%x
end function add_vector
pure function add_momentum_vector (x, y) result (xy)
    type(momentum), intent(in) :: x
    type(vector), intent(in) :: y
    type(vector) :: xy
    xy%t = x%t + y%t
    xy%x = x%x + y%x
end function add_momentum_vector
pure function add_vector_momentum (x, y) result (xy)
    type(vector), intent(in) :: x
    type(momentum), intent(in) :: y
    type(vector) :: xy
    xy%t = x%t + y%t
    xy%x = x%x + y%x
end function add_vector_momentum
pure function add_tensor2odd (x, y) result (xy)
    type(tensor2odd), intent(in) :: x, y
    type(tensor2odd) :: xy
    xy%e = x%e + y%e
    xy%b = x%b + y%b
end function add_tensor2odd

<Implementation of operations for vectors>+≡
pure function sub_momentum (x, y) result (xy)
    type(momentum), intent(in) :: x, y
    type(momentum) :: xy
    xy%t = x%t - y%t
    xy%x = x%x - y%x
end function sub_momentum
pure function sub_vector (x, y) result (xy)
    type(vector), intent(in) :: x, y
    type(vector) :: xy
    xy%t = x%t - y%t
    xy%x = x%x - y%x
end function sub_vector
pure function sub_momentum_vector (x, y) result (xy)
    type(momentum), intent(in) :: x
    type(vector), intent(in) :: y

```

```

    type(vector) :: xy
    xy%t = x%t - y%t
    xy%x = x%x - y%x
end function sub_momentum_vector
pure function sub_vector_momentum (x, y) result (xy)
    type(vector), intent(in) :: x
    type(momentum), intent(in) :: y
    type(vector) :: xy
    xy%t = x%t - y%t
    xy%x = x%x - y%x
end function sub_vector_momentum
pure function sub_tensor2odd (x, y) result (xy)
    type(tensor2odd), intent(in) :: x, y
    type(tensor2odd) :: xy
    xy%e = x%e - y%e
    xy%b = x%b - y%b
end function sub_tensor2odd

```

#### X.4.6 Norm

Not the covariant length!

*(Declaration of operations for vectors)*+≡

```

interface abs
    module procedure abs_momentum, abs_vector, abs_tensor2odd
end interface
private :: abs_momentum, abs_vector, abs_tensor2odd

```

*(Implementation of operations for vectors)*+≡

```

pure function abs_momentum (x) result (absx)
    type(momentum), intent(in) :: x
    real(kind=default) :: absx
    absx = sqrt (real (x%t*x%t + dot_product (x%x, x%x)))
end function abs_momentum
pure function abs_vector (x) result (absx)
    type(vector), intent(in) :: x
    real(kind=default) :: absx
    absx = sqrt (real (conjg(x%t)*x%t + dot_product (x%x, x%x)))
end function abs_vector
pure function abs_tensor2odd (x) result (absx)
    type(tensor2odd), intent(in) :: x
    real(kind=default) :: absx
    absx = sqrt (real (dot_product (x%e, x%e) + dot_product (x%b, x%b)))
end function abs_tensor2odd

```

#### X.4.7 Conjugation

*(Declaration of operations for vectors)*+≡

```

interface conjg
    module procedure conjg_momentum, conjg_vector, conjg_tensor2odd
end interface
private :: conjg_momentum, conjg_vector, conjg_tensor2odd

```

*(Implementation of operations for vectors)*+≡

```

pure function conjg_momentum (x) result (conjg_x)

```

```

    type(momentum), intent(in) :: x
    type(momentum) :: conjg_x
    conjg_x = x
end function conjg_momentum
pure function conjg_vector (x) result (conjg_x)
    type(vector), intent(in) :: x
    type(vector) :: conjg_x
    conjg_x%t = conjg (x%t)
    conjg_x%x = conjg (x%x)
end function conjg_vector
pure function conjg_tensor2odd (t2) result (conjg_t2)
    type(tensor2odd), intent(in) :: t2
    type(tensor2odd) :: conjg_t2
    conjg_t2%e = conjg (t2%e)
    conjg_t2%b = conjg (t2%b)
end function conjg_tensor2odd

```

#### X.4.8 $\epsilon$ -Tensors

$$\epsilon_{0123} = 1 = -\epsilon^{0123} \quad (\text{X.8})$$

in particular

$$\epsilon(p_1, p_2, p_3, p_4) = \epsilon_{\mu_1 \mu_2 \mu_3 \mu_4} p_1^{\mu_1} p_2^{\mu_2} p_3^{\mu_3} p_4^{\mu_4} = p_1^0 p_2^1 p_3^2 p_4^3 \pm \dots \quad (\text{X.9})$$

*(Declaration of operations for vectors)*+≡

```

interface pseudo_scalar
    module procedure pseudo_scalar_momentum, pseudo_scalar_vector, &
        pseudo_scalar_vec_mom
end interface
public :: pseudo_scalar
private :: pseudo_scalar_momentum, pseudo_scalar_vector

```

*(Implementation of operations for vectors)*+≡

```

pure function pseudo_scalar_momentum (p1, p2, p3, p4) result (eps1234)
    type(momentum), intent(in) :: p1, p2, p3, p4
    real(kind=default) :: eps1234
    eps1234 = &
        p1%t * p2%x(1) * (p3%x(2) * p4%x(3) - p3%x(3) * p4%x(2)) &
        + p1%t * p2%x(2) * (p3%x(3) * p4%x(1) - p3%x(1) * p4%x(3)) &
        + p1%t * p2%x(3) * (p3%x(1) * p4%x(2) - p3%x(2) * p4%x(1)) &
        - p1%x(1) * p2%x(2) * (p3%x(3) * p4%t - p3%t * p4%x(3)) &
        - p1%x(1) * p2%x(3) * (p3%t * p4%x(2) - p3%x(2) * p4%t) &
        - p1%x(1) * p2%t * (p3%x(2) * p4%x(3) - p3%x(3) * p4%x(2)) &
        + p1%x(2) * p2%x(3) * (p3%t * p4%x(1) - p3%x(1) * p4%t) &
        + p1%x(2) * p2%t * (p3%x(1) * p4%x(3) - p3%x(3) * p4%x(1)) &
        + p1%x(2) * p2%x(1) * (p3%x(3) * p4%t - p3%t * p4%x(3)) &
        - p1%x(3) * p2%t * (p3%x(1) * p4%x(2) - p3%x(2) * p4%x(1)) &
        - p1%x(3) * p2%x(1) * (p3%x(2) * p4%t - p3%t * p4%x(2)) &
        - p1%x(3) * p2%x(2) * (p3%t * p4%x(1) - p3%x(1) * p4%t)
end function pseudo_scalar_momentum

```

*(Implementation of operations for vectors)*+≡

```

pure function pseudo_scalar_vector (p1, p2, p3, p4) result (eps1234)
    type(vector), intent(in) :: p1, p2, p3, p4

```

```

complex(kind=default) :: eps1234
eps1234 = &
    p1%t      * p2%x(1) * (p3%x(2) * p4%x(3) - p3%x(3) * p4%x(2)) &
+ p1%t      * p2%x(2) * (p3%x(3) * p4%x(1) - p3%x(1) * p4%x(3)) &
+ p1%t      * p2%x(3) * (p3%x(1) * p4%x(2) - p3%x(2) * p4%x(1)) &
- p1%x(1) * p2%x(2) * (p3%x(3) * p4%t      - p3%t      * p4%x(3)) &
- p1%x(1) * p2%x(3) * (p3%t      * p4%x(2) - p3%x(2) * p4%t      ) &
- p1%x(1) * p2%t      * (p3%x(2) * p4%x(3) - p3%x(3) * p4%x(2)) &
+ p1%x(2) * p2%x(3) * (p3%t      * p4%x(1) - p3%x(1) * p4%t      ) &
+ p1%x(2) * p2%t      * (p3%x(1) * p4%x(3) - p3%x(3) * p4%x(1)) &
+ p1%x(2) * p2%x(1) * (p3%x(3) * p4%t      - p3%t      * p4%x(3)) &
- p1%x(3) * p2%t      * (p3%x(1) * p4%x(2) - p3%x(2) * p4%x(1)) &
- p1%x(3) * p2%x(1) * (p3%x(2) * p4%t      - p3%t      * p4%x(2)) &
- p1%x(3) * p2%x(2) * (p3%t      * p4%x(1) - p3%x(1) * p4%t      )
end function pseudo_scalar_vector

<Implementation of operations for vectors>+≡
pure function pseudo_scalar_vec_mom (p1, v1, p2, v2) result (eps1234)
    type(momentum), intent(in)  :: p1, p2
    type(vector), intent(in)    :: v1, v2
    complex(kind=default) :: eps1234
    eps1234 = &
        p1%t      * v1%x(1) * (p2%x(2) * v2%x(3) - p2%x(3) * v2%x(2)) &
+ p1%t      * v1%x(2) * (p2%x(3) * v2%x(1) - p2%x(1) * v2%x(3)) &
+ p1%t      * v1%x(3) * (p2%x(1) * v2%x(2) - p2%x(2) * v2%x(1)) &
- p1%x(1) * v1%x(2) * (p2%x(3) * v2%t      - p2%t      * v2%x(3)) &
- p1%x(1) * v1%x(3) * (p2%t      * v2%x(2) - p2%x(2) * v2%t      ) &
- p1%x(1) * v1%t      * (p2%x(2) * v2%x(3) - p2%x(3) * v2%x(2)) &
+ p1%x(2) * v1%x(3) * (p2%t      * v2%x(1) - p2%x(1) * v2%t      ) &
+ p1%x(2) * v1%t      * (p2%x(1) * v2%x(3) - p2%x(3) * v2%x(1)) &
+ p1%x(2) * v1%x(1) * (p2%x(3) * v2%t      - p2%t      * v2%x(3)) &
- p1%x(3) * v1%t      * (p2%x(1) * v2%x(2) - p2%x(2) * v2%x(1)) &
- p1%x(3) * v1%x(1) * (p2%x(2) * v2%t      - p2%t      * v2%x(2)) &
- p1%x(3) * v1%x(2) * (p2%t      * v2%x(1) - p2%x(1) * v2%t      )
    end function pseudo_scalar_vec_mom
    
```

$$\epsilon_{\mu}(p_1, p_2, p_3) = \epsilon_{\mu\mu_1\mu_2\mu_3} p_1^{\mu_1} p_2^{\mu_2} p_3^{\mu_3} \quad (\text{X.10})$$

i. e.

$$\epsilon_0(p_1, p_2, p_3) = p_1^1 p_2^2 p_3^3 \pm \dots \quad (\text{X.11a})$$

$$\epsilon_1(p_1, p_2, p_3) = p_1^2 p_2^3 p_3^0 \pm \dots \quad (\text{X.11b})$$

$$\epsilon_2(p_1, p_2, p_3) = -p_1^3 p_2^0 p_3^1 \pm \dots \quad (\text{X.11c})$$

$$\epsilon_3(p_1, p_2, p_3) = p_1^0 p_2^1 p_3^2 \pm \dots \quad (\text{X.11d})$$

```

<Declaration of operations for vectors>+≡
interface pseudo_vector
    module procedure pseudo_vector_momentum, pseudo_vector_vector, &
        pseudo_vector_vec_mom
end interface
public :: pseudo_vector
private :: pseudo_vector_momentum, pseudo_vector_vector
    
```

```

<Implementation of operations for vectors>+≡
pure function pseudo_vector_momentum (p1, p2, p3) result (eps123)
  type(momentum), intent(in) :: p1, p2, p3
  type(momentum) :: eps123
  eps123%t = &
    + p1%x(1) * (p2%x(2) * p3%x(3) - p2%x(3) * p3%x(2)) &
    + p1%x(2) * (p2%x(3) * p3%x(1) - p2%x(1) * p3%x(3)) &
    + p1%x(3) * (p2%x(1) * p3%x(2) - p2%x(2) * p3%x(1))
  eps123%x(1) = &
    + p1%x(2) * (p2%x(3) * p3%t - p2%t * p3%x(3)) &
    + p1%x(3) * (p2%t * p3%x(2) - p2%x(2) * p3%t) &
    + p1%t * (p2%x(2) * p3%x(3) - p2%x(3) * p3%x(2))
  eps123%x(2) = &
    - p1%x(3) * (p2%t * p3%x(1) - p2%x(1) * p3%t) &
    - p1%t * (p2%x(1) * p3%x(3) - p2%x(3) * p3%x(1)) &
    - p1%x(1) * (p2%x(3) * p3%t - p2%t * p3%x(3))
  eps123%x(3) = &
    + p1%t * (p2%x(1) * p3%x(2) - p2%x(2) * p3%x(1)) &
    + p1%x(1) * (p2%x(2) * p3%t - p2%t * p3%x(2)) &
    + p1%x(2) * (p2%t * p3%x(1) - p2%x(1) * p3%t)
end function pseudo_vector_momentum

```

```

<Implementation of operations for vectors>+≡
pure function pseudo_vector_vector (p1, p2, p3) result (eps123)
  type(vector), intent(in) :: p1, p2, p3
  type(vector) :: eps123
  eps123%t = &
    + p1%x(1) * (p2%x(2) * p3%x(3) - p2%x(3) * p3%x(2)) &
    + p1%x(2) * (p2%x(3) * p3%x(1) - p2%x(1) * p3%x(3)) &
    + p1%x(3) * (p2%x(1) * p3%x(2) - p2%x(2) * p3%x(1))
  eps123%x(1) = &
    + p1%x(2) * (p2%x(3) * p3%t - p2%t * p3%x(3)) &
    + p1%x(3) * (p2%t * p3%x(2) - p2%x(2) * p3%t) &
    + p1%t * (p2%x(2) * p3%x(3) - p2%x(3) * p3%x(2))
  eps123%x(2) = &
    - p1%x(3) * (p2%t * p3%x(1) - p2%x(1) * p3%t) &
    - p1%t * (p2%x(1) * p3%x(3) - p2%x(3) * p3%x(1)) &
    - p1%x(1) * (p2%x(3) * p3%t - p2%t * p3%x(3))
  eps123%x(3) = &
    + p1%t * (p2%x(1) * p3%x(2) - p2%x(2) * p3%x(1)) &
    + p1%x(1) * (p2%x(2) * p3%t - p2%t * p3%x(2)) &
    + p1%x(2) * (p2%t * p3%x(1) - p2%x(1) * p3%t)
end function pseudo_vector_vector

```

```

<Implementation of operations for vectors>+≡
pure function pseudo_vector_vec_mom (p1, p2, v) result (eps123)
  type(momentum), intent(in) :: p1, p2
  type(vector), intent(in) :: v
  type(vector) :: eps123
  eps123%t = &
    + p1%x(1) * (p2%x(2) * v%x(3) - p2%x(3) * v%x(2)) &
    + p1%x(2) * (p2%x(3) * v%x(1) - p2%x(1) * v%x(3)) &
    + p1%x(3) * (p2%x(1) * v%x(2) - p2%x(2) * v%x(1))
  eps123%x(1) = &
    + p1%x(2) * (p2%x(3) * v%t - p2%t * v%x(3)) &

```

```

+ p1%x(3) * (p2%t      * v%x(2) - p2%x(2) * v%t      ) &
+ p1%t      * (p2%x(2) * v%x(3) - p2%x(3) * v%x(2))
eps123%x(2) = &
- p1%x(3) * (p2%t      * v%x(1) - p2%x(1) * v%t      ) &
- p1%t      * (p2%x(1) * v%x(3) - p2%x(3) * v%x(1)) &
- p1%x(1) * (p2%x(3) * v%t      - p2%t      * v%x(3))
eps123%x(3) = &
+ p1%t      * (p2%x(1) * v%x(2) - p2%x(2) * v%x(1)) &
+ p1%x(1) * (p2%x(2) * v%t      - p2%t      * v%x(2)) &
+ p1%x(2) * (p2%t      * v%x(1) - p2%x(1) * v%t      )
end function pseudo_vector_vec_mom

```

#### X.4.9 Utilities

*<Declaration of operations for vectors>+≡*

*<Implementation of operations for vectors>+≡*

```

subroutine random_momentum (p, pabs, m)
  type(momentum), intent(out) :: p
  real(kind=default), intent(in) :: pabs, m
  real(kind=default), dimension(2) :: r
  real(kind=default) :: phi, cos_th
  call random_number (r)
  phi = 2*PI * r(1)
  cos_th = 2 * r(2) - 1
  p%t = sqrt (pabs**2 + m**2)
  p%x = pabs * (/ cos_th * cos(phi), cos_th * sin(phi), sqrt (1 - cos_th**2) /)
end subroutine random_momentum

```

#### X.5 Polarization vectors

*<omega\_polarizations.f90>≡*

*<Copleft>*

```

module omega_polarizations
  use kinds
  use constants
  use omega_vectors
  implicit none
  private
  <Declaration of polarization vectors>
  integer, parameter, public :: omega_polarizations_2010_01_A = 0
contains
  <Implementation of polarization vectors>
end module omega_polarizations

```

Here we use a phase convention for the polarization vectors compatible with the angular momentum coupling to spin 3/2 and spin 2.

$$\epsilon_1^\mu(k) = \frac{1}{|\vec{k}| \sqrt{k_x^2 + k_y^2}} (0; k_z k_x, k_y k_z, -k_x^2 - k_y^2) \quad (\text{X.12a})$$

$$\epsilon_2^\mu(k) = \frac{1}{\sqrt{k_x^2 + k_y^2}} (0; -k_y, k_x, 0) \quad (\text{X.12b})$$



$$\epsilon_3^\mu(k) = \frac{k_0}{m|\vec{k}|} \left( \vec{k}^2/k_0; k_x, k_y, k_z \right) \quad (\text{X.12c})$$

and

$$\epsilon_\pm^\mu(k) = \frac{1}{\sqrt{2}} (\epsilon_1^\mu(k) \pm i\epsilon_2^\mu(k)) \quad (\text{X.13a})$$

$$\epsilon_0^\mu(k) = \epsilon_3^\mu(k) \quad (\text{X.13b})$$

i. e.

$$\epsilon_+^\mu(k) = \frac{1}{\sqrt{2}\sqrt{k_x^2 + k_y^2}} \left( 0; \frac{k_z k_x}{|\vec{k}|} - ik_y, \frac{k_y k_z}{|\vec{k}|} + ik_x, -\frac{k_x^2 + k_y^2}{|\vec{k}|} \right) \quad (\text{X.14a})$$

$$\epsilon_-^\mu(k) = \frac{1}{\sqrt{2}\sqrt{k_x^2 + k_y^2}} \left( 0; \frac{k_z k_x}{|\vec{k}|} + ik_y, \frac{k_y k_z}{|\vec{k}|} - ik_x, -\frac{k_x^2 + k_y^2}{|\vec{k}|} \right) \quad (\text{X.14b})$$

$$\epsilon_0^\mu(k) = \frac{k_0}{m|\vec{k}|} \left( \vec{k}^2/k_0; k_x, k_y, k_z \right) \quad (\text{X.14c})$$

Determining the mass from the momenta is a numerically haphazardous for light particles. Therefore, we accept some redundancy and pass the mass explicitly.

*(Declaration of polarization vectors)*≡

```
public :: eps
```

*(Implementation of polarization vectors)*≡

```
pure function eps (m, k, s) result (e)
  type(vector) :: e
  real(kind=default), intent(in) :: m
  type(momentum), intent(in) :: k
  integer, intent(in) :: s
  real(kind=default) :: kt, kabs, kabs2, sqrt2
  sqrt2 = sqrt (2.0_default)
  kabs2 = dot_product (k%x, k%x)
  e%t = 0
  e%x = 0
  if (kabs2 > 0) then
    kabs = sqrt (kabs2)
    select case (s)
    case (1)
      kt = sqrt (k%x(1)**2 + k%x(2)**2)
      if (abs(kt) <= epsilon(kt) * kabs) then
        if (k%x(3) > 0) then
          e%x(1) = cmplx ( 1, 0, kind=default) / sqrt2
          e%x(2) = cmplx ( 0, 1, kind=default) / sqrt2
        else
          e%x(1) = cmplx (-1, 0, kind=default) / sqrt2
          e%x(2) = cmplx ( 0, 1, kind=default) / sqrt2
        end if
      else
        e%x(1) = cmplx ( k%x(3)*k%x(1)/kabs, &
          - k%x(2), kind=default) / kt / sqrt2
        e%x(2) = cmplx ( k%x(3)*k%x(2)/kabs, &
          k%x(1), kind=default) / kt / sqrt2
```

```

        e%x(3) = - kt / kabs / sqrt2
    end if
case (-1)
    kt = sqrt (k%x(1)**2 + k%x(2)**2)
    if (abs(kt) <= epsilon(kt) * kabs) then
        if (k%x(3) > 0) then
            e%x(1) = cmplx ( 1, 0, kind=default) / sqrt2
            e%x(2) = cmplx ( 0, - 1, kind=default) / sqrt2
        else
            e%x(1) = cmplx ( -1, 0, kind=default) / sqrt2
            e%x(2) = cmplx ( 0, - 1, kind=default) / sqrt2
        end if
    else
        e%x(1) = cmplx ( k%x(3)*k%x(1)/kabs, &
            k%x(2), kind=default) / kt / sqrt2
        e%x(2) = cmplx ( k%x(2)*k%x(3)/kabs, &
            - k%x(1), kind=default) / kt / sqrt2
        e%x(3) = - kt / kabs / sqrt2
    end if
case (0)
    if (m > 0) then
        e%t = kabs / m
        e%x = k%t / (m*kabs) * k%x
    end if
case (3)
    e = (0,1) * k
case (4)
    if (m > 0) then
        e = (1 / m) * k
    else
        e = (1 / k%t) * k
    end if
end select
else !!! for particles in their rest frame defined to be
    !!! polarized along the 3-direction
    select case (s)
    case (1)
        e%x(1) = cmplx ( 1, 0, kind=default) / sqrt2
        e%x(2) = cmplx ( 0, 1, kind=default) / sqrt2
    case (-1)
        e%x(1) = cmplx ( 1, 0, kind=default) / sqrt2
        e%x(2) = cmplx ( 0, - 1, kind=default) / sqrt2
    case (0)
        if (m > 0) then
            e%x(3) = 1
        end if
    case (4)
        if (m > 0) then
            e = (1 / m) * k
        else
            e = (1 / k%t) * k
        end if
    end select
end if
end if

```

```
end function eps
```

## X.6 Polarization vectors revisited

```
(omega_polarizations_madgraph.f90)≡
⟨Cotypeleft⟩
module omega_polarizations_madgraph
  use kinds
  use constants
  use omega_vectors
  implicit none
  private
  ⟨Declaration of polarization vectors for madgraph⟩
  integer, parameter, public :: omega_pols_madgraph_2010_01_A = 0
contains
  ⟨Implementation of polarization vectors for madgraph⟩
end module omega_polarizations_madgraph
```

This set of polarization vectors is compatible with HELAS [5]:

$$\epsilon_1^\mu(k) = \frac{1}{|\vec{k}|\sqrt{k_x^2 + k_y^2}} (0; k_z k_x, k_y k_z, -k_x^2 - k_y^2) \quad (\text{X.15a})$$

$$\epsilon_2^\mu(k) = \frac{1}{\sqrt{k_x^2 + k_y^2}} (0; -k_y, k_x, 0) \quad (\text{X.15b})$$

$$\epsilon_3^\mu(k) = \frac{k_0}{m|\vec{k}|} (\vec{k}^2/k_0; k_x, k_y, k_z) \quad (\text{X.15c})$$

and

$$\epsilon_\pm^\mu(k) = \frac{1}{\sqrt{2}} (\mp \epsilon_1^\mu(k) - i \epsilon_2^\mu(k)) \quad (\text{X.16a})$$

$$\epsilon_0^\mu(k) = \epsilon_3^\mu(k) \quad (\text{X.16b})$$

i. e.

$$\epsilon_+^\mu(k) = \frac{1}{\sqrt{2}\sqrt{k_x^2 + k_y^2}} \left( 0; -\frac{k_z k_x}{|\vec{k}|} + i k_y, -\frac{k_y k_z}{|\vec{k}|} - i k_x, \frac{k_x^2 + k_y^2}{|\vec{k}|} \right) \quad (\text{X.17a})$$

$$\epsilon_-^\mu(k) = \frac{1}{\sqrt{2}\sqrt{k_x^2 + k_y^2}} \left( 0; \frac{k_z k_x}{|\vec{k}|} + i k_y, \frac{k_y k_z}{|\vec{k}|} - i k_x, -\frac{k_x^2 + k_y^2}{|\vec{k}|} \right) \quad (\text{X.17b})$$

$$\epsilon_0^\mu(k) = \frac{k_0}{m|\vec{k}|} (\vec{k}^2/k_0; k_x, k_y, k_z) \quad (\text{X.17c})$$

Fortunately, for comparing with squared matrix generated by Madgraph we can also use the modified version, since the difference is only a phase and does *not* mix helicity states. Determining the mass from the momenta is a numerically haphazardous for light particles. Therefore, we accept some redundancy and pass the mass explicitly.

```
⟨Declaration of polarization vectors for madgraph⟩≡
  public :: eps
```

*(Implementation of polarization vectors for madgraph)*≡

```

pure function eps (m, k, s) result (e)
  type(vector) :: e
  real(kind=default), intent(in) :: m
  type(momentum), intent(in) :: k
  integer, intent(in) :: s
  real(kind=default) :: kt, kabs, kabs2, sqrt2
  sqrt2 = sqrt (2.0_default)
  kabs2 = dot_product (k%x, k%x)
  e%t = 0
  e%x = 0
  if (kabs2 > 0) then
    kabs = sqrt (kabs2)
    select case (s)
    case (1)
      kt = sqrt (k%x(1)**2 + k%x(2)**2)
      if (abs(kt) <= epsilon(kt) * kabs) then
        if (k%x(3) > 0) then
          e%x(1) = cmplx ( - 1, 0, kind=default) / sqrt2
          e%x(2) = cmplx ( 0, - 1, kind=default) / sqrt2
        else
          e%x(1) = cmplx ( 1, 0, kind=default) / sqrt2
          e%x(2) = cmplx ( 0, - 1, kind=default) / sqrt2
        end if
      else
        e%x(1) = cmplx ( - k%x(3)*k%x(1)/kabs, &
          k%x(2), kind=default) / kt / sqrt2
        e%x(2) = cmplx ( - k%x(2)*k%x(3)/kabs, &
          - k%x(1), kind=default) / kt / sqrt2
        e%x(3) = kt / kabs / sqrt2
      end if
    case (-1)
      kt = sqrt (k%x(1)**2 + k%x(2)**2)
      if (abs(kt) <= epsilon(kt) * kabs) then
        if (k%x(3) > 0) then
          e%x(1) = cmplx ( 1, 0, kind=default) / sqrt2
          e%x(2) = cmplx ( 0, - 1, kind=default) / sqrt2
        else
          e%x(1) = cmplx ( -1, 0, kind=default) / sqrt2
          e%x(2) = cmplx ( 0, - 1, kind=default) / sqrt2
        end if
      else
        e%x(1) = cmplx ( k%x(3)*k%x(1)/kabs, &
          k%x(2), kind=default) / kt / sqrt2
        e%x(2) = cmplx ( k%x(2)*k%x(3)/kabs, &
          - k%x(1), kind=default) / kt / sqrt2
        e%x(3) = - kt / kabs / sqrt2
      end if
    case (0)
      if (m > 0) then
        e%t = kabs / m
        e%x = k%t / (m*kabs) * k%x
      end if
    case (3)

```

```

        e = (0,1) * k
    case (4)
        if (m > 0) then
            e = (1 / m) * k
        else
            e = (1 / k%t) * k
        end if
    end select
else    !!! for particles in their rest frame defined to be
        !!! polarized along the 3-direction
    select case (s)
    case (1)
        e%x(1) = cmplx ( - 1, 0, kind=default) / sqrt2
        e%x(2) = cmplx ( 0, - 1, kind=default) / sqrt2
    case (-1)
        e%x(1) = cmplx ( 1, 0, kind=default) / sqrt2
        e%x(2) = cmplx ( 0, - 1, kind=default) / sqrt2
    case (0)
        if (m > 0) then
            e%x(3) = 1
        end if
    case (4)
        if (m > 0) then
            e = (1 / m) * k
        else
            e = (1 / k%t) * k
        end if
    end select
end if
end function eps

```

## X.7 Symmetric Tensors

Spin-2 polarization tensors are symmetric, transversal and traceless

$$\epsilon_m^{\mu\nu}(k) = \epsilon_m^{\nu\mu}(k) \quad (\text{X.18a})$$

$$k_\mu \epsilon_m^{\mu\nu}(k) = k_\nu \epsilon_m^{\mu\nu}(k) = 0 \quad (\text{X.18b})$$

$$\epsilon_{m,\mu}^\mu(k) = 0 \quad (\text{X.18c})$$

with  $m = 1, 2, 3, 4, 5$ . Our current representation is redundant and does *not* enforce symmetry or tracelessness.

```

<omega_tensors.f90>≡
<Cotypeleft>
module omega_tensors
    use kinds
    use constants
    use omega_vectors
    implicit none
    private
    public :: operator (*), operator (+), operator (-), &
            operator (.tprod.)
    public :: abs, conjg

```

```

    <intrinsic :: abs>
    <intrinsic :: conjg>
    type, public :: tensor
        ! private (omegalib needs access, but DON'T TOUCH IT!)
        complex(kind=default), dimension(0:3,0:3) :: t
    end type tensor
    <Declaration of operations for tensors>
    integer, parameter, public :: omega_tensors_2010_01_A = 0
contains
    <Implementation of operations for tensors>
end module omega_tensors

```

### X.7.1 Vector Space

#### Scalar Multiplication

```

<Declaration of operations for tensors>≡
    interface operator (*)
        module procedure integer_tensor, real_tensor, double_tensor, &
            complex_tensor, dcomplex_tensor
    end interface
    private :: integer_tensor, real_tensor, double_tensor
    private :: complex_tensor, dcomplex_tensor

<Implementation of operations for tensors>≡
    pure function integer_tensor (x, y) result (xy)
        integer, intent(in) :: x
        type(tensor), intent(in) :: y
        type(tensor) :: xy
        xy%t = x * y%t
    end function integer_tensor
    pure function real_tensor (x, y) result (xy)
        real(kind=single), intent(in) :: x
        type(tensor), intent(in) :: y
        type(tensor) :: xy
        xy%t = x * y%t
    end function real_tensor
    pure function double_tensor (x, y) result (xy)
        real(kind=default), intent(in) :: x
        type(tensor), intent(in) :: y
        type(tensor) :: xy
        xy%t = x * y%t
    end function double_tensor
    pure function complex_tensor (x, y) result (xy)
        complex(kind=single), intent(in) :: x
        type(tensor), intent(in) :: y
        type(tensor) :: xy
        xy%t = x * y%t
    end function complex_tensor
    pure function dcomplex_tensor (x, y) result (xy)
        complex(kind=default), intent(in) :: x
        type(tensor), intent(in) :: y
        type(tensor) :: xy
        xy%t = x * y%t
    end function dcomplex_tensor

```

*Addition and Subtraction*

```

<Declaration of operations for tensors>+≡
  interface operator (+)
    module procedure plus_tensor
  end interface
  private :: plus_tensor
  interface operator (-)
    module procedure neg_tensor
  end interface
  private :: neg_tensor

<Implementation of operations for tensors>+≡
  pure function plus_tensor (t1) result (t2)
    type(tensor), intent(in) :: t1
    type(tensor) :: t2
    t2 = t1
  end function plus_tensor
  pure function neg_tensor (t1) result (t2)
    type(tensor), intent(in) :: t1
    type(tensor) :: t2
    t2%t = - t1%t
  end function neg_tensor

<Declaration of operations for tensors>+≡
  interface operator (+)
    module procedure add_tensor
  end interface
  private :: add_tensor
  interface operator (-)
    module procedure sub_tensor
  end interface
  private :: sub_tensor

<Implementation of operations for tensors>+≡
  pure function add_tensor (x, y) result (xy)
    type(tensor), intent(in) :: x, y
    type(tensor) :: xy
    xy%t = x%t + y%t
  end function add_tensor
  pure function sub_tensor (x, y) result (xy)
    type(tensor), intent(in) :: x, y
    type(tensor) :: xy
    xy%t = x%t - y%t
  end function sub_tensor

<Declaration of operations for tensors>+≡
  interface operator (.tprod.)
    module procedure out_prod_vv, out_prod_vm, &
      out_prod_mv, out_prod_mm
  end interface
  private :: out_prod_vv, out_prod_vm, &
    out_prod_mv, out_prod_mm

<Implementation of operations for tensors>+≡
  pure function out_prod_vv (v, w) result (t)
    type(tensor) :: t

```

```

type(vector), intent(in) :: v, w
integer :: i, j
t%t(0,0) = v%t * w%t
t%t(0,1:3) = v%t * w%x
t%t(1:3,0) = v%x * w%t
do i = 1, 3
  do j = 1, 3
    t%t(i,j) = v%x(i) * w%x(j)
  end do
end do
end function out_prod_vv

<Implementation of operations for tensors>+≡
pure function out_prod_vm (v, m) result (t)
type(tensor) :: t
type(vector), intent(in) :: v
type(momentum), intent(in) :: m
integer :: i, j
t%t(0,0) = v%t * m%t
t%t(0,1:3) = v%t * m%x
t%t(1:3,0) = v%x * m%t
do i = 1, 3
  do j = 1, 3
    t%t(i,j) = v%x(i) * m%x(j)
  end do
end do
end function out_prod_vm

<Implementation of operations for tensors>+≡
pure function out_prod_mv (m, v) result (t)
type(tensor) :: t
type(vector), intent(in) :: v
type(momentum), intent(in) :: m
integer :: i, j
t%t(0,0) = m%t * v%t
t%t(0,1:3) = m%t * v%x
t%t(1:3,0) = m%x * v%t
do i = 1, 3
  do j = 1, 3
    t%t(i,j) = m%x(i) * v%x(j)
  end do
end do
end function out_prod_mv

<Implementation of operations for tensors>+≡
pure function out_prod_mm (m, n) result (t)
type(tensor) :: t
type(momentum), intent(in) :: m, n
integer :: i, j
t%t(0,0) = m%t * n%t
t%t(0,1:3) = m%t * n%x
t%t(1:3,0) = m%x * n%t
do i = 1, 3
  do j = 1, 3
    t%t(i,j) = m%x(i) * n%x(j)
  end do
end do

```



```

        end do
    end function out_prod_mm

<Declaration of operations for tensors>+≡
    interface abs
        module procedure abs_tensor
    end interface
    private :: abs_tensor

<Implementation of operations for tensors>+≡
    pure function abs_tensor (t) result (abs_t)
        type(tensor), intent(in) :: t
        real(kind=default) :: abs_t
        abs_t = sqrt (sum ((abs (t%t))*2))
    end function abs_tensor

<Declaration of operations for tensors>+≡
    interface conjg
        module procedure conjg_tensor
    end interface
    private :: conjg_tensor

<Implementation of operations for tensors>+≡
    pure function conjg_tensor (t) result (conjg_t)
        type(tensor), intent(in) :: t
        type(tensor) :: conjg_t
        conjg_t%t = conjg (t%t)
    end function conjg_tensor

<Declaration of operations for tensors>+≡
    interface operator (*)
        module procedure tensor_tensor, vector_tensor, tensor_vector, &
            momentum_tensor, tensor_momentum
    end interface
    private :: tensor_tensor, vector_tensor, tensor_vector, &
        momentum_tensor, tensor_momentum

<Implementation of operations for tensors>+≡
    pure function tensor_tensor (t1, t2) result (t1t2)
        type(tensor), intent(in) :: t1
        type(tensor), intent(in) :: t2
        complex(kind=default) :: t1t2
        integer :: i1, i2
        t1t2 = t1%t(0,0)*t2%t(0,0) &
            - dot_product (conjg (t1%t(0,1:)), t2%t(0,1:)) &
            - dot_product (conjg (t1%t(1:,0)), t2%t(1:,0))
        do i1 = 1, 3
            do i2 = 1, 3
                t1t2 = t1t2 + t1%t(i1,i2)*t2%t(i1,i2)
            end do
        end do
    end function tensor_tensor

<Implementation of operations for tensors>+≡
    pure function tensor_vector (t, v) result (tv)
        type(tensor), intent(in) :: t
        type(vector), intent(in) :: v
        type(vector) :: tv

```

```

    tv%t = t%t(0,0) * v%t - dot_product (conjg (t%t(0,1:)), v%x)
    tv%x(1) = t%t(0,1) * v%t - dot_product (conjg (t%t(1,1:)), v%x)
    tv%x(2) = t%t(0,2) * v%t - dot_product (conjg (t%t(2,1:)), v%x)
    tv%x(3) = t%t(0,3) * v%t - dot_product (conjg (t%t(3,1:)), v%x)
end function tensor_vector

```

*(Implementation of operations for tensors)+≡*

```

pure function vector_tensor (v, t) result (vt)
    type(vector), intent(in) :: v
    type(tensor), intent(in) :: t
    type(vector) :: vt
    vt%t = v%t * t%t(0,0) - dot_product (conjg (v%x), t%t(1:,0))
    vt%x(1) = v%t * t%t(0,1) - dot_product (conjg (v%x), t%t(1:,1))
    vt%x(2) = v%t * t%t(0,2) - dot_product (conjg (v%x), t%t(1:,2))
    vt%x(3) = v%t * t%t(0,3) - dot_product (conjg (v%x), t%t(1:,3))
end function vector_tensor

```

*(Implementation of operations for tensors)+≡*

```

pure function tensor_momentum (t, p) result (tp)
    type(tensor), intent(in) :: t
    type(momentum), intent(in) :: p
    type(vector) :: tp
    tp%t = t%t(0,0) * p%t - dot_product (conjg (t%t(0,1:)), p%x)
    tp%x(1) = t%t(0,1) * p%t - dot_product (conjg (t%t(1,1:)), p%x)
    tp%x(2) = t%t(0,2) * p%t - dot_product (conjg (t%t(2,1:)), p%x)
    tp%x(3) = t%t(0,3) * p%t - dot_product (conjg (t%t(3,1:)), p%x)
end function tensor_momentum

```

*(Implementation of operations for tensors)+≡*

```

pure function momentum_tensor (p, t) result (pt)
    type(momentum), intent(in) :: p
    type(tensor), intent(in) :: t
    type(vector) :: pt
    pt%t = p%t * t%t(0,0) - dot_product (p%x, t%t(1:,0))
    pt%x(1) = p%t * t%t(0,1) - dot_product (p%x, t%t(1:,1))
    pt%x(2) = p%t * t%t(0,2) - dot_product (p%x, t%t(1:,2))
    pt%x(3) = p%t * t%t(0,3) - dot_product (p%x, t%t(1:,3))
end function momentum_tensor

```

## X.8 Symmetric Polarization Tensors

$$\epsilon_{+2}^{\mu\nu}(k) = \epsilon_+^\mu(k)\epsilon_+^\nu(k) \quad (\text{X.19a})$$

$$\epsilon_{+1}^{\mu\nu}(k) = \frac{1}{\sqrt{2}} (\epsilon_+^\mu(k)\epsilon_0^\nu(k) + \epsilon_0^\mu(k)\epsilon_+^\nu(k)) \quad (\text{X.19b})$$

$$\epsilon_0^{\mu\nu}(k) = \frac{1}{\sqrt{6}} (\epsilon_+^\mu(k)\epsilon_-^\nu(k) + \epsilon_-^\mu(k)\epsilon_+^\nu(k) - 2\epsilon_0^\mu(k)\epsilon_0^\nu(k)) \quad (\text{X.19c})$$

$$\epsilon_{-1}^{\mu\nu}(k) = \frac{1}{\sqrt{2}} (\epsilon_-^\mu(k)\epsilon_0^\nu(k) + \epsilon_0^\mu(k)\epsilon_-^\nu(k)) \quad (\text{X.19d})$$

$$\epsilon_{-2}^{\mu\nu}(k) = \epsilon_-^\mu(k)\epsilon_-^\nu(k) \quad (\text{X.19e})$$

Note that  $\epsilon_{\pm 2, \mu}^{\mu}(k) = \epsilon_{\pm}^{\mu}(k)\epsilon_{\pm, \mu}(k) \propto \epsilon_{\pm}^{\mu}(k)\epsilon_{\mp, \mu}^*(k) = 0$  and that the sign in  $\epsilon_0^{\mu\nu}(k)$  insures its tracelessness<sup>1</sup>.

```

(omega_tensor_polarizations.f90)≡
  <Cotypeleft>
  module omega_tensor_polarizations
    use kinds
    use constants
    use omega_vectors
    use omega_tensors
    use omega_polarizations
    implicit none
    private
    <Declaration of polarization tensors>
    integer, parameter, public :: omega_tensor_pols_2010_01_A = 0
  contains
    <Implementation of polarization tensors>
  end module omega_tensor_polarizations

<Declaration of polarization tensors>≡
  public :: eps2

<Implementation of polarization tensors>≡
  pure function eps2 (m, k, s) result (t)
    type(tensor) :: t
    real(kind=default), intent(in) :: m
    type(momentum), intent(in) :: k
    integer, intent(in) :: s
    type(vector) :: ep, em, e0
    t%t = 0
    select case (s)
    case (2)
      ep = eps (m, k, 1)
      t = ep.tprod.ep
    case (1)
      ep = eps (m, k, 1)
      e0 = eps (m, k, 0)
      t = (1 / sqrt (2.0_default)) &
        * ((ep.tprod.e0) + (e0.tprod.ep))
    case (0)
      ep = eps (m, k, 1)
      e0 = eps (m, k, 0)
      em = eps (m, k, -1)
      t = (1 / sqrt (6.0_default)) &
        * ((ep.tprod.em) + (em.tprod.ep) - 2*(e0.tprod.e0))
    case (-1)
      e0 = eps (m, k, 0)
      em = eps (m, k, -1)
      t = (1 / sqrt (2.0_default)) &
        * ((em.tprod.e0) + (e0.tprod.em))
    case (-2)

```

<sup>1</sup> On the other hand, with the shift operator  $L_- |+\rangle = e^{i\phi} |0\rangle$  and  $L_- |0\rangle = e^{i\chi} |-\rangle$ , we find

$$L_-^2 |++\rangle = 2e^{2i\phi} |00\rangle + e^{i(\phi+\chi)} (|+-\rangle + |-+\rangle)$$

i. e.  $\chi - \phi = \pi$ , if we want to identify  $\epsilon_{-,0,+}^{\mu}$  with  $|-,0,+\rangle$ .

```

        em = eps (m, k, -1)
        t = em.tprod.em
    end select
end function eps2

```

## X.9 Couplings

```

⟨omega_couplings.f90⟩≡
  ⟨Copyleft⟩
  module omega_couplings
    use kinds
    use constants
    use omega_vectors
    use omega_tensors
    implicit none
    private
    ⟨Declaration of couplings⟩
    ⟨Declaration of propagators⟩
    integer, parameter, public :: omega_couplings_2010_01_A = 0
  contains
    ⟨Implementation of couplings⟩
    ⟨Implementation of propagators⟩
  end module omega_couplings

⟨Declaration of propagators⟩≡
  public :: wd_tl

⟨Declaration of propagators⟩+≡
  public :: gauss

```

$$\Theta(p^2)\Gamma \quad (X.20)$$

```

⟨Implementation of propagators⟩≡
  pure function wd_tl (p, w) result (width)
    real(kind=default) :: width
    type(momentum), intent(in) :: p
    real(kind=default), intent(in) :: w
    if (p*p > 0) then
      width = w
    else
      width = 0
    end if
  end function wd_tl

⟨Implementation of propagators⟩+≡
  pure function gauss (x, mu, w) result (gg)
    real(kind=default) :: gg
    real(kind=default), intent(in) :: x, mu, w
    if (w > 0) then
      gg = exp(-(x - mu**2)**2/4.0_default/mu**2/w**2) * &
        sqrt(sqrt(PI/2)) / w / mu
    else
      gg = 1.0_default
    end if
  end function gauss

```

*(Declaration of propagators)+≡*

```
public :: pr_phi, pr_unitarity, pr_feynman, pr_gauge, pr_rxi
public :: pj_phi, pj_unitarity
public :: pg_phi, pg_unitarity
```

$$\frac{i}{p^2 - m^2 + im\Gamma} \phi \quad (X.21)$$

*(Implementation of propagators)+≡*

```
pure function pr_phi (p, m, w, phi) result (pphi)
  complex(kind=default) :: pphi
  type(momentum), intent(in) :: p
  real(kind=default), intent(in) :: m, w
  complex(kind=default), intent(in) :: phi
  pphi = (1 / cmplx (p*p - m**2, m*w, kind=default)) * phi
end function pr_phi
```

$$\sqrt{\frac{\pi}{MT}} \phi \quad (X.22)$$

*(Implementation of propagators)+≡*

```
pure function pj_phi (m, w, phi) result (pphi)
  complex(kind=default) :: pphi
  real(kind=default), intent(in) :: m, w
  complex(kind=default), intent(in) :: phi
  pphi = (0, -1) * sqrt (PI / m / w) * phi
end function pj_phi
```

*(Implementation of propagators)+≡*

```
pure function pg_phi (p, m, w, phi) result (pphi)
  complex(kind=default) :: pphi
  type(momentum), intent(in) :: p
  real(kind=default), intent(in) :: m, w
  complex(kind=default), intent(in) :: phi
  pphi = ((0, 1) * gauss (p*p, m, w)) * phi
end function pg_phi
```

$$\frac{i}{p^2 - m^2 + im\Gamma} \left( -g_{\mu\nu} + \frac{p_\mu p_\nu}{m^2} \right) \epsilon^\nu(p) \quad (X.23)$$

NB: the explicit cast to `vector` is required here, because a specific `complex_momentum` procedure for `operator (*)` would introduce ambiguities. NB: we used to use the constructor `vector (p%t, p%x)` instead of the temporary variable, but the Intel Fortran Compiler choked on it.

*(Implementation of propagators)+≡*

```
pure function pr_unitarity (p, m, w, e) result (pe)
  type(vector) :: pe
  type(momentum), intent(in) :: p
  real(kind=default), intent(in) :: m, w
  type(vector), intent(in) :: e
  type(vector) :: pv
  pv = p
  pe = - (1 / cmplx (p*p - m**2, m*w, kind=default)) &
    * (e - (p*e / m**2) * pv)
end function pr_unitarity
```

$$\sqrt{\frac{\pi}{M\Gamma}} \left( -g_{\mu\nu} + \frac{p_\mu p_\nu}{m^2} \right) \epsilon^\nu(p) \quad (\text{X.24})$$

```

<Implementation of propagators>+≡
pure function pj_unitarity (p, m, w, e) result (pe)
  type(vector) :: pe
  type(momentum), intent(in) :: p
  real(kind=default), intent(in) :: m, w
  type(vector), intent(in) :: e
  type(vector) :: pv
  pv = p
  pe = (0, 1) * sqrt (PI / m / w) * (e - (p*e / m**2) * pv)
end function pj_unitarity

```

```

<Implementation of propagators>+≡
pure function pg_unitarity (p, m, w, e) result (pe)
  type(vector) :: pe
  type(momentum), intent(in) :: p
  real(kind=default), intent(in) :: m, w
  type(vector), intent(in) :: e
  type(vector) :: pv
  pv = p
  pe = - gauss (p*p, m, w) &
    * (e - (p*e / m**2) * pv)
end function pg_unitarity

```

$$\frac{-i}{p^2} \epsilon^\nu(p) \quad (\text{X.25})$$

```

<Implementation of propagators>+≡
pure function pr_feynman (p, e) result (pe)
  type(vector) :: pe
  type(momentum), intent(in) :: p
  type(vector), intent(in) :: e
  pe = - (1 / (p*p)) * e
end function pr_feynman

```

$$\frac{i}{p^2} \left( -g_{\mu\nu} + (1 - \xi) \frac{p_\mu p_\nu}{p^2} \right) \epsilon^\nu(p) \quad (\text{X.26})$$

```

<Implementation of propagators>+≡
pure function pr_gauge (p, xi, e) result (pe)
  type(vector) :: pe
  type(momentum), intent(in) :: p
  real(kind=default), intent(in) :: xi
  type(vector), intent(in) :: e
  real(kind=default) :: p2
  type(vector) :: pv
  p2 = p*p
  pv = p
  pe = - (1 / p2) * (e - ((1 - xi) * (p*e) / p2) * pv)
end function pr_gauge

```

$$\frac{i}{p^2 - m^2 + im\Gamma} \left( -g_{\mu\nu} + (1 - \xi) \frac{p_\mu p_\nu}{p^2 - \xi m^2} \right) \epsilon^\nu(p) \quad (\text{X.27})$$

```

<Implementation of propagators>+≡
pure function pr_rxi (p, m, w, xi, e) result (pe)
  type(vector) :: pe
  type(momentum), intent(in) :: p
  real(kind=default), intent(in) :: m, w, xi
  type(vector), intent(in) :: e
  real(kind=default) :: p2
  type(vector) :: pv
  p2 = p*p
  pv = p
  pe = - (1 / cmplx (p2 - m**2, m*w, kind=default)) &
        * (e - ((1 - xi) * (p*e) / (p2 - xi * m**2)) * pv)
end function pr_rxi

```

```

<Declaration of propagators>+≡
public :: pr_tensor

```

$$\frac{iP^{\mu\nu,\rho\sigma}(p, m)}{p^2 - m^2 + im\Gamma} T_{\rho\sigma} \quad (\text{X.28a})$$

with

$$P^{\mu\nu,\rho\sigma}(p, m) = \frac{1}{2} \left( g^{\mu\rho} - \frac{p^\mu p^\rho}{m^2} \right) \left( g^{\nu\sigma} - \frac{p^\nu p^\sigma}{m^2} \right) + \frac{1}{2} \left( g^{\mu\sigma} - \frac{p^\mu p^\sigma}{m^2} \right) \left( g^{\nu\rho} - \frac{p^\nu p^\rho}{m^2} \right) - \frac{1}{3} \left( g^{\mu\nu} - \frac{p^\mu p^\nu}{m^2} \right) \left( g^{\rho\sigma} - \frac{p^\rho p^\sigma}{m^2} \right) \quad (\text{X.28b})$$

Be careful with raising and lowering of indices:

$$g^{\mu\nu} - \frac{k^\mu k^\nu}{m^2} = \begin{pmatrix} 1 - k^0 k^0 / m^2 & -k^0 \vec{k} / m^2 \\ -\vec{k} k^0 / m^2 & -\mathbf{1} - \vec{k} \otimes \vec{k} / m^2 \end{pmatrix} \quad (\text{X.29a})$$

$$g^\mu{}_\nu - \frac{k^\mu k_\nu}{m^2} = \begin{pmatrix} 1 - k^0 k^0 / m^2 & k^0 \vec{k} / m^2 \\ -\vec{k} k^0 / m^2 & \mathbf{1} + \vec{k} \otimes \vec{k} / m^2 \end{pmatrix} \quad (\text{X.29b})$$

```

<Implementation of propagators>+≡
pure function pr_tensor (p, m, w, t) result (pt)
  type(tensor) :: pt
  type(momentum), intent(in) :: p
  real(kind=default), intent(in) :: m, w
  type(tensor), intent(in) :: t
  complex(kind=default) :: p_dd_t
  real(kind=default), dimension(0:3,0:3) :: p_uu, p_ud, p_du, p_dd
  integer :: i, j
  p_uu(0,0) = 1 - p%t * p%t / m**2
  p_uu(0,1:3) = - p%t * p%x / m**2
  p_uu(1:3,0) = p_uu(0,1:3)
  do i = 1, 3
    do j = 1, 3
      p_uu(i,j) = - p%x(i) * p%x(j) / m**2
    end do
  end do

```

```

        end do
    end do
    do i = 1, 3
        p_uu(i,i) = - 1 + p_uu(i,i)
    end do
    p_ud(:,0) = p_uu(:,0)
    p_ud(:,1:3) = - p_uu(:,1:3)
    p_du = transpose (p_ud)
    p_dd(:,0) = p_du(:,0)
    p_dd(:,1:3) = - p_du(:,1:3)
    p_dd_t = 0
    do i = 0, 3
        do j = 0, 3
            p_dd_t = p_dd_t + p_dd(i,j) * t%t(i,j)
        end do
    end do
    pt%t = matmul (p_ud, matmul (0.5_default * (t%t + transpose (t%t)), p_du)) &
        - (p_dd_t / 3.0_default) * p_uu
    pt%t = pt%t / cmplx (p*p - m**2, m*w, kind=default)
end function pr_tensor

```

### X.9.1 Triple Gauge Couplings

*(Declaration of couplings)*≡

```
public :: g_gg
```

According to (9.6c)

$$\begin{aligned}
 A^{a,\mu}(k_1 + k_2) = & -ig((k_1^\mu - k_2^\mu)A^{a_1}(k_1) \cdot A^{a_2}(k_2) \\
 & + (2k_2 + k_1) \cdot A^{a_1}(k_1)A^{a_2,\mu}(k_2) - A^{a_1,\mu}(k_1)A^{a_2}(k_2) \cdot (2k_1 + k_2)) \quad (X.30)
 \end{aligned}$$

*(Implementation of couplings)*≡

```

pure function g_gg (g, a1, k1, a2, k2) result (a)
    complex(kind=default), intent(in) :: g
    type(vector), intent(in) :: a1, a2
    type(momentum), intent(in) :: k1, k2
    type(vector) :: a
    a = (0, -1) * g * ((k1 - k2) * (a1 * a2) &
        + ((2*k2 + k1) * a1) * a2 - a1 * ((2*k1 + k2) * a2))
end function g_gg

```

### X.9.2 Quadruple Gauge Couplings

*(Declaration of couplings)*+≡

```
public :: x_gg, g_gx
```

$$T^{a,\mu\nu}(k_1 + k_2) = g(A^{a_1,\mu}(k_1)A^{a_2,\nu}(k_2) - A^{a_1,\nu}(k_1)A^{a_2,\mu}(k_2)) \quad (X.31)$$

*(Implementation of couplings)*+≡

```

pure function x_gg (g, a1, a2) result (x)
    complex(kind=default), intent(in) :: g
    type(vector), intent(in) :: a1, a2
    type(tensor2odd) :: x
    x = g * (a1 .wedge. a2)
end function x_gg

```



$$A^{a,\mu}(k_1 + k_2) = g A_\nu^{a_1}(k_1) T^{a_2, \nu\mu}(k_2) \quad (\text{X.32})$$

*(Implementation of couplings)+≡*  

```
pure function g_gx (g, a1, x) result (a)
  complex(kind=default), intent(in) :: g
  type(vector), intent(in) :: a1
  type(tensor2odd), intent(in) :: x
  type(vector) :: a
  a = g * (a1 * x)
end function g_gx
```

### X.9.3 Scalar Current

*(Declaration of couplings)+≡*  

```
public :: v_ss, s_vs
```

$$V^\mu(k_1 + k_2) = g(k_1^\mu - k_2^\mu) \phi_1(k_1) \phi_2(k_2) \quad (\text{X.33})$$

*(Implementation of couplings)+≡*  

```
pure function v_ss (g, phi1, k1, phi2, k2) result (v)
  complex(kind=default), intent(in) :: g, phi1, phi2
  type(momentum), intent(in) :: k1, k2
  type(vector) :: v
  v = (k1 - k2) * (g * phi1 * phi2)
end function v_ss
```

$$\phi(k_1 + k_2) = g(k_1^\mu + 2k_2^\mu) V_\mu(k_1) \phi(k_2) \quad (\text{X.34})$$

*(Implementation of couplings)+≡*  

```
pure function s_vs (g, v1, k1, phi2, k2) result (phi)
  complex(kind=default), intent(in) :: g, phi2
  type(vector), intent(in) :: v1
  type(momentum), intent(in) :: k1, k2
  complex(kind=default) :: phi
  phi = g * ((k1 + 2*k2) * v1) * phi2
end function s_vs
```

### X.9.4 Transversal Scalar-Vector Coupling

*(Declaration of couplings)+≡*  

```
public :: s_vv_t, v_sv_t
```

$$\phi(k_1 + k_2) = g((V_1(k_1) V_2(k_2))(k_1 k_2) - (V_1(k_1) k_2)(V_2(k_2) k_1)) \quad (\text{X.35})$$

*(Implementation of couplings)+≡*  

```
pure function s_vv_t (g, v1, k1, v2, k2) result (phi)
  complex(kind=default), intent(in) :: g
  type(vector), intent(in) :: v1, v2
  type(momentum), intent(in) :: k1, k2
  complex(kind=default) :: phi
  phi = g * ((v1*v2) * (k1*k2) - (v1*k2) * (v2*k1))
end function s_vv_t
```

$$V_1^\mu(k_\phi + k_V) = g\phi(((k_\phi + k_V)k_V)V_2^\mu - (k_\phi + k_V)V_2)k_V^\mu \quad (\text{X.36})$$

*(Implementation of couplings)*+≡  

```

pure function v_sv_t (g, phi, kphi,v, kv) result (vout)
  complex(kind=default), intent(in) :: g, phi
  type(vector), intent(in) :: v
  type(momentum), intent(in) :: kv, kphi
  type(momentum) :: kout
  type(vector) :: vout
  kout = - (kv + kphi)
  vout = g * phi * ((kout*kv) * v - (v * kout) * kv)
end function v_sv_t

```

### X.9.5 Triple Vector Couplings

*(Declaration of couplings)*+≡  

```

public :: tkv_vv, lkv_vv, tv_kv, lv_kv, kg_kgkg
public :: t5kv_vv, l5kv_vv, t5v_kv, l5v_kv, kg5_kgkg, kg_kg5kg

```

$$V^\mu(k_1 + k_2) = ig(k_1 - k_2)^\mu V_1^\nu(k_1)V_{2,\nu}(k_2) \quad (\text{X.37})$$

*(Implementation of couplings)*+≡  

```

pure function tkv_vv (g, v1, k1, v2, k2) result (v)
  complex(kind=default), intent(in) :: g
  type(vector), intent(in) :: v1, v2
  type(momentum), intent(in) :: k1, k2
  type(vector) :: v
  v = (k1 - k2) * ((0, 1) * g * (v1*v2))
end function tkv_vv

```

$$V^\mu(k_1 + k_2) = ig\epsilon^{\mu\nu\rho\sigma}(k_1 - k_2)_\nu V_{1,\rho}(k_1)V_{2,\sigma}(k_2) \quad (\text{X.38})$$

*(Implementation of couplings)*+≡  

```

pure function t5kv_vv (g, v1, k1, v2, k2) result (v)
  complex(kind=default), intent(in) :: g
  type(vector), intent(in) :: v1, v2
  type(momentum), intent(in) :: k1, k2
  type(vector) :: v
  type(vector) :: k
  k = k1 - k2
  v = (0, 1) * g * pseudo_vector (k, v1, v2)
end function t5kv_vv

```

$$V^\mu(k_1 + k_2) = ig(k_1 + k_2)^\mu V_1^\nu(k_1)V_{2,\nu}(k_2) \quad (\text{X.39})$$

*(Implementation of couplings)*+≡  

```

pure function lkv_vv (g, v1, k1, v2, k2) result (v)
  complex(kind=default), intent(in) :: g
  type(vector), intent(in) :: v1, v2
  type(momentum), intent(in) :: k1, k2
  type(vector) :: v
  v = (k1 + k2) * ((0, 1) * g * (v1*v2))
end function lkv_vv

```

$$V^\mu(k_1 + k_2) = ig\epsilon^{\mu\nu\rho\sigma}(k_1 + k_2)_\nu V_{1,\rho}(k_1)V_{2,\sigma}(k_2) \quad (\text{X.40})$$

*(Implementation of couplings)*+≡

```
pure function l5kv_vv (g, v1, k1, v2, k2) result (v)
  complex(kind=default), intent(in) :: g
  type(vector), intent(in) :: v1, v2
  type(momentum), intent(in) :: k1, k2
  type(vector) :: v
  type(vector) :: k
  k = k1 + k2
  v = (0, 1) * g * pseudo_vector (k, v1, v2)
end function l5kv_vv
```

$$V^\mu(k_1 + k_2) = ig(k_2 - k)^\nu V_{1,\nu}(k_1)V_2^\mu(k_2) = ig(2k_2 + k_1)^\nu V_{1,\nu}(k_1)V_2^\mu(k_2) \quad (\text{X.41})$$

using  $k = -k_1 - k_2$

*(Implementation of couplings)*+≡

```
pure function tv_kv (g, v1, k1, v2, k2) result (v)
  complex(kind=default), intent(in) :: g
  type(vector), intent(in) :: v1, v2
  type(momentum), intent(in) :: k1, k2
  type(vector) :: v
  v = v2 * ((0, 1) * g * ((2*k2 + k1)*v1))
end function tv_kv
```

$$V^\mu(k_1 + k_2) = ig\epsilon^{\mu\nu\rho\sigma}(2k_2 + k_1)_\nu V_{1,\rho}(k_1)V_{2,\sigma}(k_2) \quad (\text{X.42})$$

*(Implementation of couplings)*+≡

```
pure function t5v_kv (g, v1, k1, v2, k2) result (v)
  complex(kind=default), intent(in) :: g
  type(vector), intent(in) :: v1, v2
  type(momentum), intent(in) :: k1, k2
  type(vector) :: v
  type(vector) :: k
  k = k1 + 2*k2
  v = (0, 1) * g * pseudo_vector (k, v1, v2)
end function t5v_kv
```

$$V^\mu(k_1 + k_2) = -igk_1^\nu V_{1,\nu}(k_1)V_2^\mu(k_2) \quad (\text{X.43})$$

using  $k = -k_1 - k_2$

*(Implementation of couplings)*+≡

```
pure function lv_kv (g, v1, k1, v2) result (v)
  complex(kind=default), intent(in) :: g
  type(vector), intent(in) :: v1, v2
  type(momentum), intent(in) :: k1
  type(vector) :: v
  v = v2 * ((0, -1) * g * (k1*v1))
end function lv_kv
```

$$V^\mu(k_1 + k_2) = -ig\epsilon^{\mu\nu\rho\sigma}k_{1,\nu}V_{1,\rho}(k_1)V_{2,\sigma}(k_2) \quad (\text{X.44})$$

(Implementation of couplings)+≡

```
pure function l5v_kv (g, v1, k1, v2) result (v)
  complex(kind=default), intent(in) :: g
  type(vector), intent(in) :: v1, v2
  type(momentum), intent(in) :: k1
  type(vector) :: v
  type(vector) :: k
  k = k1
  v = (0, -1) * g * pseudo_vector (k, v1, v2)
end function l5v_kv
```

$$A^\mu(k_1 + k_2) = igk^\nu \left( F_{1,\nu}{}^\rho(k_1)F_{2,\rho\mu}(k_2) - F_{1,\mu}{}^\rho(k_1)F_{2,\rho\nu}(k_2) \right) \quad (\text{X.45})$$

with  $k = -k_1 - k_2$ , i. e.

$$\begin{aligned} A^\mu(k_1 + k_2) = -ig \bigg( & [(kk_2)(k_1A_2) - (k_1k_2)(kA_2)]A_1^\mu \\ & + [(k_1k_2)(kA_1) - (kk_1)(k_2A_1)]A_2^\mu \\ & + [(k_2A_1)(kA_2) - (kk_2)(A_1A_2)]k_1^\mu \\ & + [(kk_1)(A_1A_2) - (kA_1)(k_1A_2)]k_2^\mu \bigg) \quad (\text{X.46}) \end{aligned}$$

(Implementation of couplings)+≡

```
pure function kg_kgkg (g, a1, k1, a2, k2) result (a)
  complex(kind=default), intent(in) :: g
  type(vector), intent(in) :: a1, a2
  type(momentum), intent(in) :: k1, k2
  type(vector) :: a
  real(kind=default) :: k1k1, k2k2, k1k2, kk1, kk2
  complex(kind=default) :: a1a2, k2a1, ka1, k1a2, ka2
  k1k1 = k1 * k1
  k1k2 = k1 * k2
  k2k2 = k2 * k2
  kk1 = k1k1 + k1k2
  kk2 = k1k2 + k2k2
  k2a1 = k2 * a1
  ka1 = k2a1 + k1 * a1
  k1a2 = k1 * a2
  ka2 = k1a2 + k2 * a2
  a1a2 = a1 * a2
  a = (0, -1) * g * (
    (kk2 * k1a2 - k1k2 * ka2) * a1 &
    + (k1k2 * ka1 - kk1 * k2a1) * a2 &
    + (ka2 * k2a1 - kk2 * a1a2) * k1 &
    + (kk1 * a1a2 - ka1 * k1a2) * k2 )
end function kg_kgkg
```

$$A^\mu(k_1 + k_2) = ig\epsilon^{\mu\nu\rho\sigma}k_\nu F_{1,\rho}{}^\lambda(k_1)F_{2,\lambda\sigma}(k_2) \quad (\text{X.47})$$

with  $k = -k_1 - k_2$ , i. e.

$$A^\mu(k_1 + k_2) = -2ig\epsilon^{\mu\nu\rho\sigma}k_\nu \left( (k_2A_1)k_{1,\rho}A_{2,\sigma} + (k_1A_2)A_{1,\rho}k_{2,\sigma} \right)$$

$$- (A_1 A_2) k_{1,\rho} k_{2,\sigma} - (k_1 k_2) A_{1,\rho} A_{2,\sigma} \quad (\text{X.48})$$

*(Implementation of couplings)* +=

```
pure function kg5_kgkg (g, a1, k1, a2, k2) result (a)
  complex(kind=default), intent(in) :: g
  type(vector), intent(in) :: a1, a2
  type(momentum), intent(in) :: k1, k2
  type(vector) :: a
  type(vector) :: kv, k1v, k2v
  kv = - k1 - k2
  k1v = k1
  k2v = k2
  a = (0, -2) * g * (
    (k2*A1) * pseudo_vector (kv, k1v, a2 ) &
    + (k1*A2) * pseudo_vector (kv, A1 , k2v) &
    - (A1*A2) * pseudo_vector (kv, k1v, k2v) &
    - (k1*k2) * pseudo_vector (kv, a1 , a2 ) )
end function kg5_kgkg
```

$$A^\mu(k_1 + k_2) = ig k_\nu \left( \epsilon^{\mu\rho\lambda\sigma} F_{1,\rho}{}^\nu - \epsilon^{\nu\rho\lambda\sigma} F_{1,\rho}{}^\mu \right) \frac{1}{2} F_{1,\lambda\sigma} \quad (\text{X.49})$$

with  $k = -k_1 - k_2$ , i.e.

$$A^\mu(k_1+k_2) = -ig \left( \epsilon^{\mu\rho\lambda\sigma} (k k_2) A_{2,\rho} - \epsilon^{\mu\rho\lambda\sigma} (k A_2) k_{2,\rho} - k_2^\mu \epsilon^{\nu\rho\lambda\sigma} k_n u A_{2,\rho} + A_2^\mu \epsilon^{\nu\rho\lambda\sigma} k_n u k_{2,\rho} \right) k_{1,\lambda} A_{1,\sigma} \quad (\text{X.50})$$



This is not the most efficient way of doing it:  $\epsilon^{\mu\nu\rho\sigma} F_{1,\rho\sigma}$  should be cached!

*(Implementation of couplings)* +=

```
pure function kg_kg5kg (g, a1, k1, a2, k2) result (a)
  complex(kind=default), intent(in) :: g
  type(vector), intent(in) :: a1, a2
  type(momentum), intent(in) :: k1, k2
  type(vector) :: a
  type(vector) :: kv, k1v, k2v
  kv = - k1 - k2
  k1v = k1
  k2v = k2
  a = (0, -1) * g * (
    (kv*k2v) * pseudo_vector (a2 , k1v, a1) &
    - (kv*a2 ) * pseudo_vector (k2v, k1v, a1) &
    - k2v * pseudo_scalar (kv, a2, k1v, a1) &
    + a2 * pseudo_scalar (kv, k2v, k1v, a1) )
end function kg_kg5kg
```

## X.10 Graviton Couplings

*(Declaration of couplings)* +=

```
public :: s_gravs, v_gravv, grav_ss, grav_vv
```

*(Implementation of couplings)* +=

```
pure function s_gravs (g, m, k1, k2, t, s) result (phi)
  complex(kind=default), intent(in) :: g, s
  real(kind=default), intent(in) :: m
```

```

    type(momentum), intent(in) :: k1, k2
    type(tensor), intent(in) :: t
    complex(kind=default) :: phi, t_tr
    t_tr = t%(0,0) - t%(1,1) - t%(2,2) - t%(3,3)
    phi = g * s * (((t*k1)*k2) + ((t*k2)*k1) &
        - g * (m**2 + (k1*k2))*t_tr)/2.0_default
end function s_gravs

<Implementation of couplings>+=
pure function grav_ss (g, m, k1, k2, s1, s2) result (t)
    complex(kind=default), intent(in) :: g, s1, s2
    real(kind=default), intent(in) :: m
    type(momentum), intent(in) :: k1, k2
    type(tensor) :: t_metric, t
    t_metric%t = 0
    t_metric%t(0,0) = 1.0_default
    t_metric%t(1,1) = - 1.0_default
    t_metric%t(2,2) = - 1.0_default
    t_metric%t(3,3) = - 1.0_default
    t = g*s1*s2/2.0_default * (-m**2 + (k1*k2)) * t_metric &
        + (k1.tprod.k2) + (k2.tprod.k1))
end function grav_ss

<Implementation of couplings>+=
pure function v_gravv (g, m, k1, k2, t, v) result (vec)
    complex(kind=default), intent(in) :: g
    real(kind=default), intent(in) :: m
    type(momentum), intent(in) :: k1, k2
    type(vector), intent(in) :: v
    type(tensor), intent(in) :: t
    complex(kind=default) :: t_tr
    real(kind=default) :: xi
    type(vector) :: vec
    xi = 1.0_default
    t_tr = t%(0,0) - t%(1,1) - t%(2,2) - t%(3,3)
    vec = (-g)/ 2.0_default * (((k1*k2) + m**2) * &
        (t*v + v*t - t_tr * v) + t_tr * (k1*v) * k2 &
        - (k1*v) * ((k2*t) + (t*k2)) &
        - ((k1*(t*v)) + (v*(t*k1))) * k2 &
        + ((k1*(t*k2)) + (k2*(t*k1))) * v)
    !!!      Unitarity gauge: xi -> Infinity
    !!!      + (1.0_default/xi) * (t_tr * ((k1*v)*k2) + &
    !!!      (k2*v)*k2 + (k2*v)*k1 - (k1*(t*v))*k1 + &
    !!!      (k2*v)*(k2*t) - (v*(t*k1))*k1 - (k2*v)*(t*k2))
end function v_gravv

<Implementation of couplings>+=
pure function grav_vv (g, m, k1, k2, v1, v2) result (t)
    complex(kind=default), intent(in) :: g
    type(momentum), intent(in) :: k1, k2
    real(kind=default), intent(in) :: m
    real(kind=default) :: xi
    type(vector), intent (in) :: v1, v2
    type(tensor) :: t_metric, t
    xi = 0.00001_default
    t_metric%t = 0

```

```

t_metric%t(0,0) = 1.0_default
t_metric%t(1,1) = - 1.0_default
t_metric%t(2,2) = - 1.0_default
t_metric%t(3,3) = - 1.0_default
t = (-g)/2.0_default * ( &
    ((k1*k2) + m**2) * ( &
        (v1.tprod.v2) + (v2.tprod.v1) - (v1*v2) * t_metric) &
    + (v1*k2)*(v2*k1)*t_metric &
    - (k2*v1)*((v2.tprod.k1) + (k1.tprod.v2)) &
    - (k1*v2)*((v1.tprod.k2) + (k2.tprod.v1)) &
    + (v1*v2)*((k1.tprod.k2) + (k2.tprod.k1)))
!!!      Unitarity gauge: xi -> Infinity
!!!      + (1.0_default/xi) * ( &
!!!      ((k1*v1)*(k1*v2) + (k2*v1)*(k2*v2) + (k1*v1)*(k2*v2))* &
!!!      t_metric) - (k1*v1) * ((k1.tprod.v2) + (v2.tprod.k1)) &
!!!      - (k2*v2) * ((k2.tprod.v1) + (v1.tprod.k2)))
end function grav_vv

```

### X.11 Tensor Couplings

*(Declaration of couplings)+≡*  
public :: t2\_vv, v\_t2v, t2\_vv\_1, v\_t2v\_1, t2\_vv\_t, v\_t2v\_t

### X.12 Scalar-Vector Dim-5 Couplings

*(Declaration of couplings)+≡*  
public :: phi\_vv, v\_phiv, phi\_u\_vv, v\_u\_phiv

*(Implementation of couplings)+≡*  
pure function phi\_vv (g, k1, k2, v1, v2) result (phi)  
complex(kind=default), intent(in) :: g  
type(momentum), intent(in) :: k1, k2  
type(vector), intent(in) :: v1, v2  
complex(kind=default) :: phi  
phi = g \* pseudo\_scalar (k1, v1, k2, v2)  
end function phi\_vv

*(Implementation of couplings)+≡*  
pure function v\_phiv (g, phi, k1, k2, v) result (w)  
complex(kind=default), intent(in) :: g, phi  
type(vector), intent(in) :: v  
type(momentum), intent(in) :: k1, k2  
type(vector) :: w  
w = g \* phi \* pseudo\_vector (k1, k2, v)  
end function v\_phiv

*(Implementation of couplings)+≡*  
pure function phi\_u\_vv (g, k1, k2, v1, v2) result (phi)  
complex(kind=default), intent(in) :: g  
type(momentum), intent(in) :: k1, k2  
type(vector), intent(in) :: v1, v2  
complex(kind=default) :: phi  
phi = g \* ((k1\*v2)\*(-(k1+k2))\*v1) + &

```

        (k2*v1)*((-k1+k2))*v2) + &
        (((k1+k2)*(k1+k2)) * (v1*v2)))
end function phi_uv

<Implementation of couplings>+=
pure function v_u_phiv (g, phi, k1, k2, v) result (w)
  complex(kind=default), intent(in) :: g, phi
  type(vector), intent(in) :: v
  type(momentum), intent(in) :: k1, k2
  type(vector) :: w
  w = g * phi * ((k1*v)*k2 + &
    ((-k1+k2))*v)*k1 + &
    (k1*k1)*v))
end function v_u_phiv

<Implementation of couplings>+=
pure function t2_vv (g, v1, v2) result (t)
  complex(kind=default), intent(in) :: g
  type(vector), intent(in) :: v1, v2
  type(tensor) :: t
  type(tensor) :: tmp
  tmp = v1.tprod.v2
  t%t = g * (tmp%t + transpose (tmp%t))
end function t2_vv

<Implementation of couplings>+=
pure function v_t2v (g, t, v) result (tv)
  complex(kind=default), intent(in) :: g
  type(tensor), intent(in) :: t
  type(vector), intent(in) :: v
  type(vector) :: tv
  type(tensor) :: tmp
  tmp%t = t%t + transpose (t%t)
  tv = g * (tmp * v)
end function v_t2v

<Implementation of couplings>+=
pure function t2_vv_1 (g, v1, v2) result (t)
  complex(kind=default), intent(in) :: g
  complex(kind=default) :: tmp_s
  type(vector), intent(in) :: v1, v2
  type(tensor) :: tmp
  type(tensor) :: t_metric, t
  t_metric%t = 0
  t_metric%t(0,0) = 1.0_default
  t_metric%t(1,1) = - 1.0_default
  t_metric%t(2,2) = - 1.0_default
  t_metric%t(3,3) = - 1.0_default
  tmp = v1.tprod.v2
  tmp_s = v1 * v2
  t%t = g * (tmp%t + transpose (tmp%t) - tmp_s * t_metric%t)
end function t2_vv_1

<Implementation of couplings>+=
pure function v_t2v_1 (g, t, v) result (tv)
  complex(kind=default), intent(in) :: g
  type(tensor), intent(in) :: t

```



```

    type(vector), intent(in) :: v
    type(vector) :: tv, tmp_tv
    type(tensor) :: tmp
    tmp_tv = ( t%t(0,0)-t%t(1,1)-t%t(2,2)-t%t(3,3) ) * v
    tmp%t = t%t + transpose (t%t)
    tv = g * (tmp * v - tmp_tv)
end function v_t2v_1

<Implementation of couplings>+=
pure function t2_vv_t (g, v1, k1, v2, k2) result (t)
    complex(kind=default), intent(in) :: g
    complex(kind=default) :: tmp_s
    type(vector), intent(in) :: v1, v2
    type(momentum), intent(in) :: k1, k2
    type(tensor) :: tmp, tmp_v1k2, tmp_v2k1, tmp_k1k2, tmp2
    type(tensor) :: t_metric, t
    t_metric%t = 0
    t_metric%t(0,0) = 1.0_default
    t_metric%t(1,1) = - 1.0_default
    t_metric%t(2,2) = - 1.0_default
    t_metric%t(3,3) = - 1.0_default
    tmp = v1.tprod.v2
    tmp_s = v1 * v2
    tmp_v1k2 = (v2 * k1) * (v1.tprod.k2)
    tmp_v2k1 = (v1 * k2) * (v2.tprod.k1)
    tmp_k1k2 = tmp_s * (k1.tprod.k2)
    tmp2%t = tmp_v1k2%t + tmp_v2k1%t - tmp_k1k2%t
    t%t = g * ( (k1*k2) * (tmp%t + transpose (tmp%t) - tmp_s * t_metric%t ) &
        + ((v1 * k2) * (v2 * k1)) * t_metric%t &
        - tmp2%t - transpose(tmp2%t))
end function t2_vv_t

<Implementation of couplings>+=
pure function v_t2v_t (g, t, kt, v, kv) result (tv)
    complex(kind=default), intent(in) :: g
    type(tensor), intent(in) :: t
    type(vector), intent(in) :: v
    type(momentum), intent(in) :: kt, kv
    type(momentum) :: kout
    type(vector) :: tv, tmp_tv
    type(tensor) :: tmp
    kout = - (kt + kv)
    tmp_tv = ( t%t(0,0)-t%t(1,1)-t%t(2,2)-t%t(3,3) ) * v
    tmp%t = t%t + transpose (t%t)
    tv = g * ( (tmp * v - tmp_tv) * (kv * kout) &
        + ( t%t(0,0)-t%t(1,1)-t%t(2,2)-t%t(3,3) ) * (kout * v ) * kv &
        - (kout * v) * ( tmp * kv) &
        - (v* (t * kout) + kout * (t * v)) * kv &
        + (kout* (t * kv) + kv * (t * kout)) * v)
end function v_t2v_t

<Declaration of couplings>+=
public :: t2_vv_d5_1, v_t2v_d5_1

<Implementation of couplings>+=
pure function t2_vv_d5_1 (g, v1, k1, v2, k2) result (t)

```

```

        complex(kind=default), intent(in) :: g
        type(vector), intent(in) :: v1, v2
        type(momentum), intent(in) :: k1, k2
        type(tensor) :: t
        t = (g * (v1 * v2)) * (k1-k2).tprod.(k1-k2)
    end function t2_vv_d5_1

<Implementation of couplings>+≡
    pure function v_t2v_d5_1 (g, t1, k1, v2, k2) result (tv)
        complex(kind=default), intent(in) :: g
        type(tensor), intent(in) :: t1
        type(vector), intent(in) :: v2
        type(momentum), intent(in) :: k1, k2
        type(vector) :: tv
        tv = (g * ((k1+2*k2).tprod.(k1+2*k2) * t1)) * v2
    end function v_t2v_d5_1

<Declaration of couplings>+≡
    public :: t2_vv_d5_2, v_t2v_d5_2

<Implementation of couplings>+≡
    pure function t2_vv_d5_2 (g, v1, k1, v2, k2) result (t)
        complex(kind=default), intent(in) :: g
        type(vector), intent(in) :: v1, v2
        type(momentum), intent(in) :: k1, k2
        type(tensor) :: t
        t = (g * (k2 * v1)) * (k2-k1).tprod.v2
        t%t = t%t + transpose (t%t)
    end function t2_vv_d5_2

<Implementation of couplings>+≡
    pure function v_t2v_d5_2 (g, t1, k1, v2, k2) result (tv)
        complex(kind=default), intent(in) :: g
        type(tensor), intent(in) :: t1
        type(vector), intent(in) :: v2
        type(momentum), intent(in) :: k1, k2
        type(vector) :: tv
        type(tensor) :: tmp
        type(momentum) :: k1_k2, k1_2k2
        k1_k2 = k1 + k2
        k1_2k2 = k1_k2 + k2
        tmp%t = t1%t + transpose (t1%t)
        tv = (g * (k1_k2 * v2)) * (k1_2k2 * tmp)
    end function v_t2v_d5_2

<Declaration of couplings>+≡
    public :: t2_vv_d7, v_t2v_d7

<Implementation of couplings>+≡
    pure function t2_vv_d7 (g, v1, k1, v2, k2) result (t)
        complex(kind=default), intent(in) :: g
        type(vector), intent(in) :: v1, v2
        type(momentum), intent(in) :: k1, k2
        type(tensor) :: t
        t = (g * (k2 * v1) * (k1 * v2)) * (k1-k2).tprod.(k1-k2)
    end function t2_vv_d7

```

```

<Implementation of couplings>+=
pure function v_t2v_d7 (g, t1, k1, v2, k2) result (tv)
  complex(kind=default), intent(in) :: g
  type(tensor), intent(in) :: t1
  type(vector), intent(in) :: v2
  type(momentum), intent(in) :: k1, k2
  type(vector) :: tv
  type(vector) :: k1_k2, k1_2k2
  k1_k2 = k1 + k2
  k1_2k2 = k1_k2 + k2
  tv = (- g * (k1_k2 * v2) * (k1_2k2.tprod.k1_2k2 * t1)) * k2
end function v_t2v_d7

```

### X.13 Spinor Couplings

```

<omega_spinor_couplings.f90>=
<Copyleft>
module omega_spinor_couplings
  use kinds
  use constants
  use omega_spinors
  use omega_vectors
  use omega_tensors
  use omega_couplings
  implicit none
  private
  <Declaration of spinor on shell wave functions>
  <Declaration of spinor off shell wave functions>
  <Declaration of spinor currents>
  <Declaration of spinor propagators>
  integer, parameter, public :: omega_spinor_cppls_2010_01_A = 0
contains
  <Implementation of spinor on shell wave functions>
  <Implementation of spinor off shell wave functions>
  <Implementation of spinor currents>
  <Implementation of spinor propagators>
end module omega_spinor_couplings

```

See table X.1 for the names of Fortran functions. We could have used long names instead, but this would increase the chance of running past continuation line limits without adding much to the legibility.

#### X.13.1 Fermionic Vector and Axial Couplings

There's more than one chiral representation. This one is compatible with HELAS [5].

$$\gamma^0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix}, \gamma_5 = i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \quad (\text{X.51})$$

$\bar{\psi}(g_V\gamma^\mu - g_A\gamma^\mu\gamma_5)\psi$	<code>va_ff</code> ( $g_V, g_A, \bar{\psi}, \psi$ )
$g_V\bar{\psi}\gamma^\mu\psi$	<code>v_ff</code> ( $g_V, \bar{\psi}, \psi$ )
$g_A\bar{\psi}\gamma_5\gamma^\mu\psi$	<code>a_ff</code> ( $g_A, \bar{\psi}, \psi$ )
$g_L\bar{\psi}\gamma^\mu(1 - \gamma_5)\psi$	<code>vl_ff</code> ( $g_L, \bar{\psi}, \psi$ )
$g_R\bar{\psi}\gamma^\mu(1 + \gamma_5)\psi$	<code>vr_ff</code> ( $g_R, \bar{\psi}, \psi$ )
$\bar{\psi}(g_V - g_A\gamma_5)\psi$	<code>f_vaf</code> ( $g_V, g_A, V, \psi$ )
$g_V\bar{\psi}\psi$	<code>f_vf</code> ( $g_V, V, \psi$ )
$g_A\bar{\psi}\gamma_5\psi$	<code>f_af</code> ( $g_A, V, \psi$ )
$g_L\bar{\psi}(1 - \gamma_5)\psi$	<code>f_vlf</code> ( $g_L, V, \psi$ )
$g_R\bar{\psi}(1 + \gamma_5)\psi$	<code>f_vrf</code> ( $g_R, V, \psi$ )
$\bar{\psi}\bar{V}(g_V - g_A\gamma_5)\psi$	<code>f_fva</code> ( $g_V, g_A, \bar{\psi}, V$ )
$g_V\bar{\psi}\bar{V}$	<code>f_fv</code> ( $g_V, \bar{\psi}, V$ )
$g_A\bar{\psi}\gamma_5\bar{V}$	<code>f_fa</code> ( $g_A, \bar{\psi}, V$ )
$g_L\bar{\psi}\bar{V}(1 - \gamma_5)$	<code>f_fvl</code> ( $g_L, \bar{\psi}, V$ )
$g_R\bar{\psi}\bar{V}(1 + \gamma_5)$	<code>f_fvr</code> ( $g_R, \bar{\psi}, V$ )

Table X.1: Mnemonically abbreviated names of Fortran functions implementing fermionic vector and axial currents.

Therefore

$$g_S + g_P\gamma_5 = \begin{pmatrix} g_S - g_P & 0 & 0 & 0 \\ 0 & g_S - g_P & 0 & 0 \\ 0 & 0 & g_S + g_P & 0 \\ 0 & 0 & 0 & g_S + g_P \end{pmatrix} \quad (\text{X.52a})$$

$$g_V\gamma^0 - g_A\gamma^0\gamma_5 = \begin{pmatrix} 0 & 0 & g_V - g_A & 0 \\ 0 & 0 & 0 & g_V - g_A \\ g_V + g_A & 0 & 0 & 0 \\ 0 & g_V + g_A & 0 & 0 \end{pmatrix} \quad (\text{X.52b})$$

$$g_V\gamma^1 - g_A\gamma^1\gamma_5 = \begin{pmatrix} 0 & 0 & 0 & g_V - g_A \\ 0 & 0 & g_V - g_A & 0 \\ 0 & -g_V - g_A & 0 & 0 \\ -g_V - g_A & 0 & 0 & 0 \end{pmatrix} \quad (\text{X.52c})$$

$$g_V\gamma^2 - g_A\gamma^2\gamma_5 = \begin{pmatrix} 0 & 0 & 0 & -i(g_V - g_A) \\ 0 & 0 & i(g_V - g_A) & 0 \\ 0 & i(g_V + g_A) & 0 & 0 \\ -i(g_V + g_A) & 0 & 0 & 0 \end{pmatrix} \quad (\text{X.52d})$$

$$g_V\gamma^3 - g_A\gamma^3\gamma_5 = \begin{pmatrix} 0 & 0 & g_V - g_A & 0 \\ 0 & 0 & 0 & -g_V + g_A \\ -g_V - g_A & 0 & 0 & 0 \\ 0 & g_V + g_A & 0 & 0 \end{pmatrix} \quad (\text{X.52e})$$

*(Declaration of spinor currents)*≡

```
public :: va_ff, v_ff, a_ff, vl_ff, vr_ff, vlr_ff, grav_ff, va2_ff, &
         tva_ff, tlr_ff, trl_ff, tvam_ff, tlrn_ff, trlm_ff, va3_ff
```

*(Implementation of spinor currents)*≡

$\bar{\psi}(g_S + g_P\gamma_5)\psi$	<code>sp_ff(<math>g_S, g_P, \bar{\psi}, \psi</math>)</code>
$g_S\bar{\psi}\psi$	<code>s_ff(<math>g_S, \bar{\psi}, \psi</math>)</code>
$g_P\bar{\psi}\gamma_5\psi$	<code>p_ff(<math>g_P, \bar{\psi}, \psi</math>)</code>
$g_L\bar{\psi}(1 - \gamma_5)\psi$	<code>sl_ff(<math>g_L, \bar{\psi}, \psi</math>)</code>
$g_R\bar{\psi}(1 + \gamma_5)\psi$	<code>sr_ff(<math>g_R, \bar{\psi}, \psi</math>)</code>
$\phi(g_S + g_P\gamma_5)\psi$	<code>f_spf(<math>g_S, g_P, \phi, \psi</math>)</code>
$g_S\phi\psi$	<code>f_sf(<math>g_S, \phi, \psi</math>)</code>
$g_P\phi\gamma_5\psi$	<code>f_pf(<math>g_P, \phi, \psi</math>)</code>
$g_L\phi(1 - \gamma_5)\psi$	<code>f_slf(<math>g_L, \phi, \psi</math>)</code>
$g_R\phi(1 + \gamma_5)\psi$	<code>f_srf(<math>g_R, \phi, \psi</math>)</code>
$\psi\phi(g_S + g_P\gamma_5)$	<code>f_fsp(<math>g_S, g_P, \psi, \phi</math>)</code>
$g_S\psi\phi$	<code>f_fs(<math>g_S, \psi, \phi</math>)</code>
$g_P\psi\phi\gamma_5$	<code>f_fp(<math>g_P, \psi, \phi</math>)</code>
$g_L\psi\phi(1 - \gamma_5)$	<code>f_fsl(<math>g_L, \psi, \phi</math>)</code>
$g_R\psi\phi(1 + \gamma_5)$	<code>f_fsr(<math>g_R, \psi, \phi</math>)</code>

Table X.2: Mnemonically abbreviated names of Fortran functions implementing fermionic scalar and pseudo scalar “currents”.

```

pure function va_ff (gv, ga, psibar, psi) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: gv, ga
  type(conjspinor), intent(in) :: psibar
  type(spinor), intent(in) :: psi
  complex(kind=default) :: gl, gr
  complex(kind=default) :: g13, g14, g23, g24, g31, g32, g41, g42
  gl = gv + ga
  gr = gv - ga
  g13 = psibar%a(1)*psi%a(3)
  g14 = psibar%a(1)*psi%a(4)
  g23 = psibar%a(2)*psi%a(3)
  g24 = psibar%a(2)*psi%a(4)
  g31 = psibar%a(3)*psi%a(1)
  g32 = psibar%a(3)*psi%a(2)
  g41 = psibar%a(4)*psi%a(1)
  g42 = psibar%a(4)*psi%a(2)
  j%t = gr * ( g13 + g24) + gl * ( g31 + g42)
  j%x(1) = gr * ( g14 + g23) - gl * ( g32 + g41)
  j%x(2) = (gr * ( - g14 + g23) + gl * ( g32 - g41)) * (0, 1)
  j%x(3) = gr * ( g13 - g24) + gl * ( - g31 + g42)
end function va_ff

```

(Implementation of spinor currents)+≡

```

pure function va2_ff (gva, psibar, psi) result (j)
  type(vector) :: j
  complex(kind=default), intent(in), dimension(2) :: gva
  type(conjspinor), intent(in) :: psibar
  type(spinor), intent(in) :: psi
  complex(kind=default) :: gl, gr
  complex(kind=default) :: g13, g14, g23, g24, g31, g32, g41, g42
  gl = gva(1) + gva(2)

```

```

gr = gva(1) - gva(2)
g13 = psibar%a(1)*psi%a(3)
g14 = psibar%a(1)*psi%a(4)
g23 = psibar%a(2)*psi%a(3)
g24 = psibar%a(2)*psi%a(4)
g31 = psibar%a(3)*psi%a(1)
g32 = psibar%a(3)*psi%a(2)
g41 = psibar%a(4)*psi%a(1)
g42 = psibar%a(4)*psi%a(2)
j%t = gr * ( g13 + g24) + gl * ( g31 + g42)
j%x(1) = gr * ( g14 + g23) - gl * ( g32 + g41)
j%x(2) = (gr * ( - g14 + g23) + gl * ( g32 - g41)) * (0, 1)
j%x(3) = gr * ( g13 - g24) + gl * ( - g31 + g42)
end function va2_ff

(Implementation of spinor currents)+≡
pure function va3_ff (gv, ga, psibar, psi) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: gv, ga
  type(conjspinor), intent(in) :: psibar
  type(spinor), intent(in) :: psi
  j = va_ff (gv, ga, psibar, psi)
  j%t = 0.0_default
end function va3_ff

(Implementation of spinor currents)+≡
pure function tva_ff (gv, ga, psibar, psi) result (t)
  type(tensor2odd) :: t
  complex(kind=default), intent(in) :: gv, ga
  type(conjspinor), intent(in) :: psibar
  type(spinor), intent(in) :: psi
  complex(kind=default) :: gl, gr
  complex(kind=default) :: g12, g21, g1m2, g34, g43, g3m4
  gr = gv + ga
  gl = gv - ga
  g12 = psibar%a(1)*psi%a(2)
  g21 = psibar%a(2)*psi%a(1)
  g1m2 = psibar%a(1)*psi%a(1) - psibar%a(2)*psi%a(2)
  g34 = psibar%a(3)*psi%a(4)
  g43 = psibar%a(4)*psi%a(3)
  g3m4 = psibar%a(3)*psi%a(3) - psibar%a(4)*psi%a(4)
  t%e(1) = (gl * ( - g12 - g21) + gr * ( g34 + g43)) * (0, 1)
  t%e(2) = gl * ( - g12 + g21) + gr * ( g34 - g43)
  t%e(3) = (gl * ( - g1m2 ) + gr * ( g3m4 )) * (0, 1)
  t%b(1) = gl * ( g12 + g21) + gr * ( g34 + g43)
  t%b(2) = (gl * ( - g12 + g21) + gr * ( - g34 + g43)) * (0, 1)
  t%b(3) = gl * ( g1m2 ) + gr * ( g3m4 )
end function tva_ff

(Implementation of spinor currents)+≡
pure function tlr_ff (gl, gr, psibar, psi) result (t)
  type(tensor2odd) :: t
  complex(kind=default), intent(in) :: gl, gr
  type(conjspinor), intent(in) :: psibar
  type(spinor), intent(in) :: psi
  t = tva_ff (gr+gl, gr-gl, psibar, psi)

```

```

end function tlr_ff

<Implementation of spinor currents>+=
pure function trl_ff (gr, gl, psibar, psi) result (t)
  type(tensor2odd) :: t
  complex(kind=default), intent(in) :: gl, gr
  type(conjspinor), intent(in) :: psibar
  type(spinor), intent(in) :: psi
  t = tva_ff (gr+gl, gr-gl, psibar, psi)
end function trl_ff

<Implementation of spinor currents>+=
pure function tvam_ff (gv, ga, psibar, psi, p) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: gv, ga
  type(conjspinor), intent(in) :: psibar
  type(spinor), intent(in) :: psi
  type(momentum), intent(in) :: p
  j = (tva_ff(gv, ga, psibar, psi) * p) * (0,1)
end function tvam_ff

<Implementation of spinor currents>+=
pure function tlrm_ff (gl, gr, psibar, psi, p) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: gl, gr
  type(conjspinor), intent(in) :: psibar
  type(spinor), intent(in) :: psi
  type(momentum), intent(in) :: p
  j = tvam_ff (gr+gl, gr-gl, psibar, psi, p)
end function tlrm_ff

<Implementation of spinor currents>+=
pure function trlm_ff (gr, gl, psibar, psi, p) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: gl, gr
  type(conjspinor), intent(in) :: psibar
  type(spinor), intent(in) :: psi
  type(momentum), intent(in) :: p
  j = tvam_ff (gr+gl, gr-gl, psibar, psi, p)
end function trlm_ff

Special cases that avoid some multiplications

<Implementation of spinor currents>+=
pure function v_ff (gv, psibar, psi) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: gv
  type(conjspinor), intent(in) :: psibar
  type(spinor), intent(in) :: psi
  complex(kind=default) :: g13, g14, g23, g24, g31, g32, g41, g42
  g13 = psibar%a(1)*psi%a(3)
  g14 = psibar%a(1)*psi%a(4)
  g23 = psibar%a(2)*psi%a(3)
  g24 = psibar%a(2)*psi%a(4)
  g31 = psibar%a(3)*psi%a(1)
  g32 = psibar%a(3)*psi%a(2)
  g41 = psibar%a(4)*psi%a(1)
  g42 = psibar%a(4)*psi%a(2)

```

```

j%t    =   gv * (   g13 + g24 + g31 + g42)
j%x(1) =   gv * (   g14 + g23 - g32 - g41)
j%x(2) =   gv * ( - g14 + g23 + g32 - g41) * (0, 1)
j%x(3) =   gv * (   g13 - g24 - g31 + g42)
end function v_ff

```

*(Implementation of spinor currents)+≡*

```

pure function a_ff (ga, psibar, psi) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: ga
  type(conjspinor), intent(in) :: psibar
  type(spinor), intent(in) :: psi
  complex(kind=default) :: g13, g14, g23, g24, g31, g32, g41, g42
  g13 = psibar%a(1)*psi%a(3)
  g14 = psibar%a(1)*psi%a(4)
  g23 = psibar%a(2)*psi%a(3)
  g24 = psibar%a(2)*psi%a(4)
  g31 = psibar%a(3)*psi%a(1)
  g32 = psibar%a(3)*psi%a(2)
  g41 = psibar%a(4)*psi%a(1)
  g42 = psibar%a(4)*psi%a(2)
  j%t    =   ga * ( - g13 - g24 + g31 + g42)
  j%x(1) = - ga * (   g14 + g23 + g32 + g41)
  j%x(2) =   ga * (   g14 - g23 + g32 - g41) * (0, 1)
  j%x(3) =   ga * ( - g13 + g24 - g31 + g42)
end function a_ff

```

*(Implementation of spinor currents)+≡*

```

pure function vl_ff (gl, psibar, psi) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: gl
  type(conjspinor), intent(in) :: psibar
  type(spinor), intent(in) :: psi
  complex(kind=default) :: gl2
  complex(kind=default) :: g31, g32, g41, g42
  gl2 = 2 * gl
  g31 = psibar%a(3)*psi%a(1)
  g32 = psibar%a(3)*psi%a(2)
  g41 = psibar%a(4)*psi%a(1)
  g42 = psibar%a(4)*psi%a(2)
  j%t    =   gl2 * (   g31 + g42)
  j%x(1) = - gl2 * (   g32 + g41)
  j%x(2) =   gl2 * (   g32 - g41) * (0, 1)
  j%x(3) =   gl2 * ( - g31 + g42)
end function vl_ff

```

*(Implementation of spinor currents)+≡*

```

pure function vr_ff (gr, psibar, psi) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: gr
  type(conjspinor), intent(in) :: psibar
  type(spinor), intent(in) :: psi
  complex(kind=default) :: gr2
  complex(kind=default) :: g13, g14, g23, g24
  gr2 = 2 * gr
  g13 = psibar%a(1)*psi%a(3)

```



```

g14 = psibar%a(1)*psi%a(4)
g23 = psibar%a(2)*psi%a(3)
g24 = psibar%a(2)*psi%a(4)
j%t   = gr2 * ( g13 + g24)
j%x(1) = gr2 * ( g14 + g23)
j%x(2) = gr2 * ( - g14 + g23) * (0, 1)
j%x(3) = gr2 * ( g13 - g24)
end function vr_ff

```

*(Implementation of spinor currents)*+≡

```

pure function grav_ff (g, m, kb, k, psibar, psi) result (j)
  type(tensor) :: j
  complex(kind=default), intent(in) :: g
  real(kind=default), intent(in) :: m
  type(conjspinor), intent(in) :: psibar
  type(spinor), intent(in) :: psi
  type(momentum), intent(in) :: kb, k
  complex(kind=default) :: g2, g8, c_dum
  type(vector) :: v_dum
  type(tensor) :: t_metric
  t_metric%t = 0
  t_metric%t(0,0) = 1.0_default
  t_metric%t(1,1) = - 1.0_default
  t_metric%t(2,2) = - 1.0_default
  t_metric%t(3,3) = - 1.0_default
  g2 = g/2.0_default
  g8 = g/8.0_default
  v_dum = v_ff(g8, psibar, psi)
  c_dum = (- m) * s_ff (g2, psibar, psi) - (kb+k)*v_dum
  j = c_dum*t_metric - (((kb+k).tprod.v_dum) + &
    (v_dum.tprod.(kb+k)))
end function grav_ff

```

$$g_L \gamma_\mu (1 - \gamma_5) + g_R \gamma_\mu (1 + \gamma_5) = (g_L + g_R) \gamma_\mu - (g_L - g_R) \gamma_\mu \gamma_5 = g_V \gamma_\mu - g_A \gamma_\mu \gamma_5 \quad (\text{X.53})$$

... give the compiler the benefit of the doubt that it will optimize the function all. If not, we could inline it ...

*(Implementation of spinor currents)*+≡

```

pure function vlr_ff (gl, gr, psibar, psi) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: gl, gr
  type(conjspinor), intent(in) :: psibar
  type(spinor), intent(in) :: psi
  j = va_ff (gl+gr, gl-gr, psibar, psi)
end function vlr_ff

```

and

$$\psi - \not{a} \gamma_5 = \begin{pmatrix} 0 & 0 & v_- - a_- & -v^* + a^* \\ 0 & 0 & -v + a & v_+ - a_+ \\ v_+ + a_+ & v^* + a^* & 0 & 0 \\ v + a & v_- + a_- & 0 & 0 \end{pmatrix} \quad (\text{X.54})$$

with  $v_{\pm} = v_0 \pm v_3$ ,  $a_{\pm} = a_0 \pm a_3$ ,  $v = v_1 + iv_2$ ,  $v^* = v_1 - iv_2$ ,  $a = a_1 + ia_2$ , and  $a^* = a_1 - ia_2$ . But note that  $\cdot^*$  is *not* complex conjugation for complex  $v_{\mu}$  or  $a_{\mu}$ .

```
(Declaration of spinor currents)+≡
  public :: f_vaf, f_vf, f_af, f_vlf, f_vrf, f_vlrf, f_va2f, &
           f_tvaf, f_tlr, f_trlf, f_tvamf, f_tlrnf, f_trlnf, f_va3f
```

```
(Implementation of spinor currents)+≡
  pure function f_vaf (gv, ga, v, psi) result (vpsi)
    type(spinor) :: vpsi
    complex(kind=default), intent(in) :: gv, ga
    type(vector), intent(in) :: v
    type(spinor), intent(in) :: psi
    complex(kind=default) :: gl, gr
    complex(kind=default) :: vp, vm, v12, v12s
    gl = gv + ga
    gr = gv - ga
    vp = v%t + v%x(3)
    vm = v%t - v%x(3)
    v12 = v%x(1) + (0,1)*v%x(2)
    v12s = v%x(1) - (0,1)*v%x(2)
    vpsi%a(1) = gr * ( vm * psi%a(3) - v12s * psi%a(4))
    vpsi%a(2) = gr * ( - v12 * psi%a(3) + vp * psi%a(4))
    vpsi%a(3) = gl * ( vp * psi%a(1) + v12s * psi%a(2))
    vpsi%a(4) = gl * ( v12 * psi%a(1) + vm * psi%a(2))
  end function f_vaf
```

```
(Implementation of spinor currents)+≡
  pure function f_va2f (gva, v, psi) result (vpsi)
    type(spinor) :: vpsi
    complex(kind=default), intent(in), dimension(2) :: gva
    type(vector), intent(in) :: v
    type(spinor), intent(in) :: psi
    complex(kind=default) :: gl, gr
    complex(kind=default) :: vp, vm, v12, v12s
    gl = gva(1) + gva(2)
    gr = gva(1) - gva(2)
    vp = v%t + v%x(3)
    vm = v%t - v%x(3)
    v12 = v%x(1) + (0,1)*v%x(2)
    v12s = v%x(1) - (0,1)*v%x(2)
    vpsi%a(1) = gr * ( vm * psi%a(3) - v12s * psi%a(4))
    vpsi%a(2) = gr * ( - v12 * psi%a(3) + vp * psi%a(4))
    vpsi%a(3) = gl * ( vp * psi%a(1) + v12s * psi%a(2))
    vpsi%a(4) = gl * ( v12 * psi%a(1) + vm * psi%a(2))
  end function f_va2f
```

```
(Implementation of spinor currents)+≡
  pure function f_va3f (gv, ga, v, psi) result (vpsi)
    type(spinor) :: vpsi
    complex(kind=default), intent(in) :: gv, ga
    type(vector), intent(in) :: v
    type(spinor), intent(in) :: psi
    complex(kind=default) :: gl, gr
    complex(kind=default) :: vp, vm, v12, v12s
```

```

gl = gv + ga
gr = gv - ga
vp = v%x(3) !+ v%t
vm = - v%x(3) !+ v%t
v12 = v%x(1) + (0,1)*v%x(2)
v12s = v%x(1) - (0,1)*v%x(2)
vpsi%a(1) = gr * ( vm * psi%a(3) - v12s * psi%a(4))
vpsi%a(2) = gr * ( - v12 * psi%a(3) + vp * psi%a(4))
vpsi%a(3) = gl * ( vp * psi%a(1) + v12s * psi%a(2))
vpsi%a(4) = gl * ( v12 * psi%a(1) + vm * psi%a(2))
end function f_va3f

```

*(Implementation of spinor currents)+≡*

```

pure function f_tvaf (gv, ga, t, psi) result (tpsi)
  type(spinor) :: tpsi
  complex(kind=default), intent(in) :: gv, ga
  type(tensor2odd), intent(in) :: t
  type(spinor), intent(in) :: psi
  complex(kind=default) :: gl, gr
  complex(kind=default) :: e21, e21s, b12, b12s, be3, be3s
  gr = gv + ga
  gl = gv - ga
  e21 = t%e(2) + t%e(1)*(0,1)
  e21s = t%e(2) - t%e(1)*(0,1)
  b12 = t%b(1) + t%b(2)*(0,1)
  b12s = t%b(1) - t%b(2)*(0,1)
  be3 = t%b(3) + t%e(3)*(0,1)
  be3s = t%b(3) - t%e(3)*(0,1)
  tpsi%a(1) = 2*gl * ( psi%a(1) * be3 + psi%a(2) * ( e21 +b12s))
  tpsi%a(2) = 2*gl * ( - psi%a(2) * be3 + psi%a(1) * (-e21s+b12 ))
  tpsi%a(3) = 2*gr * ( psi%a(3) * be3s + psi%a(4) * (-e21 +b12s))
  tpsi%a(4) = 2*gr * ( - psi%a(4) * be3s + psi%a(3) * ( e21s+b12 ))
end function f_tvaf

```

*(Implementation of spinor currents)+≡*

```

pure function f_tlrif (gl, gr, t, psi) result (tpsi)
  type(spinor) :: tpsi
  complex(kind=default), intent(in) :: gl, gr
  type(tensor2odd), intent(in) :: t
  type(spinor), intent(in) :: psi
  tpsi = f_tvaf (gr+gl, gr-gl, t, psi)
end function f_tlrif

```

*(Implementation of spinor currents)+≡*

```

pure function f_trlif (gr, gl, t, psi) result (tpsi)
  type(spinor) :: tpsi
  complex(kind=default), intent(in) :: gl, gr
  type(tensor2odd), intent(in) :: t
  type(spinor), intent(in) :: psi
  tpsi = f_tvaf (gr+gl, gr-gl, t, psi)
end function f_trlif

```

*(Implementation of spinor currents)+≡*

```

pure function f_tvamf (gv, ga, v, psi, k) result (vpsi)
  type(spinor) :: vpsi
  complex(kind=default), intent(in) :: gv, ga

```

```

    type(vector), intent(in) :: v
    type(spinor), intent(in) :: psi
    type(momentum), intent(in) :: k
    type(tensor2odd) :: t
    t = (v.wedge.k) * (0, 0.5)
    vpsi = f_tvaf(gv, ga, t, psi)
end function f_tvamf

<Implementation of spinor currents>+≡
pure function f_tlrnf (gl, gr, v, psi, k) result (vpsi)
    type(spinor) :: vpsi
    complex(kind=default), intent(in) :: gl, gr
    type(vector), intent(in) :: v
    type(spinor), intent(in) :: psi
    type(momentum), intent(in) :: k
    vpsi = f_tvamf (gr+gl, gr-gl, v, psi, k)
end function f_tlrnf

<Implementation of spinor currents>+≡
pure function f_trlnf (gr, gl, v, psi, k) result (vpsi)
    type(spinor) :: vpsi
    complex(kind=default), intent(in) :: gl, gr
    type(vector), intent(in) :: v
    type(spinor), intent(in) :: psi
    type(momentum), intent(in) :: k
    vpsi = f_tvamf (gr+gl, gr-gl, v, psi, k)
end function f_trlnf

<Implementation of spinor currents>+≡
pure function f_vf (gv, v, psi) result (vpsi)
    type(spinor) :: vpsi
    complex(kind=default), intent(in) :: gv
    type(vector), intent(in) :: v
    type(spinor), intent(in) :: psi
    complex(kind=default) :: vp, vm, v12, v12s
    vp = v%t + v%x(3)
    vm = v%t - v%x(3)
    v12 = v%x(1) + (0,1)*v%x(2)
    v12s = v%x(1) - (0,1)*v%x(2)
    vpsi%a(1) = gv * ( vm * psi%a(3) - v12s * psi%a(4))
    vpsi%a(2) = gv * ( - v12 * psi%a(3) + vp * psi%a(4))
    vpsi%a(3) = gv * ( vp * psi%a(1) + v12s * psi%a(2))
    vpsi%a(4) = gv * ( v12 * psi%a(1) + vm * psi%a(2))
end function f_vf

<Implementation of spinor currents>+≡
pure function f_af (ga, v, psi) result (vpsi)
    type(spinor) :: vpsi
    complex(kind=default), intent(in) :: ga
    type(vector), intent(in) :: v
    type(spinor), intent(in) :: psi
    complex(kind=default) :: vp, vm, v12, v12s
    vp = v%t + v%x(3)
    vm = v%t - v%x(3)
    v12 = v%x(1) + (0,1)*v%x(2)
    v12s = v%x(1) - (0,1)*v%x(2)

```

```

vpsi%a(1) = ga * ( - vm * psi%a(3) + v12s * psi%a(4))
vpsi%a(2) = ga * ( v12 * psi%a(3) - vp * psi%a(4))
vpsi%a(3) = ga * ( vp * psi%a(1) + v12s * psi%a(2))
vpsi%a(4) = ga * ( v12 * psi%a(1) + vm * psi%a(2))
end function f_af

```

*(Implementation of spinor currents)*+≡

```

pure function f_vlf (gl, v, psi) result (vpsi)
  type(spinor) :: vpsi
  complex(kind=default), intent(in) :: gl
  type(vector), intent(in) :: v
  type(spinor), intent(in) :: psi
  complex(kind=default) :: gl2
  complex(kind=default) :: vp, vm, v12, v12s
  gl2 = 2 * gl
  vp = v%t + v%x(3)
  vm = v%t - v%x(3)
  v12 = v%x(1) + (0,1)*v%x(2)
  v12s = v%x(1) - (0,1)*v%x(2)
  vpsi%a(1) = 0
  vpsi%a(2) = 0
  vpsi%a(3) = gl2 * ( vp * psi%a(1) + v12s * psi%a(2))
  vpsi%a(4) = gl2 * ( v12 * psi%a(1) + vm * psi%a(2))
end function f_vlf

```

*(Implementation of spinor currents)*+≡

```

pure function f_vrf (gr, v, psi) result (vpsi)
  type(spinor) :: vpsi
  complex(kind=default), intent(in) :: gr
  type(vector), intent(in) :: v
  type(spinor), intent(in) :: psi
  complex(kind=default) :: gr2
  complex(kind=default) :: vp, vm, v12, v12s
  gr2 = 2 * gr
  vp = v%t + v%x(3)
  vm = v%t - v%x(3)
  v12 = v%x(1) + (0,1)*v%x(2)
  v12s = v%x(1) - (0,1)*v%x(2)
  vpsi%a(1) = gr2 * ( vm * psi%a(3) - v12s * psi%a(4))
  vpsi%a(2) = gr2 * ( - v12 * psi%a(3) + vp * psi%a(4))
  vpsi%a(3) = 0
  vpsi%a(4) = 0
end function f_vrf

```

*(Implementation of spinor currents)*+≡

```

pure function f_vlrf (gl, gr, v, psi) result (vpsi)
  type(spinor) :: vpsi
  complex(kind=default), intent(in) :: gl, gr
  type(vector), intent(in) :: v
  type(spinor), intent(in) :: psi
  vpsi = f_vaf (gl+gr, gl-gr, v, psi)
end function f_vlrf

```

*(Declaration of spinor currents)*+≡

```

public :: f_fva, f_fv, f_fa, f_fvl, f_fvr, f_fvrl, f_fva2, &
         f_ftva, f_ftlr, f_ftrl, f_ftvam, f_ftlrm, f_ftrlm, f_fva3

```

*(Implementation of spinor currents)*+≡

```
pure function f_fva (gv, ga, psibar, v) result (psibarv)
  type(conjspinor) :: psibarv
  complex(kind=default), intent(in) :: gv, ga
  type(conjspinor), intent(in) :: psibar
  type(vector), intent(in) :: v
  complex(kind=default) :: gl, gr
  complex(kind=default) :: vp, vm, v12, v12s
  gl = gv + ga
  gr = gv - ga
  vp = v%t + v%x(3)
  vm = v%t - v%x(3)
  v12 = v%x(1) + (0,1)*v%x(2)
  v12s = v%x(1) - (0,1)*v%x(2)
  psibarv%a(1) = gl * ( psibar%a(3) * vp + psibar%a(4) * v12)
  psibarv%a(2) = gl * ( psibar%a(3) * v12s + psibar%a(4) * vm )
  psibarv%a(3) = gr * ( psibar%a(1) * vm - psibar%a(2) * v12)
  psibarv%a(4) = gr * ( - psibar%a(1) * v12s + psibar%a(2) * vp )
end function f_fva
```

*(Implementation of spinor currents)*+≡

```
pure function f_fva2 (gva, psibar, v) result (psibarv)
  type(conjspinor) :: psibarv
  complex(kind=default), intent(in), dimension(2) :: gva
  type(conjspinor), intent(in) :: psibar
  type(vector), intent(in) :: v
  complex(kind=default) :: gl, gr
  complex(kind=default) :: vp, vm, v12, v12s
  gl = gva(1) + gva(2)
  gr = gva(1) - gva(2)
  vp = v%t + v%x(3)
  vm = v%t - v%x(3)
  v12 = v%x(1) + (0,1)*v%x(2)
  v12s = v%x(1) - (0,1)*v%x(2)
  psibarv%a(1) = gl * ( psibar%a(3) * vp + psibar%a(4) * v12)
  psibarv%a(2) = gl * ( psibar%a(3) * v12s + psibar%a(4) * vm )
  psibarv%a(3) = gr * ( psibar%a(1) * vm - psibar%a(2) * v12)
  psibarv%a(4) = gr * ( - psibar%a(1) * v12s + psibar%a(2) * vp )
end function f_fva2
```

*(Implementation of spinor currents)*+≡

```
pure function f_fva3 (gv, ga, psibar, v) result (psibarv)
  type(conjspinor) :: psibarv
  complex(kind=default), intent(in) :: gv, ga
  type(conjspinor), intent(in) :: psibar
  type(vector), intent(in) :: v
  complex(kind=default) :: gl, gr
  complex(kind=default) :: vp, vm, v12, v12s
  gl = gv + ga
  gr = gv - ga
  vp = v%x(3) !+ v%t
  vm = - v%x(3) !+ v%t
  v12 = v%x(1) + (0,1)*v%x(2)
  v12s = v%x(1) - (0,1)*v%x(2)
  psibarv%a(1) = gl * ( psibar%a(3) * vp + psibar%a(4) * v12)
```

```

    psibarv%a(2) = gl * ( psibar%a(3) * v12s + psibar%a(4) * vm )
    psibarv%a(3) = gr * ( psibar%a(1) * vm - psibar%a(2) * v12 )
    psibarv%a(4) = gr * ( - psibar%a(1) * v12s + psibar%a(2) * vp )
end function f_fva3

```

(Implementation of spinor currents)+≡

```

pure function f_ftva (gv, ga, psibar, t) result (psibart)
    type(conjspinor) :: psibart
    complex(kind=default), intent(in) :: gv, ga
    type(conjspinor), intent(in) :: psibar
    type(tensor2odd), intent(in) :: t
    complex(kind=default) :: gl, gr
    complex(kind=default) :: e21, e21s, b12, b12s, be3, be3s
    gr = gv + ga
    gl = gv - ga
    e21 = t%e(2) + t%e(1)*(0,1)
    e21s = t%e(2) - t%e(1)*(0,1)
    b12 = t%b(1) + t%b(2)*(0,1)
    b12s = t%b(1) - t%b(2)*(0,1)
    be3 = t%b(3) + t%e(3)*(0,1)
    be3s = t%b(3) - t%e(3)*(0,1)
    psibart%a(1) = 2*gl * ( psibar%a(1) * be3 + psibar%a(2) * (-e21s+b12) )
    psibart%a(2) = 2*gl * ( - psibar%a(2) * be3 + psibar%a(1) * (e21+b12s) )
    psibart%a(3) = 2*gr * ( psibar%a(3) * be3s + psibar%a(4) * (e21s+b12) )
    psibart%a(4) = 2*gr * ( - psibar%a(4) * be3s + psibar%a(3) * (-e21+b12s) )
end function f_ftva

```

(Implementation of spinor currents)+≡

```

pure function f_ftlr (gl, gr, psibar, t) result (psibart)
    type(conjspinor) :: psibart
    complex(kind=default), intent(in) :: gl, gr
    type(conjspinor), intent(in) :: psibar
    type(tensor2odd), intent(in) :: t
    psibart = f_ftva (gr+gl, gr-gl, psibar, t)
end function f_ftlr

```

(Implementation of spinor currents)+≡

```

pure function f_ftrl (gr, gl, psibar, t) result (psibart)
    type(conjspinor) :: psibart
    complex(kind=default), intent(in) :: gl, gr
    type(conjspinor), intent(in) :: psibar
    type(tensor2odd), intent(in) :: t
    psibart = f_ftva (gr+gl, gr-gl, psibar, t)
end function f_ftrl

```

(Implementation of spinor currents)+≡

```

pure function f_ftvam (gv, ga, psibar, v, k) result (psibarv)
    type(conjspinor) :: psibarv
    complex(kind=default), intent(in) :: gv, ga
    type(conjspinor), intent(in) :: psibar
    type(vector), intent(in) :: v
    type(momentum), intent(in) :: k
    type(tensor2odd) :: t
    t = (v.wedge.k) * (0, 0.5)
    psibarv = f_ftva(gv, ga, psibar, t)
end function f_ftvam

```

```

<Implementation of spinor currents>+=
pure function f_ftlrm (gl, gr, psibar, v, k) result (psibarv)
  type(conjspinor) :: psibarv
  complex(kind=default), intent(in) :: gl, gr
  type(conjspinor), intent(in) :: psibar
  type(vector), intent(in) :: v
  type(momentum), intent(in) :: k
  psibarv = f_ftvam (gr+gl, gr-gl, psibar, v, k)
end function f_ftlrm

<Implementation of spinor currents>+=
pure function f_ftrlm (gr, gl, psibar, v, k) result (psibarv)
  type(conjspinor) :: psibarv
  complex(kind=default), intent(in) :: gl, gr
  type(conjspinor), intent(in) :: psibar
  type(vector), intent(in) :: v
  type(momentum), intent(in) :: k
  psibarv = f_ftvam (gr+gl, gr-gl, psibar, v, k)
end function f_ftrlm

<Implementation of spinor currents>+=
pure function f_fv (gv, psibar, v) result (psibarv)
  type(conjspinor) :: psibarv
  complex(kind=default), intent(in) :: gv
  type(conjspinor), intent(in) :: psibar
  type(vector), intent(in) :: v
  complex(kind=default) :: vp, vm, v12, v12s
  vp = v%t + v%x(3)
  vm = v%t - v%x(3)
  v12 = v%x(1) + (0,1)*v%x(2)
  v12s = v%x(1) - (0,1)*v%x(2)
  psibarv%a(1) = gv * ( psibar%a(3) * vp + psibar%a(4) * v12 )
  psibarv%a(2) = gv * ( psibar%a(3) * v12s + psibar%a(4) * vm )
  psibarv%a(3) = gv * ( psibar%a(1) * vm - psibar%a(2) * v12 )
  psibarv%a(4) = gv * ( - psibar%a(1) * v12s + psibar%a(2) * vp )
end function f_fv

<Implementation of spinor currents>+=
pure function f_fa (ga, psibar, v) result (psibarv)
  type(conjspinor) :: psibarv
  complex(kind=default), intent(in) :: ga
  type(vector), intent(in) :: v
  type(conjspinor), intent(in) :: psibar
  complex(kind=default) :: vp, vm, v12, v12s
  vp = v%t + v%x(3)
  vm = v%t - v%x(3)
  v12 = v%x(1) + (0,1)*v%x(2)
  v12s = v%x(1) - (0,1)*v%x(2)
  psibarv%a(1) = ga * ( psibar%a(3) * vp + psibar%a(4) * v12 )
  psibarv%a(2) = ga * ( psibar%a(3) * v12s + psibar%a(4) * vm )
  psibarv%a(3) = ga * ( - psibar%a(1) * vm + psibar%a(2) * v12 )
  psibarv%a(4) = ga * ( psibar%a(1) * v12s - psibar%a(2) * vp )
end function f_fa

<Implementation of spinor currents>+=
pure function f_fvl (gl, psibar, v) result (psibarv)

```



```

type(conjspinor) :: psibarv
complex(kind=default), intent(in) :: gl
type(conjspinor), intent(in) :: psibar
type(vector), intent(in) :: v
complex(kind=default) :: gl2
complex(kind=default) :: vp, vm, v12, v12s
gl2 = 2 * gl
vp = v%t + v%x(3)
vm = v%t - v%x(3)
v12 = v%x(1) + (0,1)*v%x(2)
v12s = v%x(1) - (0,1)*v%x(2)
psibarv%a(1) = gl2 * ( psibar%a(3) * vp + psibar%a(4) * v12)
psibarv%a(2) = gl2 * ( psibar%a(3) * v12s + psibar%a(4) * vm )
psibarv%a(3) = 0
psibarv%a(4) = 0
end function f_fvl

<Implementation of spinor currents>+≡
pure function f_fvr (gr, psibar, v) result (psibarv)
type(conjspinor) :: psibarv
complex(kind=default), intent(in) :: gr
type(conjspinor), intent(in) :: psibar
type(vector), intent(in) :: v
complex(kind=default) :: gr2
complex(kind=default) :: vp, vm, v12, v12s
gr2 = 2 * gr
vp = v%t + v%x(3)
vm = v%t - v%x(3)
v12 = v%x(1) + (0,1)*v%x(2)
v12s = v%x(1) - (0,1)*v%x(2)
psibarv%a(1) = 0
psibarv%a(2) = 0
psibarv%a(3) = gr2 * ( psibar%a(1) * vm - psibar%a(2) * v12)
psibarv%a(4) = gr2 * ( - psibar%a(1) * v12s + psibar%a(2) * vp )
end function f_fvr

<Implementation of spinor currents>+≡
pure function f_fvlr (gl, gr, psibar, v) result (psibarv)
type(conjspinor) :: psibarv
complex(kind=default), intent(in) :: gl, gr
type(conjspinor), intent(in) :: psibar
type(vector), intent(in) :: v
psibarv = f_fva (gl+gr, gl-gr, psibar, v)
end function f_fvlr

```

### X.13.2 Fermionic Scalar and Pseudo Scalar Couplings

```

<Declaration of spinor currents>+≡
public :: sp_ff, s_ff, p_ff, sl_ff, sr_ff, slr_ff

<Implementation of spinor currents>+≡
pure function sp_ff (gs, gp, psibar, psi) result (j)
complex(kind=default) :: j
complex(kind=default), intent(in) :: gs, gp
type(conjspinor), intent(in) :: psibar

```

```

    type(spinor), intent(in) :: psi
    j = (gs - gp) * (psibar%a(1)*psi%a(1) + psibar%a(2)*psi%a(2)) &
        + (gs + gp) * (psibar%a(3)*psi%a(3) + psibar%a(4)*psi%a(4))
end function sp_ff

<Implementation of spinor currents>+=
pure function s_ff (gs, psibar, psi) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: gs
    type(conjspinor), intent(in) :: psibar
    type(spinor), intent(in) :: psi
    j = gs * (psibar * psi)
end function s_ff

<Implementation of spinor currents>+=
pure function p_ff (gp, psibar, psi) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: gp
    type(conjspinor), intent(in) :: psibar
    type(spinor), intent(in) :: psi
    j = gp * ( psibar%a(3)*psi%a(3) + psibar%a(4)*psi%a(4) &
        - psibar%a(1)*psi%a(1) - psibar%a(2)*psi%a(2))
end function p_ff

<Implementation of spinor currents>+=
pure function sl_ff (gl, psibar, psi) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: gl
    type(conjspinor), intent(in) :: psibar
    type(spinor), intent(in) :: psi
    j = 2 * gl * (psibar%a(1)*psi%a(1) + psibar%a(2)*psi%a(2))
end function sl_ff

<Implementation of spinor currents>+=
pure function sr_ff (gr, psibar, psi) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: gr
    type(conjspinor), intent(in) :: psibar
    type(spinor), intent(in) :: psi
    j = 2 * gr * (psibar%a(3)*psi%a(3) + psibar%a(4)*psi%a(4))
end function sr_ff


$$g_L(1 - \gamma_5) + g_R(1 + \gamma_5) = (g_R + g_L) + (g_R - g_L)\gamma_5 = g_S + g_P\gamma_5 \quad (\text{X.55})$$


<Implementation of spinor currents>+=
pure function slr_ff (gl, gr, psibar, psi) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: gl, gr
    type(conjspinor), intent(in) :: psibar
    type(spinor), intent(in) :: psi
    j = sp_ff (gr+gl, gr-gl, psibar, psi)
end function slr_ff

<Declaration of spinor currents>+=
public :: f_spf, f_sf, f_pf, f_slf, f_srf, f_slrf

```

```

<Implementation of spinor currents>+≡
pure function f_spf (gs, gp, phi, psi) result (phipsi)
  type(spinor) :: phipsi
  complex(kind=default), intent(in) :: gs, gp
  complex(kind=default), intent(in) :: phi
  type(spinor), intent(in) :: psi
  phipsi%a(1:2) = ((gs - gp) * phi) * psi%a(1:2)
  phipsi%a(3:4) = ((gs + gp) * phi) * psi%a(3:4)
end function f_spf

<Implementation of spinor currents>+≡
pure function f_sf (gs, phi, psi) result (phipsi)
  type(spinor) :: phipsi
  complex(kind=default), intent(in) :: gs
  complex(kind=default), intent(in) :: phi
  type(spinor), intent(in) :: psi
  phipsi%a = (gs * phi) * psi%a
end function f_sf

<Implementation of spinor currents>+≡
pure function f_pf (gp, phi, psi) result (phipsi)
  type(spinor) :: phipsi
  complex(kind=default), intent(in) :: gp
  complex(kind=default), intent(in) :: phi
  type(spinor), intent(in) :: psi
  phipsi%a(1:2) = (- gp * phi) * psi%a(1:2)
  phipsi%a(3:4) = ( gp * phi) * psi%a(3:4)
end function f_pf

<Implementation of spinor currents>+≡
pure function f_slf (gl, phi, psi) result (phipsi)
  type(spinor) :: phipsi
  complex(kind=default), intent(in) :: gl
  complex(kind=default), intent(in) :: phi
  type(spinor), intent(in) :: psi
  phipsi%a(1:2) = (2 * gl * phi) * psi%a(1:2)
  phipsi%a(3:4) = 0
end function f_slf

<Implementation of spinor currents>+≡
pure function f_srf (gr, phi, psi) result (phipsi)
  type(spinor) :: phipsi
  complex(kind=default), intent(in) :: gr
  complex(kind=default), intent(in) :: phi
  type(spinor), intent(in) :: psi
  phipsi%a(1:2) = 0
  phipsi%a(3:4) = (2 * gr * phi) * psi%a(3:4)
end function f_srf

<Implementation of spinor currents>+≡
pure function f_slrf (gl, gr, phi, psi) result (phipsi)
  type(spinor) :: phipsi
  complex(kind=default), intent(in) :: gl, gr
  complex(kind=default), intent(in) :: phi
  type(spinor), intent(in) :: psi
  phipsi = f_spf (gr+gl, gr-gl, phi, psi)
end function f_slrf

```

---

```

<Declaration of spinor currents>+≡
  public :: f_fsp, f_fs, f_fp, f_fsl, f_fsr, f_fslr

<Implementation of spinor currents>+≡
  pure function f_fsp (gs, gp, psibar, phi) result (psibarphi)
    type(conjspinor) :: psibarphi
    complex(kind=default), intent(in) :: gs, gp
    type(conjspinor), intent(in) :: psibar
    complex(kind=default), intent(in) :: phi
    psibarphi%a(1:2) = ((gs - gp) * phi) * psibar%a(1:2)
    psibarphi%a(3:4) = ((gs + gp) * phi) * psibar%a(3:4)
  end function f_fsp

<Implementation of spinor currents>+≡
  pure function f_fs (gs, psibar, phi) result (psibarphi)
    type(conjspinor) :: psibarphi
    complex(kind=default), intent(in) :: gs
    type(conjspinor), intent(in) :: psibar
    complex(kind=default), intent(in) :: phi
    psibarphi%a = (gs * phi) * psibar%a
  end function f_fs

<Implementation of spinor currents>+≡
  pure function f_fp (gp, psibar, phi) result (psibarphi)
    type(conjspinor) :: psibarphi
    complex(kind=default), intent(in) :: gp
    type(conjspinor), intent(in) :: psibar
    complex(kind=default), intent(in) :: phi
    psibarphi%a(1:2) = (- gp * phi) * psibar%a(1:2)
    psibarphi%a(3:4) = ( gp * phi) * psibar%a(3:4)
  end function f_fp

<Implementation of spinor currents>+≡
  pure function f_fsl (gl, psibar, phi) result (psibarphi)
    type(conjspinor) :: psibarphi
    complex(kind=default), intent(in) :: gl
    type(conjspinor), intent(in) :: psibar
    complex(kind=default), intent(in) :: phi
    psibarphi%a(1:2) = (2 * gl * phi) * psibar%a(1:2)
    psibarphi%a(3:4) = 0
  end function f_fsl

<Implementation of spinor currents>+≡
  pure function f_fsr (gr, psibar, phi) result (psibarphi)
    type(conjspinor) :: psibarphi
    complex(kind=default), intent(in) :: gr
    type(conjspinor), intent(in) :: psibar
    complex(kind=default), intent(in) :: phi
    psibarphi%a(1:2) = 0
    psibarphi%a(3:4) = (2 * gr * phi) * psibar%a(3:4)
  end function f_fsr

<Implementation of spinor currents>+≡
  pure function f_fslr (gl, gr, psibar, phi) result (psibarphi)
    type(conjspinor) :: psibarphi
    complex(kind=default), intent(in) :: gl, gr
    type(conjspinor), intent(in) :: psibar

```

```

        complex(kind=default), intent(in) :: phi
        psibarphi = f_fsp (gr+gl, gr-gl, psibar, phi)
    end function f_fslr

<Declaration of spinor currents>+≡
    public :: f_gravf, f_fgrav

<Implementation of spinor currents>+≡
    pure function f_gravf (g, m, kb, k, t, psi) result (tpsi)
        type(spinor) :: tpsi
        complex(kind=default), intent(in) :: g
        real(kind=default), intent(in) :: m
        type(spinor), intent(in) :: psi
        type(tensor), intent(in) :: t
        type(momentum), intent(in) :: kb, k
        complex(kind=default) :: g2, g8, t_tr
        type(vector) :: kkb
        kkb = k + kb
        g2 = g / 2.0_default
        g8 = g / 8.0_default
        t_tr = t%t(0,0) - t%t(1,1) - t%t(2,2) - t%t(3,3)
        tpsi = (- f_sf (g2, cmplx (m,0.0, kind=default), psi) &
                - f_vf ((g8*m), kkb, psi)) * t_tr - &
                f_vf (g8,(t*kkb + kkb*t),psi)
    end function f_gravf

<Implementation of spinor currents>+≡
    pure function f_fgrav (g, m, kb, k, psibar, t) result (psibart)
        type(conjspinor) :: psibart
        complex(kind=default), intent(in) :: g
        real(kind=default), intent(in) :: m
        type(conjspinor), intent(in) :: psibar
        type(tensor), intent(in) :: t
        type(momentum), intent(in) :: kb, k
        type(vector) :: kkb
        complex(kind=default) :: g2, g8, t_tr
        kkb = k + kb
        g2 = g / 2.0_default
        g8 = g / 8.0_default
        t_tr = t%t(0,0) - t%t(1,1) - t%t(2,2) - t%t(3,3)
        psibart = (- f_fs (g2, psibar, cmplx (m, 0.0, kind=default)) &
                - f_fv ((g8 * m), psibar, kkb)) * t_tr - &
                f_fv (g8,psibar,(t*kkb + kkb*t))
    end function f_fgrav

```

### X.13.3 On Shell Wave Functions

```

<Declaration of spinor on shell wave functions>≡
    public :: u, ubar, v, vbar
    private :: chi_plus, chi_minus

```

$$\chi_+(\vec{p}) = \frac{1}{\sqrt{2|\vec{p}|(|\vec{p}| + p_3)}} \begin{pmatrix} |\vec{p}| + p_3 \\ p_1 + ip_2 \end{pmatrix} \quad (\text{X.56a})$$

$$\chi_{-}(\vec{p}) = \frac{1}{\sqrt{2|\vec{p}|(|\vec{p}| + p_3)}} \begin{pmatrix} -p_1 + ip_2 \\ |\vec{p}| + p_3 \end{pmatrix} \quad (\text{X.56b})$$

```

(Implementation of spinor on shell wave functions)=
pure function chi_plus (p) result (chi)
  complex(kind=default), dimension(2) :: chi
  type(momentum), intent(in) :: p
  real(kind=default) :: pabs
  pabs = sqrt (dot_product (p%x, p%x))
  if (pabs + p%x(3) <= 1000 * epsilon (pabs) * pabs) then
    chi = (/ cmplx ( 0.0, 0.0, kind=default), &
           cmplx ( 1.0, 0.0, kind=default) /)
  else
    chi = 1 / sqrt (2*pabs*(pabs + p%x(3))) &
          * (/ cmplx (pabs + p%x(3), kind=default), &
             cmplx (p%x(1), p%x(2), kind=default) /)
  end if
end function chi_plus

```

```

(Implementation of spinor on shell wave functions)+=
pure function chi_minus (p) result (chi)
  complex(kind=default), dimension(2) :: chi
  type(momentum), intent(in) :: p
  real(kind=default) :: pabs
  pabs = sqrt (dot_product (p%x, p%x))
  if (pabs + p%x(3) <= 1000 * epsilon (pabs) * pabs) then
    chi = (/ cmplx (-1.0, 0.0, kind=default), &
           cmplx ( 0.0, 0.0, kind=default) /)
  else
    chi = 1 / sqrt (2*pabs*(pabs + p%x(3))) &
          * (/ cmplx (-p%x(1), p%x(2), kind=default), &
             cmplx (pabs + p%x(3), kind=default) /)
  end if
end function chi_minus

```

$$u_{\pm}(p, |m|) = \begin{pmatrix} \sqrt{p_0 \mp |\vec{p}|} \cdot \chi_{\pm}(\vec{p}) \\ \sqrt{p_0 \pm |\vec{p}|} \cdot \chi_{\pm}(\vec{p}) \end{pmatrix} \quad u_{\pm}(p, -|m|) = \begin{pmatrix} -i\sqrt{p_0 \mp |\vec{p}|} \cdot \chi_{\pm}(\vec{p}) \\ +i\sqrt{p_0 \pm |\vec{p}|} \cdot \chi_{\pm}(\vec{p}) \end{pmatrix} \quad (\text{X.57})$$

Determining the mass from the momenta is a numerically haphazardous for light particles. Therefore, we accept some redundancy and pass the mass explicitly. Even if the mass is not used in the chiral representation, we do so for symmetry with polarization vectors and to be prepared for other representations.

```

(Implementation of spinor on shell wave functions)+=
pure function u (mass, p, s) result (psi)
  type(spinor) :: psi
  real(kind=default), intent(in) :: mass
  type(momentum), intent(in) :: p
  integer, intent(in) :: s
  complex(kind=default), dimension(2) :: chi
  real(kind=default) :: pabs, delta, m
  m = abs(mass)
  pabs = sqrt (dot_product (p%x, p%x))
  if (m < epsilon (m) * pabs) then

```

```

        delta = 0
    else
        delta = sqrt (max (p%t - pabs, 0._default))
    end if
    select case (s)
    case (1)
        chi = chi_plus (p)
        psi%a(1:2) = delta * chi
        psi%a(3:4) = sqrt (p%t + pabs) * chi
    case (-1)
        chi = chi_minus (p)
        psi%a(1:2) = sqrt (p%t + pabs) * chi
        psi%a(3:4) = delta * chi
    case default
        pabs = m ! make the compiler happy and use m
        psi%a = 0
    end select
    if (mass < 0) then
        psi%a(1:2) = - imago * psi%a(1:2)
        psi%a(3:4) = + imago * psi%a(3:4)
    end if
end function u

```

*(Implementation of spinor on shell wave functions)+≡*

```

pure function ubar (m, p, s) result (psibar)
    type(conjspinor) :: psibar
    real(kind=default), intent(in) :: m
    type(momentum), intent(in) :: p
    integer, intent(in) :: s
    type(spinor) :: psi
    psi = u (m, p, s)
    psibar%a(1:2) = conjg (psi%a(3:4))
    psibar%a(3:4) = conjg (psi%a(1:2))
end function ubar

```

$$v_{\pm}(p) = \begin{pmatrix} \mp \sqrt{p_0 \pm |\vec{p}|} \cdot \chi_{\mp}(\vec{p}) \\ \pm \sqrt{p_0 \mp |\vec{p}|} \cdot \chi_{\mp}(\vec{p}) \end{pmatrix} \quad (\text{X.58})$$

*(Implementation of spinor on shell wave functions)+≡*

```

pure function v (mass, p, s) result (psi)
    type(spinor) :: psi
    real(kind=default), intent(in) :: mass
    type(momentum), intent(in) :: p
    integer, intent(in) :: s
    complex(kind=default), dimension(2) :: chi
    real(kind=default) :: pabs, delta, m
    m = abs(mass)
    pabs = sqrt (dot_product (p%x, p%x))
    if (m < epsilon (m) * pabs) then
        delta = 0
    else
        delta = sqrt (max (p%t - pabs, 0._default))
    end if
    select case (s)
    case (1)

```

```

    chi = chi_minus (p)
    psi%a(1:2) = - sqrt (p%t + pabs) * chi
    psi%a(3:4) = delta * chi
case (-1)
    chi = chi_plus (p)
    psi%a(1:2) = delta * chi
    psi%a(3:4) = - sqrt (p%t + pabs) * chi
case default
    pabs = m ! make the compiler happy and use m
    psi%a = 0
end select
if (mass < 0) then
    psi%a(1:2) = - imago * psi%a(1:2)
    psi%a(3:4) = + imago * psi%a(3:4)
end if
end function v

```

*(Implementation of spinor on shell wave functions)*  $\equiv$

```

pure function vbar (m, p, s) result (psibar)
    type(conjspinor) :: psibar
    real(kind=default), intent(in) :: m
    type(momentum), intent(in) :: p
    integer, intent(in) :: s
    type(spinor) :: psi
    psi = v (m, p, s)
    psibar%a(1:2) = conjg (psi%a(3:4))
    psibar%a(3:4) = conjg (psi%a(1:2))
end function vbar

```

#### X.13.4 Off Shell Wave Functions

I've just taken this over from Christian Schwinn's version.

*(Declaration of spinor off shell wave functions)*  $\equiv$

```

public :: brs_u, brs_ubar, brs_v, brs_vbar

```

The off-shell wave functions needed for gauge checking are obtained from the LSZ-formulas:

$$\langle \text{Out} | d^\dagger | \text{In} \rangle = i \int d^4x \bar{v} e^{-ikx} (i\rlap{\not{D}} - m) \langle \text{Out} | \psi | \text{In} \rangle \quad (\text{X.59a})$$

$$\langle \text{Out} | b | \text{In} \rangle = -i \int d^4x \bar{u} e^{ikx} (i\rlap{\not{D}} - m) \langle \text{Out} | \psi | \text{In} \rangle \quad (\text{X.59b})$$

$$\langle \text{Out} | d | \text{In} \rangle = i \int d^4x \langle \text{Out} | \bar{\psi} | \text{In} \rangle (-i\overleftarrow{\rlap{\not{D}}} - m) v e^{ikx} \quad (\text{X.59c})$$

$$\langle \text{Out} | b^\dagger | \text{In} \rangle = -i \int d^4x \langle \text{Out} | \bar{\psi} | \text{In} \rangle (-i\overleftarrow{\rlap{\not{D}}} - m) u e^{-ikx} \quad (\text{X.59d})$$

Since the relative sign between fermions and antifermions is ignored for on-shell amplitudes we must also ignore it here, so all wavefunctions must have a  $(-i)$  factor. In momentum space we have:

$$brsu(p) = (-i)(\not{p} - m)u(p) \quad (\text{X.60})$$

*(Implementation of spinor off shell wave functions)*  $\equiv$



```

pure function brs_u (m, p, s) result (dpsi)
  type(spinor) :: dpsi, psi
  real(kind=default), intent(in) :: m
  type(momentum), intent(in) :: p
  integer, intent(in) :: s
  type (vector)::vp
  complex(kind=default), parameter :: one = (1, 0)
  vp=p
  psi=u(m,p,s)
  dpsi=cplx(0.0,-1.0)*(f_vf(one,vp,psi)-m*psi)
end function brs_u

```

$$brsv(p) = i(\not{p} + m)v(p) \quad (X.61)$$

*(Implementation of spinor off shell wave functions)+≡*

```

pure function brs_v (m, p, s) result (dpsi)
  type(spinor) :: dpsi, psi
  real(kind=default), intent(in) :: m
  type(momentum), intent(in) :: p
  integer, intent(in) :: s
  type (vector)::vp
  complex(kind=default), parameter :: one = (1, 0)
  vp=p
  psi=v(m,p,s)
  dpsi=cplx(0.0,1.0)*(f_vf(one,vp,psi)+m*psi)
end function brs_v

```

$$brs\bar{u}(p) = (-i)\bar{u}(p)(\not{p} - m) \quad (X.62)$$

*(Implementation of spinor off shell wave functions)+≡*

```

pure function brs_ubar (m, p, s) result (dpsibar)
  type(conjspinor) :: dpsibar, psibar
  real(kind=default), intent(in) :: m
  type(momentum), intent(in) :: p
  integer, intent(in) :: s
  type (vector)::vp
  complex(kind=default), parameter :: one = (1, 0)
  vp=p
  psibar=ubar(m,p,s)
  dpsibar=cplx(0.0,-1.0)*(f_fv(one,psibar,vp)-m*psibar)
end function brs_ubar

```

$$brs\bar{v}(p) = (i)\bar{v}(p)(\not{p} + m) \quad (X.63)$$

*(Implementation of spinor off shell wave functions)+≡*

```

pure function brs_vbar (m, p, s) result (dpsibar)
  type(conjspinor) :: dpsibar, psibar
  real(kind=default), intent(in) :: m
  type(momentum), intent(in) :: p
  integer, intent(in) :: s
  type (vector)::vp
  complex(kind=default), parameter :: one = (1, 0)
  vp=p
  psibar=vbar(m,p,s)

```

```

    dpsibar=cmplx(0.0,1.0)*(f_fv(one,psibar,vp)+m*psibar)
  end function brs_vbar

```

NB: The remarks on momentum flow in the propagators don't apply here since the incoming momenta are flipped for the wave functions.

### X.13.5 Propagators

NB: the common factor of  $i$  is extracted:

```

⟨Declaration of spinor propagators⟩≡
  public :: pr_psi, pr_psibar
  public :: pj_psi, pj_psibar
  public :: pg_psi, pg_psibar

```

$$\frac{i(-\not{p} + m)}{p^2 - m^2 + im\Gamma}\psi \quad (\text{X.64})$$

NB: the sign of the momentum comes about because all momenta are treated as *outgoing* and the particle charge flow is therefore opposite to the momentum.

```

⟨Implementation of spinor propagators⟩≡
  pure function pr_psi (p, m, w, psi) result (ppsi)
    type(spinor) :: ppsi
    type(momentum), intent(in) :: p
    real(kind=default), intent(in) :: m, w
    type(spinor), intent(in) :: psi
    type(vector) :: vp
    complex(kind=default), parameter :: one = (1, 0)
    vp = p
    ppsi = (1 / cmplx (p*p - m**2, m*w, kind=default)) &
      * (- f_vf (one, vp, psi) + m * psi)
  end function pr_psi

```

$$\sqrt{\frac{\pi}{M\Gamma}}(-\not{p} + m)\psi \quad (\text{X.65})$$

```

⟨Implementation of spinor propagators⟩+≡
  pure function pj_psi (p, m, w, psi) result (ppsi)
    type(spinor) :: ppsi
    type(momentum), intent(in) :: p
    real(kind=default), intent(in) :: m, w
    type(spinor), intent(in) :: psi
    type(vector) :: vp
    complex(kind=default), parameter :: one = (1, 0)
    vp = p
    ppsi = (0, -1) * sqrt (PI / m / w) * (- f_vf (one, vp, psi) + m * psi)
  end function pj_psi

```

```

⟨Implementation of spinor propagators⟩+≡
  pure function pg_psi (p, m, w, psi) result (ppsi)
    type(spinor) :: ppsi
    type(momentum), intent(in) :: p
    real(kind=default), intent(in) :: m, w
    type(spinor), intent(in) :: psi
    type(vector) :: vp
    complex(kind=default), parameter :: one = (1, 0)

```

```

vp = p
ppsi = gauss(p*p, m, w) * (- f_vf (one, vp, psi) + m * psi)
end function pg_psi

```

$$\bar{\psi} \frac{i(\not{p} + m)}{p^2 - m^2 + im\Gamma} \quad (\text{X.66})$$

NB: the sign of the momentum comes about because all momenta are treated as *outgoing* and the antiparticle charge flow is therefore parallel to the momentum.

*(Implementation of spinor propagators)*+≡

```

pure function pr_psibar (p, m, w, psibar) result (ppsibar)
  type(conjspinor) :: ppsibar
  type(momentum), intent(in) :: p
  real(kind=default), intent(in) :: m, w
  type(conjspinor), intent(in) :: psibar
  type(vector) :: vp
  complex(kind=default), parameter :: one = (1, 0)
  vp = p
  ppsibar = (1 / cmplx (p*p - m**2, m*w, kind=default)) &
    * (f_fv (one, psibar, vp) + m * psibar)
end function pr_psibar

```

$$\sqrt{\frac{\pi}{M\Gamma}} \bar{\psi}(\not{p} + m) \quad (\text{X.67})$$

NB: the sign of the momentum comes about because all momenta are treated as *outgoing* and the antiparticle charge flow is therefore parallel to the momentum.

*(Implementation of spinor propagators)*+≡

```

pure function pj_psibar (p, m, w, psibar) result (ppsibar)
  type(conjspinor) :: ppsibar
  type(momentum), intent(in) :: p
  real(kind=default), intent(in) :: m, w
  type(conjspinor), intent(in) :: psibar
  type(vector) :: vp
  complex(kind=default), parameter :: one = (1, 0)
  vp = p
  ppsibar = (0, -1) * sqrt (PI / m / w) * (f_fv (one, psibar, vp) + m * psibar)
end function pj_psibar

```

*(Implementation of spinor propagators)*+≡

```

pure function pg_psibar (p, m, w, psibar) result (ppsibar)
  type(conjspinor) :: ppsibar
  type(momentum), intent(in) :: p
  real(kind=default), intent(in) :: m, w
  type(conjspinor), intent(in) :: psibar
  type(vector) :: vp
  complex(kind=default), parameter :: one = (1, 0)
  vp = p
  ppsibar = gauss (p*p, m, w) * (f_fv (one, psibar, vp) + m * psibar)
end function pg_psibar

```

$$\frac{i(-\not{p} + m)}{p^2 - m^2 + im\Gamma} \sum_n \psi_n \otimes \bar{\psi}_n \quad (\text{X.68})$$

NB: the temporary variables `psi(1:4)` are not nice, but the compilers should be able to optimize the unnecessary copies away. In any case, even if the copies are performed, they are (probably) negligible compared to the floating point multiplications anyway ...

```

<(Not used yet) Declaration of operations for spinors>≡
  type, public :: spinordyad
    ! private (omegalib needs access, but DON'T TOUCH IT!)
    complex(kind=default), dimension(4,4) :: a
  end type spinordyad

<(Not used yet) Implementation of spinor propagators>≡
  pure function pr_dyadleft (p, m, w, psipsibar) result (psipsibarp)
    type(spinordyad) :: psipsibarp
    type(momentum), intent(in) :: p
    real(kind=default), intent(in) :: m, w
    type(spinordyad), intent(in) :: psipsibar
    integer :: i
    type(vector) :: vp
    type(spinor), dimension(4) :: psi
    complex(kind=default) :: pole
    complex(kind=default), parameter :: one = (1, 0)
    vp = p
    pole = 1 / cplx (p*p - m**2, m*w, kind=default)
    do i = 1, 4
      psi(i)%a = psipsibar%a(:,i)
      psi(i) = pole * (- f_vf (one, vp, psi(i)) + m * psi(i))
      psipsibarp%a(:,i) = psi(i)%a
    end do
  end function pr_dyadleft

```

$$\sum_n \psi_n \otimes \bar{\psi}_n \frac{i(\not{p} + m)}{p^2 - m^2 + im\Gamma} \quad (\text{X.69})$$

```

<(Not used yet) Implementation of spinor propagators>+≡
  pure function pr_dyadright (p, m, w, psipsibar) result (psipsibarp)
    type(spinordyad) :: psipsibarp
    type(momentum), intent(in) :: p
    real(kind=default), intent(in) :: m, w
    type(spinordyad), intent(in) :: psipsibar
    integer :: i
    type(vector) :: vp
    type(conjspinor), dimension(4) :: psibar
    complex(kind=default) :: pole
    complex(kind=default), parameter :: one = (1, 0)
    vp = p
    pole = 1 / cplx (p*p - m**2, m*w, kind=default)
    do i = 1, 4
      psibar(i)%a = psipsibar%a(i,:)
      psibar(i) = pole * (f_fv (one, psibar(i), vp) + m * psibar(i))
      psipsibarp%a(i,:) = psibar(i)%a
    end do
  end function pr_dyadright

```

## X.14 Spinor Couplings Revisited

```

(omega_bispinor_couplings.f90)≡
  <Cpyleft>
  module omega_bispinor_couplings
    use kinds
    use constants
    use omega_bispinors
    use omega_vectorspinors
    use omega_vectors
    use omega_couplings
    implicit none
    private
    <Declaration of bispinor on shell wave functions>
    <Declaration of bispinor off shell wave functions>
    <Declaration of bispinor currents>
    <Declaration of bispinor propagators>
    integer, parameter, public :: omega_bispinor_cp1s_2010_01_A = 0
  contains
    <Implementation of bispinor on shell wave functions>
    <Implementation of bispinor off shell wave functions>
    <Implementation of bispinor currents>
    <Implementation of bispinor propagators>
  end module omega_bispinor_couplings

```

See table X.1 for the names of Fortran functions. We could have used long names instead, but this would increase the chance of running past continuation line limits without adding much to the legibility.

### X.14.1 Fermionic Vector and Axial Couplings

There's more than one chiral representation. This one is compatible with HELAS [5].

$$\gamma^0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix}, \quad \gamma_5 = i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}, \quad (\text{X.70a})$$

$$C = \begin{pmatrix} \epsilon & 0 \\ 0 & -\epsilon \end{pmatrix}, \quad \epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}. \quad (\text{X.70b})$$

Therefore

$$g_S + g_P\gamma_5 = \begin{pmatrix} g_S - g_P & 0 & 0 & 0 \\ 0 & g_S - g_P & 0 & 0 \\ 0 & 0 & g_S + g_P & 0 \\ 0 & 0 & 0 & g_S + g_P \end{pmatrix} \quad (\text{X.71a})$$

$$g_V\gamma^0 - g_A\gamma^0\gamma_5 = \begin{pmatrix} 0 & 0 & g_V - g_A & 0 \\ 0 & 0 & 0 & g_V - g_A \\ g_V + g_A & 0 & 0 & 0 \\ 0 & g_V + g_A & 0 & 0 \end{pmatrix} \quad (\text{X.71b})$$

$$g_V\gamma^1 - g_A\gamma^1\gamma_5 = \begin{pmatrix} 0 & 0 & 0 & g_V - g_A \\ 0 & 0 & g_V - g_A & 0 \\ 0 & -g_V - g_A & 0 & 0 \\ -g_V - g_A & 0 & 0 & 0 \end{pmatrix} \quad (\text{X.71c})$$

$$g_V \gamma^2 - g_A \gamma^2 \gamma_5 = \begin{pmatrix} 0 & 0 & 0 & -i(g_V - g_A) \\ 0 & 0 & i(g_V - g_A) & 0 \\ 0 & i(g_V + g_A) & 0 & 0 \\ -i(g_V + g_A) & 0 & 0 & 0 \end{pmatrix} \quad (\text{X.71d})$$

$$g_V \gamma^3 - g_A \gamma^3 \gamma_5 = \begin{pmatrix} 0 & 0 & g_V - g_A & 0 \\ 0 & 0 & 0 & -g_V + g_A \\ -g_V - g_A & 0 & 0 & 0 \\ 0 & g_V + g_A & 0 & 0 \end{pmatrix} \quad (\text{X.71e})$$

and

$$C(g_S + g_P \gamma_5) = \begin{pmatrix} 0 & g_S - g_P & 0 & 0 \\ -g_S + g_P & 0 & 0 & 0 \\ 0 & 0 & 0 & -g_S - g_P \\ 0 & 0 & g_S + g_P & 0 \end{pmatrix} \quad (\text{X.72a})$$

$$C(g_V \gamma^0 - g_A \gamma^0 \gamma_5) = \begin{pmatrix} 0 & 0 & 0 & g_V - g_A \\ 0 & 0 & -g_V + g_A & 0 \\ 0 & -g_V - g_A & 0 & 0 \\ g_V + g_A & 0 & 0 & 0 \end{pmatrix} \quad (\text{X.72b})$$

$$C(g_V \gamma^1 - g_A \gamma^1 \gamma_5) = \begin{pmatrix} 0 & 0 & g_V - g_A & 0 \\ 0 & 0 & 0 & -g_V + g_A \\ g_V + g_A & 0 & 0 & 0 \\ 0 & -g_V - g_A & 0 & 0 \end{pmatrix} \quad (\text{X.72c})$$

$$C(g_V \gamma^2 - g_A \gamma^2 \gamma_5) = \begin{pmatrix} 0 & 0 & i(g_V - g_A) & 0 \\ 0 & 0 & 0 & i(g_V - g_A) \\ i(g_V + g_A) & 0 & 0 & 0 \\ 0 & i(g_V + g_A) & 0 & 0 \end{pmatrix} \quad (\text{X.72d})$$

$$C(g_V \gamma^3 - g_A \gamma^3 \gamma_5) = \begin{pmatrix} 0 & 0 & 0 & -g_V + g_A \\ 0 & 0 & -g_V + g_A & 0 \\ 0 & -g_V - g_A & 0 & 0 \\ -g_V - g_A & 0 & 0 & 0 \end{pmatrix} \quad (\text{X.72e})$$

*(Declaration of bispinor currents)*≡

```
public :: va_ff, v_ff, a_ff, vl_ff, vr_ff, vlr_ff, va2_ff
```

*(Implementation of bispinor currents)*≡

```
pure function va_ff (gv, ga, psil, psir) result (j)
    type(vector) :: j
    complex(kind=default), intent(in) :: gv, ga
    type(bispinor), intent(in) :: psil, psir
    complex(kind=default) :: gl, gr
    complex(kind=default) :: g13, g14, g23, g24, g31, g32, g41, g42
    gl = gv + ga
    gr = gv - ga
    g13 = psil%a(1)*psir%a(3)
    g14 = psil%a(1)*psir%a(4)
    g23 = psil%a(2)*psir%a(3)
    g24 = psil%a(2)*psir%a(4)
```

```

g31 = psil%a(3)*psir%a(1)
g32 = psil%a(3)*psir%a(2)
g41 = psil%a(4)*psir%a(1)
g42 = psil%a(4)*psir%a(2)
j%t   = gr * ( g14 - g23) + gl * ( - g32 + g41)
j%x(1) = gr * ( g13 - g24) + gl * ( g31 - g42)
j%x(2) = (gr * ( g13 + g24) + gl * ( g31 + g42)) * (0, 1)
j%x(3) = gr * ( - g14 - g23) + gl * ( - g32 - g41)
end function va_ff

```

*(Implementation of bispinor currents)+≡*

```

pure function va2_ff (gva, psil, psir) result (j)
  type(vector) :: j
  complex(kind=default), intent(in), dimension(2) :: gva
  type(bispinor), intent(in) :: psil, psir
  complex(kind=default) :: gl, gr
  complex(kind=default) :: g13, g14, g23, g24, g31, g32, g41, g42
  gl = gva(1) + gva(2)
  gr = gva(1) - gva(2)
  g13 = psil%a(1)*psir%a(3)
  g14 = psil%a(1)*psir%a(4)
  g23 = psil%a(2)*psir%a(3)
  g24 = psil%a(2)*psir%a(4)
  g31 = psil%a(3)*psir%a(1)
  g32 = psil%a(3)*psir%a(2)
  g41 = psil%a(4)*psir%a(1)
  g42 = psil%a(4)*psir%a(2)
  j%t   = gr * ( g14 - g23) + gl * ( - g32 + g41)
  j%x(1) = gr * ( g13 - g24) + gl * ( g31 - g42)
  j%x(2) = (gr * ( g13 + g24) + gl * ( g31 + g42)) * (0, 1)
  j%x(3) = gr * ( - g14 - g23) + gl * ( - g32 - g41)
end function va2_ff

```

*(Implementation of bispinor currents)+≡*

```

pure function v_ff (gv, psil, psir) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: gv
  type(bispinor), intent(in) :: psil, psir
  complex(kind=default) :: g13, g14, g23, g24, g31, g32, g41, g42
  g13 = psil%a(1)*psir%a(3)
  g14 = psil%a(1)*psir%a(4)
  g23 = psil%a(2)*psir%a(3)
  g24 = psil%a(2)*psir%a(4)
  g31 = psil%a(3)*psir%a(1)
  g32 = psil%a(3)*psir%a(2)
  g41 = psil%a(4)*psir%a(1)
  g42 = psil%a(4)*psir%a(2)
  j%t   = gv * ( g14 - g23 - g32 + g41)
  j%x(1) = gv * ( g13 - g24 + g31 - g42)
  j%x(2) = gv * ( g13 + g24 + g31 + g42) * (0, 1)
  j%x(3) = gv * ( - g14 - g23 - g32 - g41)
end function v_ff

```

*(Implementation of bispinor currents)+≡*

```

pure function a_ff (ga, psil, psir) result (j)
  type(vector) :: j

```

```

complex(kind=default), intent(in) :: ga
type(bispinor), intent(in) :: psil, psir
complex(kind=default) :: g13, g14, g23, g24, g31, g32, g41, g42
g13 = psil%a(1)*psir%a(3)
g14 = psil%a(1)*psir%a(4)
g23 = psil%a(2)*psir%a(3)
g24 = psil%a(2)*psir%a(4)
g31 = psil%a(3)*psir%a(1)
g32 = psil%a(3)*psir%a(2)
g41 = psil%a(4)*psir%a(1)
g42 = psil%a(4)*psir%a(2)
j%t = -ga * ( g14 - g23 + g32 - g41)
j%x(1) = -ga * ( g13 - g24 - g31 + g42)
j%x(2) = -ga * ( g13 + g24 - g31 - g42) * (0, 1)
j%x(3) = -ga * ( - g14 - g23 + g32 + g41)
end function a_ff

<Implementation of bispinor currents>+≡
pure function vl_ff (gl, psil, psir) result (j)
type(vector) :: j
complex(kind=default), intent(in) :: gl
type(bispinor), intent(in) :: psil, psir
complex(kind=default) :: gl2
complex(kind=default) :: g31, g32, g41, g42
gl2 = 2 * gl
g31 = psil%a(3)*psir%a(1)
g32 = psil%a(3)*psir%a(2)
g41 = psil%a(4)*psir%a(1)
g42 = psil%a(4)*psir%a(2)
j%t = gl2 * ( - g32 + g41)
j%x(1) = gl2 * ( g31 - g42)
j%x(2) = gl2 * ( g31 + g42) * (0, 1)
j%x(3) = gl2 * ( - g32 - g41)
end function vl_ff

<Implementation of bispinor currents>+≡
pure function vr_ff (gr, psil, psir) result (j)
type(vector) :: j
complex(kind=default), intent(in) :: gr
type(bispinor), intent(in) :: psil, psir
complex(kind=default) :: gr2
complex(kind=default) :: g13, g14, g23, g24
gr2 = 2 * gr
g13 = psil%a(1)*psir%a(3)
g14 = psil%a(1)*psir%a(4)
g23 = psil%a(2)*psir%a(3)
g24 = psil%a(2)*psir%a(4)
j%t = gr2 * ( g14 - g23)
j%x(1) = gr2 * ( g13 - g24)
j%x(2) = gr2 * ( g13 + g24) * (0, 1)
j%x(3) = gr2 * ( - g14 - g23)
end function vr_ff

<Implementation of bispinor currents>+≡
pure function vlr_ff (gl, gr, psibar, psi) result (j)
type(vector) :: j

```



```

complex(kind=default), intent(in) :: gl, gr
type(bispinor), intent(in) :: psibar
type(bispinor), intent(in) :: psi
j = va_ff (gl+gr, gl-gr, psibar, psi)
end function vlr_ff
and

```

$$\not{p} - \not{q}\gamma_5 = \begin{pmatrix} 0 & 0 & v_- - a_- & -v^* + a^* \\ 0 & 0 & -v + a & v_+ - a_+ \\ v_+ + a_+ & v^* + a^* & 0 & 0 \\ v + a & v_- + a_- & 0 & 0 \end{pmatrix} \quad (\text{X.73})$$

with  $v_{\pm} = v_0 \pm v_3$ ,  $a_{\pm} = a_0 \pm a_3$ ,  $v = v_1 + iv_2$ ,  $v^* = v_1 - iv_2$ ,  $a = a_1 + ia_2$ , and  $a^* = a_1 - ia_2$ . But note that  $\cdot^*$  is *not* complex conjugation for complex  $v_{\mu}$  or  $a_{\mu}$ .

```

<Declaration of bispinor currents>+≡
public :: f_vaf, f_vf, f_af, f_vlf, f_vrf, f_vlrf, f_va2f

<Implementation of bispinor currents>+≡
pure function f_vaf (gv, ga, v, psi) result (vpsi)
type(bispinor) :: vpsi
complex(kind=default), intent(in) :: gv, ga
type(vector), intent(in) :: v
type(bispinor), intent(in) :: psi
complex(kind=default) :: gl, gr
complex(kind=default) :: vp, vm, v12, v12s
gl = gv + ga
gr = gv - ga
vp = v%t + v%x(3)
vm = v%t - v%x(3)
v12 = v%x(1) + (0,1)*v%x(2)
v12s = v%x(1) - (0,1)*v%x(2)
vpsi%a(1) = gr * ( vm * psi%a(3) - v12s * psi%a(4))
vpsi%a(2) = gr * ( - v12 * psi%a(3) + vp * psi%a(4))
vpsi%a(3) = gl * ( vp * psi%a(1) + v12s * psi%a(2))
vpsi%a(4) = gl * ( v12 * psi%a(1) + vm * psi%a(2))
end function f_vaf

<Implementation of bispinor currents>+≡
pure function f_va2f (gva, v, psi) result (vpsi)
type(bispinor) :: vpsi
complex(kind=default), intent(in), dimension(2) :: gva
type(vector), intent(in) :: v
type(bispinor), intent(in) :: psi
complex(kind=default) :: gl, gr
complex(kind=default) :: vp, vm, v12, v12s
gl = gva(1) + gva(2)
gr = gva(1) - gva(2)
vp = v%t + v%x(3)
vm = v%t - v%x(3)
v12 = v%x(1) + (0,1)*v%x(2)
v12s = v%x(1) - (0,1)*v%x(2)
vpsi%a(1) = gr * ( vm * psi%a(3) - v12s * psi%a(4))
vpsi%a(2) = gr * ( - v12 * psi%a(3) + vp * psi%a(4))
vpsi%a(3) = gl * ( vp * psi%a(1) + v12s * psi%a(2))

```

```

    vpsi%a(4) = gl * (    v12 * psi%a(1) + vm    * psi%a(2))
end function f_va2f

```

*(Implementation of bispinor currents)*+≡

```

pure function f_vf (gv, v, psi) result (vpsi)
  type(bispinor) :: vpsi
  complex(kind=default), intent(in) :: gv
  type(vector), intent(in) :: v
  type(bispinor), intent(in) :: psi
  complex(kind=default) :: vp, vm, v12, v12s
  vp = v%t + v%x(3)
  vm = v%t - v%x(3)
  v12 = v%x(1) + (0,1)*v%x(2)
  v12s = v%x(1) - (0,1)*v%x(2)
  vpsi%a(1) = gv * (    vm * psi%a(3) - v12s * psi%a(4))
  vpsi%a(2) = gv * ( - v12 * psi%a(3) + vp    * psi%a(4))
  vpsi%a(3) = gv * (    vp * psi%a(1) + v12s * psi%a(2))
  vpsi%a(4) = gv * (    v12 * psi%a(1) + vm    * psi%a(2))
end function f_vf

```

*(Implementation of bispinor currents)*+≡

```

pure function f_af (ga, v, psi) result (vpsi)
  type(bispinor) :: vpsi
  complex(kind=default), intent(in) :: ga
  type(vector), intent(in) :: v
  type(bispinor), intent(in) :: psi
  complex(kind=default) :: vp, vm, v12, v12s
  vp = v%t + v%x(3)
  vm = v%t - v%x(3)
  v12 = v%x(1) + (0,1)*v%x(2)
  v12s = v%x(1) - (0,1)*v%x(2)
  vpsi%a(1) = ga * ( - vm * psi%a(3) + v12s * psi%a(4))
  vpsi%a(2) = ga * (    v12 * psi%a(3) - vp    * psi%a(4))
  vpsi%a(3) = ga * (    vp * psi%a(1) + v12s * psi%a(2))
  vpsi%a(4) = ga * (    v12 * psi%a(1) + vm    * psi%a(2))
end function f_af

```

*(Implementation of bispinor currents)*+≡

```

pure function f_vlf (gl, v, psi) result (vpsi)
  type(bispinor) :: vpsi
  complex(kind=default), intent(in) :: gl
  type(vector), intent(in) :: v
  type(bispinor), intent(in) :: psi
  complex(kind=default) :: gl2
  complex(kind=default) :: vp, vm, v12, v12s
  gl2 = 2 * gl
  vp = v%t + v%x(3)
  vm = v%t - v%x(3)
  v12 = v%x(1) + (0,1)*v%x(2)
  v12s = v%x(1) - (0,1)*v%x(2)
  vpsi%a(1) = 0
  vpsi%a(2) = 0
  vpsi%a(3) = gl2 * (    vp * psi%a(1) + v12s * psi%a(2))
  vpsi%a(4) = gl2 * (    v12 * psi%a(1) + vm    * psi%a(2))
end function f_vlf

```

```

<Implementation of bispinor currents>+≡
pure function f_vrf (gr, v, psi) result (vpsi)
  type(bispinor) :: vpsi
  complex(kind=default), intent(in) :: gr
  type(vector), intent(in) :: v
  type(bispinor), intent(in) :: psi
  complex(kind=default) :: gr2
  complex(kind=default) :: vp, vm, v12, v12s
  gr2 = 2 * gr
  vp = v%t + v%x(3)
  vm = v%t - v%x(3)
  v12 = v%x(1) + (0,1)*v%x(2)
  v12s = v%x(1) - (0,1)*v%x(2)
  vpsi%a(1) = gr2 * ( vm * psi%a(3) - v12s * psi%a(4))
  vpsi%a(2) = gr2 * ( - v12 * psi%a(3) + vp * psi%a(4))
  vpsi%a(3) = 0
  vpsi%a(4) = 0
end function f_vrf

<Implementation of bispinor currents>+≡
pure function f_vlrf (gl, gr, v, psi) result (vpsi)
  type(bispinor) :: vpsi
  complex(kind=default), intent(in) :: gl, gr
  type(vector), intent(in) :: v
  type(bispinor), intent(in) :: psi
  vpsi = f_vaf (gl+gr, gl-gr, v, psi)
end function f_vlrf

```

#### X.14.2 Fermionic Scalar and Pseudo Scalar Couplings

```

<Declaration of bispinor currents>+≡
public :: sp_ff, s_ff, p_ff, sl_ff, sr_ff, slr_ff

<Implementation of bispinor currents>+≡
pure function sp_ff (gs, gp, psil, psir) result (j)
  complex(kind=default) :: j
  complex(kind=default), intent(in) :: gs, gp
  type(bispinor), intent(in) :: psil, psir
  j = (gs - gp) * (psil%a(1)*psir%a(2) - psil%a(2)*psir%a(1)) &
      + (gs + gp) * (- psil%a(3)*psir%a(4) + psil%a(4)*psir%a(3))
end function sp_ff

<Implementation of bispinor currents>+≡
pure function s_ff (gs, psil, psir) result (j)
  complex(kind=default) :: j
  complex(kind=default), intent(in) :: gs
  type(bispinor), intent(in) :: psil, psir
  j = gs * (psil * psir)
end function s_ff

<Implementation of bispinor currents>+≡
pure function p_ff (gp, psil, psir) result (j)
  complex(kind=default) :: j
  complex(kind=default), intent(in) :: gp
  type(bispinor), intent(in) :: psil, psir
  j = gp * (- psil%a(1)*psir%a(2) + psil%a(2)*psir%a(1) &

```

```

        - psil%a(3)*psir%a(4) + psil%a(4)*psir%a(3))
    end function p_ff

<Implementation of bispinor currents>+≡
    pure function sl_ff (gl, psil, psir) result (j)
        complex(kind=default) :: j
        complex(kind=default), intent(in) :: gl
        type(bispinor), intent(in) :: psil, psir
        j = 2 * gl * (psil%a(1)*psir%a(2) - psil%a(2)*psir%a(1))
    end function sl_ff

<Implementation of bispinor currents>+≡
    pure function sr_ff (gr, psil, psir) result (j)
        complex(kind=default) :: j
        complex(kind=default), intent(in) :: gr
        type(bispinor), intent(in) :: psil, psir
        j = 2 * gr * (- psil%a(3)*psir%a(4) + psil%a(4)*psir%a(3))
    end function sr_ff

<Implementation of bispinor currents>+≡
    pure function slr_ff (gl, gr, psibar, psi) result (j)
        complex(kind=default) :: j
        complex(kind=default), intent(in) :: gl, gr
        type(bispinor), intent(in) :: psibar
        type(bispinor), intent(in) :: psi
        j = sp_ff (gr+gl, gr-gl, psibar, psi)
    end function slr_ff

<Declaration of bispinor currents>+≡
    public :: f_spf, f_sf, f_pf, f_slf, f_srf, f_slrf

<Implementation of bispinor currents>+≡
    pure function f_spf (gs, gp, phi, psi) result (phipsi)
        type(bispinor) :: phipsi
        complex(kind=default), intent(in) :: gs, gp
        complex(kind=default), intent(in) :: phi
        type(bispinor), intent(in) :: psi
        phipsi%a(1:2) = ((gs - gp) * phi) * psi%a(1:2)
        phipsi%a(3:4) = ((gs + gp) * phi) * psi%a(3:4)
    end function f_spf

<Implementation of bispinor currents>+≡
    pure function f_sf (gs, phi, psi) result (phipsi)
        type(bispinor) :: phipsi
        complex(kind=default), intent(in) :: gs
        complex(kind=default), intent(in) :: phi
        type(bispinor), intent(in) :: psi
        phipsi%a = (gs * phi) * psi%a
    end function f_sf

<Implementation of bispinor currents>+≡
    pure function f_pf (gp, phi, psi) result (phipsi)
        type(bispinor) :: phipsi
        complex(kind=default), intent(in) :: gp
        complex(kind=default), intent(in) :: phi
        type(bispinor), intent(in) :: psi
        phipsi%a(1:2) = (- gp * phi) * psi%a(1:2)
        phipsi%a(3:4) = ( gp * phi) * psi%a(3:4)

```

```

end function f_pf

<Implementation of bispinor currents>+≡
pure function f_slf (gl, phi, psi) result (phipsi)
  type(bispinor) :: phipsi
  complex(kind=default), intent(in) :: gl
  complex(kind=default), intent(in) :: phi
  type(bispinor), intent(in) :: psi
  phipsi%a(1:2) = (2 * gl * phi) * psi%a(1:2)
  phipsi%a(3:4) = 0
end function f_slf

<Implementation of bispinor currents>+≡
pure function f_srf (gr, phi, psi) result (phipsi)
  type(bispinor) :: phipsi
  complex(kind=default), intent(in) :: gr
  complex(kind=default), intent(in) :: phi
  type(bispinor), intent(in) :: psi
  phipsi%a(1:2) = 0
  phipsi%a(3:4) = (2 * gr * phi) * psi%a(3:4)
end function f_srf

<Implementation of bispinor currents>+≡
pure function f_slrf (gl, gr, phi, psi) result (phipsi)
  type(bispinor) :: phipsi
  complex(kind=default), intent(in) :: gl, gr
  complex(kind=default), intent(in) :: phi
  type(bispinor), intent(in) :: psi
  phipsi = f_spf (gr+gl, gr-gl, phi, psi)
end function f_slrf

```

### X.14.3 Couplings for BRST Transformations

#### 3-Couplings

The lists of needed gamma matrices can be found in the next subsection with the gravitino couplings.

```

<Declaration of bispinor currents>+≡
private :: vv_ff, f_vvf

<Declaration of bispinor currents>+≡
public :: vmom_ff, mom_ff, mom5_ff, moml_ff, momr_ff, lmom_ff, rmom_ff

<Implementation of bispinor currents>+≡
pure function vv_ff (psibar, psi, k) result (psibarpsi)
  type(vector) :: psibarpsi
  type(bispinor), intent(in) :: psibar, psi
  type(vector), intent(in) :: k
  complex(kind=default) :: kp, km, k12, k12s
  type(bispinor) :: kgpsi1, kgpsi2, kgpsi3, kgpsi4
  kp = k%t + k%x(3)
  km = k%t - k%x(3)
  k12 = k%x(1) + (0,1)*k%x(2)
  k12s = k%x(1) - (0,1)*k%x(2)
  kgpsi1%a(1) = -k%x(3) * psi%a(1) - k12s * psi%a(2)
  kgpsi1%a(2) = -k12 * psi%a(1) + k%x(3) * psi%a(2)

```

```

kgpsi1%a(3) = k%x(3) * psi%a(3) + k12s * psi%a(4)
kgpsi1%a(4) = k12 * psi%a(3) - k%x(3) * psi%a(4)
kgpsi2%a(1) = ((0,-1) * k%x(2)) * psi%a(1) - km * psi%a(2)
kgpsi2%a(2) = - kp * psi%a(1) + ((0,1) * k%x(2)) * psi%a(2)
kgpsi2%a(3) = ((0,-1) * k%x(2)) * psi%a(3) + kp * psi%a(4)
kgpsi2%a(4) = km * psi%a(3) + ((0,1) * k%x(2)) * psi%a(4)
kgpsi3%a(1) = (0,1) * (k%x(1) * psi%a(1) + km * psi%a(2))
kgpsi3%a(2) = (0,-1) * (kp * psi%a(1) + k%x(1) * psi%a(2))
kgpsi3%a(3) = (0,1) * (k%x(1) * psi%a(3) - kp * psi%a(4))
kgpsi3%a(4) = (0,1) * (km * psi%a(3) - k%x(1) * psi%a(4))
kgpsi4%a(1) = -k%t * psi%a(1) - k12s * psi%a(2)
kgpsi4%a(2) = k12 * psi%a(1) + k%t * psi%a(2)
kgpsi4%a(3) = k%t * psi%a(3) - k12s * psi%a(4)
kgpsi4%a(4) = k12 * psi%a(3) - k%t * psi%a(4)
psibarpsi%t = 2 * (psibar * kgpsi1)
psibarpsi%x(1) = 2 * (psibar * kgpsi2)
psibarpsi%x(2) = 2 * (psibar * kgpsi3)
psibarpsi%x(3) = 2 * (psibar * kgpsi4)
end function vv_ff

```

*(Implementation of bispinor currents)+≡*

```

pure function f_vvf (v, psi, k) result (kvpsi)
    type(bispinor) :: kvpsi
    type(bispinor), intent(in) :: psi
    type(vector), intent(in) :: k, v
    complex(kind=default) :: kv30, kv21, kv01, kv31, kv02, kv32
    complex(kind=default) :: ap, am, bp, bm, bps, bms
    kv30 = k%x(3) * v%t - k%t * v%x(3)
    kv21 = (0,1) * (k%x(2) * v%x(1) - k%x(1) * v%x(2))
    kv01 = k%t * v%x(1) - k%x(1) * v%t
    kv31 = k%x(3) * v%x(1) - k%x(1) * v%x(3)
    kv02 = (0,1) * (k%t * v%x(2) - k%x(2) * v%t)
    kv32 = (0,1) * (k%x(3) * v%x(2) - k%x(2) * v%x(3))
    ap = 2 * (kv30 + kv21)
    am = 2 * (-kv30 + kv21)
    bp = 2 * (kv01 + kv31 + kv02 + kv32)
    bm = 2 * (kv01 - kv31 + kv02 - kv32)
    bps = 2 * (kv01 + kv31 - kv02 - kv32)
    bms = 2 * (kv01 - kv31 - kv02 + kv32)
    kvpsi%a(1) = am * psi%a(1) + bms * psi%a(2)
    kvpsi%a(2) = bp * psi%a(1) - am * psi%a(2)
    kvpsi%a(3) = ap * psi%a(3) - bps * psi%a(4)
    kvpsi%a(4) = -bm * psi%a(3) - ap * psi%a(4)
end function f_vvf

```

*(Implementation of bispinor currents)+≡*

```

pure function vmom_ff (g, psibar, psi, k) result (psibarpsi)
    type(vector) :: psibarpsi
    complex(kind=default), intent(in) :: g
    type(bispinor), intent(in) :: psibar, psi
    type(momentum), intent(in) :: k
    type(vector) :: vk
    vk = k
    psibarpsi = g * vv_ff (psibar, psi, vk)
end function vmom_ff

```

```

<Implementation of bispinor currents>+≡
pure function mom_ff (g, m, psibar, psi, k) result (psibarpsi)
  complex(kind=default) :: psibarpsi
  type(bispinor), intent(in) :: psibar, psi
  type(momentum), intent(in) :: k
  complex(kind=default), intent(in) :: g, m
  type(bispinor) :: kmpsi
  complex(kind=default) :: kp, km, k12, k12s
  kp = k%t + k%x(3)
  km = k%t - k%x(3)
  k12 = k%x(1) + (0,1)*k%x(2)
  k12s = k%x(1) - (0,1)*k%x(2)
  kmpsi%a(1) = km * psi%a(3) - k12s * psi%a(4)
  kmpsi%a(2) = kp * psi%a(4) - k12 * psi%a(3)
  kmpsi%a(3) = kp * psi%a(1) + k12s * psi%a(2)
  kmpsi%a(4) = k12 * psi%a(1) + km * psi%a(2)
  psibarpsi = g * (psibar * kmpsi) + s_ff (m, psibar, psi)
end function mom_ff

<Implementation of bispinor currents>+≡
pure function mom5_ff (g, m, psibar, psi, k) result (psibarpsi)
  complex(kind=default) :: psibarpsi
  type(bispinor), intent(in) :: psibar, psi
  type(momentum), intent(in) :: k
  complex(kind=default), intent(in) :: g, m
  type(bispinor) :: g5psi
  g5psi%a(1:2) = - psi%a(1:2)
  g5psi%a(3:4) = psi%a(3:4)
  psibarpsi = mom_ff (g, m, psibar, g5psi, k)
end function mom5_ff

<Implementation of bispinor currents>+≡
pure function moml_ff (g, m, psibar, psi, k) result (psibarpsi)
  complex(kind=default) :: psibarpsi
  type(bispinor), intent(in) :: psibar, psi
  type(momentum), intent(in) :: k
  complex(kind=default), intent(in) :: g, m
  type(bispinor) :: leftpsi
  leftpsi%a(1:2) = 2 * psi%a(1:2)
  leftpsi%a(3:4) = 0
  psibarpsi = mom_ff (g, m, psibar, leftpsi, k)
end function moml_ff

<Implementation of bispinor currents>+≡
pure function momr_ff (g, m, psibar, psi, k) result (psibarpsi)
  complex(kind=default) :: psibarpsi
  type(bispinor), intent(in) :: psibar, psi
  type(momentum), intent(in) :: k
  complex(kind=default), intent(in) :: g, m
  type(bispinor) :: rightpsi
  rightpsi%a(1:2) = 0
  rightpsi%a(3:4) = 2 * psi%a(3:4)
  psibarpsi = mom_ff (g, m, psibar, rightpsi, k)
end function momr_ff

<Implementation of bispinor currents>+≡

```

```

pure function lmom_ff (g, m, psibar, psi, k) result (psibarpsi)
  complex(kind=default) :: psibarpsi
  type(bispinor), intent(in) :: psibar, psi
  type(momentum), intent(in) :: k
  complex(kind=default), intent(in) :: g, m
  psibarpsi = mom_ff (g, m, psibar, psi, k) + &
    mom5_ff (g,-m, psibar, psi, k)
end function lmom_ff

<Implementation of bispinor currents>+≡
pure function rmom_ff (g, m, psibar, psi, k) result (psibarpsi)
  complex(kind=default) :: psibarpsi
  type(bispinor), intent(in) :: psibar, psi
  type(momentum), intent(in) :: k
  complex(kind=default), intent(in) :: g, m
  psibarpsi = mom_ff (g, m, psibar, psi, k) - &
    mom5_ff (g,-m, psibar, psi, k)
end function rmom_ff

<Declaration of bispinor currents>+≡
public :: f_vmomf, f_momf, f_mom5f, f_momlf, f_momrf, f_lmomf, f_rmomf

<Implementation of bispinor currents>+≡
pure function f_vmomf (g, v, psi, k) result (kvpsi)
  type(bispinor) :: kvpsi
  type(bispinor), intent(in) :: psi
  complex(kind=default), intent(in) :: g
  type(momentum), intent(in) :: k
  type(vector), intent(in) :: v
  type(vector) :: vk
  vk = k
  kvpsi = g * f_vvf (v, psi, vk)
end function f_vmomf

<Implementation of bispinor currents>+≡
pure function f_momf (g, m, phi, psi, k) result (kmpsi)
  type(bispinor) :: kmpsi
  type(bispinor), intent(in) :: psi
  complex(kind=default), intent(in) :: phi, g, m
  type(momentum), intent(in) :: k
  complex(kind=default) :: kp, km, k12, k12s
  kp = k%t + k%x(3)
  km = k%t - k%x(3)
  k12 = k%x(1) + (0,1)*k%x(2)
  k12s = k%x(1) - (0,1)*k%x(2)
  kmpsi%a(1) = km * psi%a(3) - k12s * psi%a(4)
  kmpsi%a(2) = -k12 * psi%a(3) + kp * psi%a(4)
  kmpsi%a(3) = kp * psi%a(1) + k12s * psi%a(2)
  kmpsi%a(4) = k12 * psi%a(1) + km * psi%a(2)
  kmpsi = g * (phi * kmpsi) + f_sf (m, phi, psi)
end function f_momf

<Implementation of bispinor currents>+≡
pure function f_mom5f (g, m, phi, psi, k) result (kmpsi)
  type(bispinor) :: kmpsi
  type(bispinor), intent(in) :: psi
  complex(kind=default), intent(in) :: phi, g, m

```



```

    type(momentum), intent(in) :: k
    type(bispinor) :: g5psi
    g5psi%a(1:2) = - psi%a(1:2)
    g5psi%a(3:4) = psi%a(3:4)
    kmpsi = f_momf (g, m, phi, g5psi, k)
end function f_mom5f

<Implementation of bispinor currents>+≡
pure function f_momlf (g, m, phi, psi, k) result (kmpsi)
    type(bispinor) :: kmpsi
    type(bispinor), intent(in) :: psi
    complex(kind=default), intent(in) :: phi, g, m
    type(momentum), intent(in) :: k
    type(bispinor) :: leftpsi
    leftpsi%a(1:2) = 2 * psi%a(1:2)
    leftpsi%a(3:4) = 0
    kmpsi = f_momf (g, m, phi, leftpsi, k)
end function f_momlf

<Implementation of bispinor currents>+≡
pure function f_momrf (g, m, phi, psi, k) result (kmpsi)
    type(bispinor) :: kmpsi
    type(bispinor), intent(in) :: psi
    complex(kind=default), intent(in) :: phi, g, m
    type(momentum), intent(in) :: k
    type(bispinor) :: rightpsi
    rightpsi%a(1:2) = 0
    rightpsi%a(3:4) = 2 * psi%a(3:4)
    kmpsi = f_momf (g, m, phi, rightpsi, k)
end function f_momrf

<Implementation of bispinor currents>+≡
pure function f_lmomf (g, m, phi, psi, k) result (kmpsi)
    type(bispinor) :: kmpsi
    type(bispinor), intent(in) :: psi
    complex(kind=default), intent(in) :: phi, g, m
    type(momentum), intent(in) :: k
    kmpsi = f_momf (g, m, phi, psi, k) + &
        f_mom5f (g,-m, phi, psi, k)
end function f_lmomf

<Implementation of bispinor currents>+≡
pure function f_rmomf (g, m, phi, psi, k) result (kmpsi)
    type(bispinor) :: kmpsi
    type(bispinor), intent(in) :: psi
    complex(kind=default), intent(in) :: phi, g, m
    type(momentum), intent(in) :: k
    kmpsi = f_momf (g, m, phi, psi, k) - &
        f_mom5f (g,-m, phi, psi, k)
end function f_rmomf

```

#### 4-Couplings

```

<Declaration of bispinor currents>+≡
public :: v2_ff, sv1_ff, sv2_ff, pv1_ff, pv2_ff, svl1_ff, svl2_ff, &
        svr1_ff, svr2_ff, svlr1_ff, svlr2_ff

```

```

<Implementation of bispinor currents>+≡
pure function v2_ff (g, psibar, v, psi) result (v2)
  type(vector) :: v2
  complex(kind=default), intent(in) :: g
  type(bispinor), intent(in) :: psibar, psi
  type(vector), intent(in) :: v
  v2 = (-g) * vv_ff (psibar, psi, v)
end function v2_ff

<Implementation of bispinor currents>+≡
pure function sv1_ff (g, psibar, v, psi) result (phi)
  complex(kind=default) :: phi
  type(bispinor), intent(in) :: psibar, psi
  type(vector), intent(in) :: v
  complex(kind=default), intent(in) :: g
  phi = psibar * f_vf (g, v, psi)
end function sv1_ff

<Implementation of bispinor currents>+≡
pure function sv2_ff (g, psibar, phi, psi) result (v)
  type(vector) :: v
  complex(kind=default), intent(in) :: phi, g
  type(bispinor), intent(in) :: psibar, psi
  v = phi * v_ff (g, psibar, psi)
end function sv2_ff

<Implementation of bispinor currents>+≡
pure function pv1_ff (g, psibar, v, psi) result (phi)
  complex(kind=default) :: phi
  type(bispinor), intent(in) :: psibar, psi
  type(vector), intent(in) :: v
  complex(kind=default), intent(in) :: g
  phi = - (psibar * f_af (g, v, psi))
end function pv1_ff

<Implementation of bispinor currents>+≡
pure function pv2_ff (g, psibar, phi, psi) result (v)
  type(vector) :: v
  complex(kind=default), intent(in) :: phi, g
  type(bispinor), intent(in) :: psibar, psi
  v = -(phi * a_ff (g, psibar, psi))
end function pv2_ff

<Implementation of bispinor currents>+≡
pure function svl1_ff (g, psibar, v, psi) result (phi)
  complex(kind=default) :: phi
  type(bispinor), intent(in) :: psibar, psi
  type(vector), intent(in) :: v
  complex(kind=default), intent(in) :: g
  phi = psibar * f_vlf (g, v, psi)
end function svl1_ff

<Implementation of bispinor currents>+≡
pure function svl2_ff (g, psibar, phi, psi) result (v)
  type(vector) :: v
  complex(kind=default), intent(in) :: phi, g
  type(bispinor), intent(in) :: psibar, psi

```

```

    v = phi * vl_ff (g, psibar, psi)
end function svl2_ff

<Implementation of bispinor currents>+≡
pure function svr1_ff (g, psibar, v, psi) result (phi)
    complex(kind=default) :: phi
    type(bispinor), intent(in) :: psibar, psi
    type(vector), intent(in) :: v
    complex(kind=default), intent(in) :: g
    phi = psibar * f_vrf (g, v, psi)
end function svr1_ff

<Implementation of bispinor currents>+≡
pure function svr2_ff (g, psibar, phi, psi) result (v)
    type(vector) :: v
    complex(kind=default), intent(in) :: phi, g
    type(bispinor), intent(in) :: psibar, psi
    v = phi * vr_ff (g, psibar, psi)
end function svr2_ff

<Implementation of bispinor currents>+≡
pure function svlr1_ff (gl, gr, psibar, v, psi) result (phi)
    complex(kind=default) :: phi
    type(bispinor), intent(in) :: psibar, psi
    type(vector), intent(in) :: v
    complex(kind=default), intent(in) :: gl, gr
    phi = psibar * f_vlrf (gl, gr, v, psi)
end function svlr1_ff

<Implementation of bispinor currents>+≡
pure function svlr2_ff (gl, gr, psibar, phi, psi) result (v)
    type(vector) :: v
    complex(kind=default), intent(in) :: phi, gl, gr
    type(bispinor), intent(in) :: psibar, psi
    v = phi * vlr_ff (gl, gr, psibar, psi)
end function svlr2_ff

<Declaration of bispinor currents>+≡
public :: f_v2f, f_svf, f_pvf, f_svlf, f_svrff, f_svlrf

<Implementation of bispinor currents>+≡
pure function f_v2f (g, v1, v2, psi) result (vpsi)
    type(bispinor) :: vpsi
    complex(kind=default), intent(in) :: g
    type(bispinor), intent(in) :: psi
    type(vector), intent(in) :: v1, v2
    vpsi = g * f_vvf (v2, psi, v1)
end function f_v2f

<Implementation of bispinor currents>+≡
pure function f_svf (g, phi, v, psi) result (pvpsi)
    type(bispinor) :: pvpsi
    complex(kind=default), intent(in) :: g, phi
    type(bispinor), intent(in) :: psi
    type(vector), intent(in) :: v
    pvpsi = phi * f_vf (g, v, psi)
end function f_svf

```

```

<Implementation of bispinor currents>+≡
pure function f_pvf (g, phi, v, psi) result (pvpsi)
  type(bispinor) :: pvpsi
  complex(kind=default), intent(in) :: g, phi
  type(bispinor), intent(in) :: psi
  type(vector), intent(in) :: v
  pvpsi = -(phi * f_af (g, v, psi))
end function f_pvf

<Implementation of bispinor currents>+≡
pure function f_svlf (g, phi, v, psi) result (pvpsi)
  type(bispinor) :: pvpsi
  complex(kind=default), intent(in) :: g, phi
  type(bispinor), intent(in) :: psi
  type(vector), intent(in) :: v
  pvpsi = phi * f_vlf (g, v, psi)
end function f_svlf

<Implementation of bispinor currents>+≡
pure function f_svr (g, phi, v, psi) result (pvpsi)
  type(bispinor) :: pvpsi
  complex(kind=default), intent(in) :: g, phi
  type(bispinor), intent(in) :: psi
  type(vector), intent(in) :: v
  pvpsi = phi * f_vrf (g, v, psi)
end function f_svr

<Implementation of bispinor currents>+≡
pure function f_svlrf (gl, gr, phi, v, psi) result (pvpsi)
  type(bispinor) :: pvpsi
  complex(kind=default), intent(in) :: gl, gr, phi
  type(bispinor), intent(in) :: psi
  type(vector), intent(in) :: v
  pvpsi = phi * f_vlrf (gl, gr, v, psi)
end function f_svlrf

```

#### X.14.4 Gravitino Couplings

```

<Declaration of bispinor currents>+≡
public :: pot_grf, pot_fgr, s_grf, s_fgr, p_grf, p_fgr, &
  sl_grf, sl_fgr, sr_grf, sr_fgr, slr_grf, slr_fgr

<Declaration of bispinor currents>+≡
private :: fgvgr, fgv5gr, fggvgr, grkgf, grkggf, grkkggf, &
  fgkgr, fg5gkgr, grvgf, grg5vgf, grkgggf, fggkgr

<Implementation of bispinor currents>+≡
pure function pot_grf (g, gravbar, psi) result (j)
  complex(kind=default) :: j
  complex(kind=default), intent(in) :: g
  type(vectorspinor), intent(in) :: gravbar
  type(bispinor), intent(in) :: psi
  type(vectorspinor) :: gamma_psi
  gamma_psi%psi(1)%a(1) = psi%a(3)
  gamma_psi%psi(1)%a(2) = psi%a(4)
  gamma_psi%psi(1)%a(3) = psi%a(1)

```

```

gamma_psi%psi(1)%a(4) = psi%a(2)
gamma_psi%psi(2)%a(1) = psi%a(4)
gamma_psi%psi(2)%a(2) = psi%a(3)
gamma_psi%psi(2)%a(3) = - psi%a(2)
gamma_psi%psi(2)%a(4) = - psi%a(1)
gamma_psi%psi(3)%a(1) = (0,-1) * psi%a(4)
gamma_psi%psi(3)%a(2) = (0,1) * psi%a(3)
gamma_psi%psi(3)%a(3) = (0,1) * psi%a(2)
gamma_psi%psi(3)%a(4) = (0,-1) * psi%a(1)
gamma_psi%psi(4)%a(1) = psi%a(3)
gamma_psi%psi(4)%a(2) = - psi%a(4)
gamma_psi%psi(4)%a(3) = - psi%a(1)
gamma_psi%psi(4)%a(4) = psi%a(2)
j = g * (gravbar * gamma_psi)
end function pot_grf

```

(Implementation of bispinor currents)+≡

```

pure function pot_fgr (g, psibar, grav) result (j)
  complex(kind=default) :: j
  complex(kind=default), intent(in) :: g
  type(bispinor), intent(in) :: psibar
  type(vectorspinor), intent(in) :: grav
  type(bispinor) :: gamma_grav
  gamma_grav%a(1) = grav%psi(1)%a(3) - grav%psi(2)%a(4) + &
    ((0,1)*grav%psi(3)%a(4)) - grav%psi(4)%a(3)
  gamma_grav%a(2) = grav%psi(1)%a(4) - grav%psi(2)%a(3) - &
    ((0,1)*grav%psi(3)%a(3)) + grav%psi(4)%a(4)
  gamma_grav%a(3) = grav%psi(1)%a(1) + grav%psi(2)%a(2) - &
    ((0,1)*grav%psi(3)%a(2)) + grav%psi(4)%a(1)
  gamma_grav%a(4) = grav%psi(1)%a(2) + grav%psi(2)%a(1) + &
    ((0,1)*grav%psi(3)%a(1)) - grav%psi(4)%a(2)
  j = g * (psibar * gamma_grav)
end function pot_fgr

```

(Implementation of bispinor currents)+≡

```

pure function grvgf (gravbar, psi, k) result (j)
  complex(kind=default) :: j
  complex(kind=default) :: kp, km, k12, k12s
  type(vectorspinor), intent(in) :: gravbar
  type(bispinor), intent(in) :: psi
  type(vector), intent(in) :: k
  type(vectorspinor) :: kg_psi
  kp = k%t + k%x(3)
  km = k%t - k%x(3)
  k12 = k%x(1) + (0,1)*k%x(2)
  k12s = k%x(1) - (0,1)*k%x(2)
  !!! Since we are taking the spinor product here, NO explicit
  !!! charge conjugation matrix is needed!
  kg_psi%psi(1)%a(1) = km * psi%a(1) - k12s * psi%a(2)
  kg_psi%psi(1)%a(2) = (-k12) * psi%a(1) + kp * psi%a(2)
  kg_psi%psi(1)%a(3) = kp * psi%a(3) + k12s * psi%a(4)
  kg_psi%psi(1)%a(4) = k12 * psi%a(3) + km * psi%a(4)
  kg_psi%psi(2)%a(1) = k12s * psi%a(1) - km * psi%a(2)
  kg_psi%psi(2)%a(2) = (-kp) * psi%a(1) + k12 * psi%a(2)
  kg_psi%psi(2)%a(3) = k12s * psi%a(3) + kp * psi%a(4)

```

```

kg_psi%psi(2)%a(4) = km * psi%a(3) + k12 * psi%a(4)
kg_psi%psi(3)%a(1) = (0,1) * (k12s * psi%a(1) + km * psi%a(2))
kg_psi%psi(3)%a(2) = (0,1) * (- kp * psi%a(1) - k12 * psi%a(2))
kg_psi%psi(3)%a(3) = (0,1) * (k12s * psi%a(3) - kp * psi%a(4))
kg_psi%psi(3)%a(4) = (0,1) * (km * psi%a(3) - k12 * psi%a(4))
kg_psi%psi(4)%a(1) = (-km) * psi%a(1) - k12s * psi%a(2)
kg_psi%psi(4)%a(2) = k12 * psi%a(1) + kp * psi%a(2)
kg_psi%psi(4)%a(3) = kp * psi%a(3) - k12s * psi%a(4)
kg_psi%psi(4)%a(4) = k12 * psi%a(3) - km * psi%a(4)
j = gravbar * kg_psi
end function grvgf

<Implementation of bispinor currents>+=
pure function grg5vgf (gravbar, psi, k) result (j)
  complex(kind=default) :: j
  type(vectorspinor), intent(in) :: gravbar
  type(bispinor), intent(in) :: psi
  type(vector), intent(in) :: k
  type(bispinor) :: g5_psi
  g5_psi%a(1:2) = - psi%a(1:2)
  g5_psi%a(3:4) = psi%a(3:4)
  j = grvgf (gravbar, g5_psi, k)
end function grg5vgf

<Implementation of bispinor currents>+=
pure function s_grf (g, gravbar, psi, k) result (j)
  complex(kind=default) :: j
  complex(kind=default), intent(in) :: g
  type(vectorspinor), intent(in) :: gravbar
  type(bispinor), intent(in) :: psi
  type(momentum), intent(in) :: k
  type(vector) :: vk
  vk = k
  j = g * grvgf (gravbar, psi, vk)
end function s_grf

<Implementation of bispinor currents>+=
pure function sl_grf (gl, gravbar, psi, k) result (j)
  complex(kind=default) :: j
  complex(kind=default), intent(in) :: gl
  type(vectorspinor), intent(in) :: gravbar
  type(bispinor), intent(in) :: psi
  type(bispinor) :: psi_l
  type(momentum), intent(in) :: k
  psi_l%a(1:2) = psi%a(1:2)
  psi_l%a(3:4) = 0
  j = s_grf (gl, gravbar, psi_l, k)
end function sl_grf

<Implementation of bispinor currents>+=
pure function sr_grf (gr, gravbar, psi, k) result (j)
  complex(kind=default) :: j
  complex(kind=default), intent(in) :: gr
  type(vectorspinor), intent(in) :: gravbar
  type(bispinor), intent(in) :: psi
  type(bispinor) :: psi_r

```

```

    type(momentum), intent(in) :: k
    psi_r%a(1:2) = 0
    psi_r%a(3:4) = psi%a(3:4)
    j = s_grf (gr, gravbar, psi_r, k)
end function sr_grf

<Implementation of bispinor currents>+≡
pure function slr_grf (gl, gr, gravbar, psi, k) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: gl, gr
    type(vectorspinor), intent(in) :: gravbar
    type(bispinor), intent(in) :: psi
    type(momentum), intent(in) :: k
    j = sl_grf (gl, gravbar, psi, k) + sr_grf (gr, gravbar, psi, k)
end function slr_grf

<Implementation of bispinor currents>+≡
pure function fgkgr (psibar, grav, k) result (j)
    complex(kind=default) :: j
    complex(kind=default) :: kp, km, k12, k12s
    type(bispinor), intent(in) :: psibar
    type(vectorspinor), intent(in) :: grav
    type(vector), intent(in) :: k
    type(bispinor) :: gk_grav
    kp = k%t + k%x(3)
    km = k%t - k%x(3)
    k12 = k%x(1) + (0,1)*k%x(2)
    k12s = k%x(1) - (0,1)*k%x(2)
    !!! Since we are taking the spinor product here, NO explicit
    !!! charge conjugation matrix is needed!
    gk_grav%a(1) = kp * grav%psi(1)%a(1) + k12s * grav%psi(1)%a(2) &
        - k12 * grav%psi(2)%a(1) - km * grav%psi(2)%a(2) &
        + (0,1) * k12 * grav%psi(3)%a(1) &
        + (0,1) * km * grav%psi(3)%a(2) &
        - kp * grav%psi(4)%a(1) - k12s * grav%psi(4)%a(2)
    gk_grav%a(2) = k12 * grav%psi(1)%a(1) + km * grav%psi(1)%a(2) &
        - kp * grav%psi(2)%a(1) - k12s * grav%psi(2)%a(2) &
        - (0,1) * kp * grav%psi(3)%a(1) &
        - (0,1) * k12s * grav%psi(3)%a(2) &
        + k12 * grav%psi(4)%a(1) + km * grav%psi(4)%a(2)
    gk_grav%a(3) = km * grav%psi(1)%a(3) - k12s * grav%psi(1)%a(4) &
        - k12 * grav%psi(2)%a(3) + kp * grav%psi(2)%a(4) &
        + (0,1) * k12 * grav%psi(3)%a(3) &
        - (0,1) * kp * grav%psi(3)%a(4) &
        + km * grav%psi(4)%a(3) - k12s * grav%psi(4)%a(4)
    gk_grav%a(4) = - k12 * grav%psi(1)%a(3) + kp * grav%psi(1)%a(4) &
        + km * grav%psi(2)%a(3) - k12s * grav%psi(2)%a(4) &
        + (0,1) * km * grav%psi(3)%a(3) &
        - (0,1) * k12s * grav%psi(3)%a(4) &
        + k12 * grav%psi(4)%a(3) - kp * grav%psi(4)%a(4)
    j = psibar * gk_grav
end function fgkgr

<Implementation of bispinor currents>+≡
pure function fg5gkgr (psibar, grav, k) result (j)
    complex(kind=default) :: j

```

```

    type(bispinor), intent(in) :: psibar
    type(vectorspinor), intent(in) :: grav
    type(vector), intent(in) :: k
    type(bispinor) :: psibar_g5
    psibar_g5%a(1:2) = - psibar%a(1:2)
    psibar_g5%a(3:4) = psibar%a(3:4)
    j = fgkgr (psibar_g5, grav, k)
end function fg5gkgr

<Implementation of bispinor currents>+≡
pure function s_fgr (g, psibar, grav, k) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: g
    type(bispinor), intent(in) :: psibar
    type(vectorspinor), intent(in) :: grav
    type(momentum), intent(in) :: k
    type(vector) :: vk
    vk = k
    j = g * fgkgr (psibar, grav, vk)
end function s_fgr

<Implementation of bispinor currents>+≡
pure function sl_fgr (gl, psibar, grav, k) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: gl
    type(bispinor), intent(in) :: psibar
    type(bispinor) :: psibar_l
    type(vectorspinor), intent(in) :: grav
    type(momentum), intent(in) :: k
    psibar_l%a(1:2) = psibar%a(1:2)
    psibar_l%a(3:4) = 0
    j = s_fgr (gl, psibar_l, grav, k)
end function sl_fgr

<Implementation of bispinor currents>+≡
pure function sr_fgr (gr, psibar, grav, k) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: gr
    type(bispinor), intent(in) :: psibar
    type(bispinor) :: psibar_r
    type(vectorspinor), intent(in) :: grav
    type(momentum), intent(in) :: k
    psibar_r%a(1:2) = 0
    psibar_r%a(3:4) = psibar%a(3:4)
    j = s_fgr (gr, psibar_r, grav, k)
end function sr_fgr

<Implementation of bispinor currents>+≡
pure function slr_fgr (gl, gr, psibar, grav, k) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: gl, gr
    type(bispinor), intent(in) :: psibar
    type(vectorspinor), intent(in) :: grav
    type(momentum), intent(in) :: k
    j = sl_fgr (gl, psibar, grav, k) + sr_fgr (gr, psibar, grav, k)
end function slr_fgr

```



```

<Implementation of bispinor currents>+=
pure function p_grf (g, gravbar, psi, k) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: g
    type(vectorspinor), intent(in) :: gravbar
    type(bispinor), intent(in) :: psi
    type(momentum), intent(in) :: k
    type(vector) :: vk
    vk = k
    j = g * grg5vgf (gravbar, psi, vk)
end function p_grf

<Implementation of bispinor currents>+=
pure function p_fgr (g, psibar, grav, k) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: g
    type(bispinor), intent(in) :: psibar
    type(vectorspinor), intent(in) :: grav
    type(momentum), intent(in) :: k
    type(vector) :: vk
    vk = k
    j = g * fg5gkgr (psibar, grav, vk)
end function p_fgr

<Declaration of bispinor currents>+=
public :: f_potgr, f_sgr, f_pgr, f_vgr, f_vlgr, f_slgr, f_srgr, f_slgr

<Implementation of bispinor currents>+=
pure function f_potgr (g, phi, psi) result (phipsi)
    type(bispinor) :: phipsi
    complex(kind=default), intent(in) :: g
    complex(kind=default), intent(in) :: phi
    type(vectorspinor), intent(in) :: psi
    phipsi%a(1) = (g * phi) * (psi%psi(1)%a(3) - psi%psi(2)%a(4) + &
        ((0,1)*psi%psi(3)%a(4)) - psi%psi(4)%a(3))
    phipsi%a(2) = (g * phi) * (psi%psi(1)%a(4) - psi%psi(2)%a(3) - &
        ((0,1)*psi%psi(3)%a(3)) + psi%psi(4)%a(4))
    phipsi%a(3) = (g * phi) * (psi%psi(1)%a(1) + psi%psi(2)%a(2) - &
        ((0,1)*psi%psi(3)%a(2)) + psi%psi(4)%a(1))
    phipsi%a(4) = (g * phi) * (psi%psi(1)%a(2) + psi%psi(2)%a(1) + &
        ((0,1)*psi%psi(3)%a(1)) - psi%psi(4)%a(2))
end function f_potgr
    
```

The slashed notation:

$$\not{k} = \begin{pmatrix} 0 & 0 & k_- & -k^* \\ 0 & 0 & -k & k_+ \\ k_+ & k^* & 0 & 0 \\ k & k_- & 0 & 0 \end{pmatrix}, \quad \not{k}\gamma_5 = \begin{pmatrix} 0 & 0 & k_- & -k^* \\ 0 & 0 & -k & k_+ \\ -k_+ & -k^* & 0 & 0 \\ -k & -k_- & 0 & 0 \end{pmatrix} \quad (\text{X.74})$$

with  $k_{\pm} = k_0 \pm k_3$ ,  $k = k_1 + ik_2$ ,  $k^* = k_1 - ik_2$ . But note that  $\cdot^*$  is *not* complex conjugation for complex  $k_{\mu}$ .

$$\gamma^0 \not{k} = \begin{pmatrix} k_+ & k^* & 0 & 0 \\ k & k_- & 0 & 0 \\ 0 & 0 & k_- & -k^* \\ 0 & 0 & -k & k_+ \end{pmatrix}, \quad \gamma^0 \not{k}\gamma^5 = \begin{pmatrix} -k_+ & -k^* & 0 & 0 \\ -k & -k_- & 0 & 0 \\ 0 & 0 & k_- & -k^* \\ 0 & 0 & -k & k_+ \end{pmatrix} \quad (\text{X.75a})$$

$$\gamma^1 \not{k} = \begin{pmatrix} k & k_- & 0 & 0 \\ k_+ & k^* & 0 & 0 \\ 0 & 0 & k & -k_+ \\ 0 & 0 & -k_- & k^* \end{pmatrix}, \quad \gamma^1 \not{k} \gamma^5 = \begin{pmatrix} -k & -k_- & 0 & 0 \\ -k_+ & -k^* & 0 & 0 \\ 0 & 0 & k & -k_+ \\ 0 & 0 & -k_- & k^* \end{pmatrix} \quad (\text{X.75b})$$

$$\gamma^2 \not{k} = \begin{pmatrix} -ik & -ik_- & 0 & 0 \\ ik_+ & ik^* & 0 & 0 \\ 0 & 0 & -ik & ik_+ \\ 0 & 0 & -ik_- & ik^* \end{pmatrix}, \quad \gamma^2 \not{k} \gamma^5 = \begin{pmatrix} ik & ik_- & 0 & 0 \\ -ik_+ & -ik^* & 0 & 0 \\ 0 & 0 & -ik & ik_+ \\ 0 & 0 & -ik_- & ik^* \end{pmatrix} \quad (\text{X.75c})$$

$$\gamma^3 \not{k} = \begin{pmatrix} k_+ & k^* & 0 & 0 \\ -k & -k_- & 0 & 0 \\ 0 & 0 & -k_- & k^* \\ 0 & 0 & -k & k_+ \end{pmatrix}, \quad \gamma^3 \not{k} \gamma^5 = \begin{pmatrix} -k_+ & -k^* & 0 & 0 \\ k & k_- & 0 & 0 \\ 0 & 0 & -k_- & k^* \\ 0 & 0 & -k & k_+ \end{pmatrix} \quad (\text{X.75d})$$

and

$$\not{k} \gamma^0 = \begin{pmatrix} k_- & -k^* & 0 & 0 \\ -k & k_+ & 0 & 0 \\ 0 & 0 & k_+ & k^* \\ 0 & 0 & k & k_- \end{pmatrix}, \quad \not{k} \gamma^0 \gamma^5 = \begin{pmatrix} -k_- & k^* & 0 & 0 \\ k & -k_+ & 0 & 0 \\ 0 & 0 & k_+ & k^* \\ 0 & 0 & k & k_- \end{pmatrix} \quad (\text{X.76a})$$

$$\not{k} \gamma^1 = \begin{pmatrix} k^* & -k_- & 0 & 0 \\ -k_+ & k & 0 & 0 \\ 0 & 0 & k^* & k_+ \\ 0 & 0 & k_- & k \end{pmatrix}, \quad \not{k} \gamma^1 \gamma^5 = \begin{pmatrix} -k^* & k_- & 0 & 0 \\ k_+ & -k & 0 & 0 \\ 0 & 0 & k^* & k_+ \\ 0 & 0 & k_- & k \end{pmatrix} \quad (\text{X.76b})$$

$$\not{k} \gamma^2 = \begin{pmatrix} ik^* & ik_- & 0 & 0 \\ -ik_+ & -ik & 0 & 0 \\ 0 & 0 & ik^* & -ik_+ \\ 0 & 0 & ik_- & -ik \end{pmatrix}, \quad \not{k} \gamma^2 \gamma^5 = \begin{pmatrix} -ik^* & -ik_- & 0 & 0 \\ ik_+ & ik & 0 & 0 \\ 0 & 0 & ik^* & -ik_+ \\ 0 & 0 & ik_- & -ik \end{pmatrix} \quad (\text{X.76c})$$

$$\not{k} \gamma^3 = \begin{pmatrix} -k_- & -k^* & 0 & 0 \\ k & k_+ & 0 & 0 \\ 0 & 0 & k_+ & -k^* \\ 0 & 0 & k & -k_- \end{pmatrix}, \quad \not{k} \gamma^3 \gamma^5 = \begin{pmatrix} k_- & k^* & 0 & 0 \\ -k & -k_+ & 0 & 0 \\ 0 & 0 & k_+ & -k^* \\ 0 & 0 & k & -k_- \end{pmatrix} \quad (\text{X.76d})$$

and

$$C \gamma^0 \not{k} = \begin{pmatrix} k & k_- & 0 & 0 \\ -k_+ & -k^* & 0 & 0 \\ 0 & 0 & k & -k_+ \\ 0 & 0 & k_- & -k^* \end{pmatrix}, \quad C \gamma^0 \not{k} \gamma^5 = \begin{pmatrix} -k & -k_- & 0 & 0 \\ k_+ & k^* & 0 & 0 \\ 0 & 0 & k & -k_+ \\ 0 & 0 & k_- & -k^* \end{pmatrix} \quad (\text{X.77a})$$

$$C\gamma^1 \not{k} = \begin{pmatrix} k_+ & k^* & 0 & 0 \\ -k & -k_- & 0 & 0 \\ 0 & 0 & k_- & -k^* \\ 0 & 0 & k & -k_+ \end{pmatrix}, \quad C\gamma^1 \not{k} \gamma^5 = \begin{pmatrix} -k_+ & -k^* & 0 & 0 \\ k & k_- & 0 & 0 \\ 0 & 0 & k_- & -k^* \\ 0 & 0 & k & -k_+ \end{pmatrix} \quad (\text{X.77b})$$

$$C\gamma^2 \not{k} = \begin{pmatrix} ik_+ & ik^* & 0 & 0 \\ ik & ik_- & 0 & 0 \\ 0 & 0 & ik_- & -ik^* \\ 0 & 0 & -ik & ik_+ \end{pmatrix}, \quad C\gamma^2 \not{k} \gamma^5 = \begin{pmatrix} -ik_+ & -ik^* & 0 & 0 \\ -ik & -ik_- & 0 & 0 \\ 0 & 0 & ik_- & -ik^* \\ 0 & 0 & -ik & ik_+ \end{pmatrix} \quad (\text{X.77c})$$

$$C\gamma^3 \not{k} = \begin{pmatrix} -k & -k_- & 0 & 0 \\ -k_+ & -k^* & 0 & 0 \\ 0 & 0 & k & -k_+ \\ 0 & 0 & -k_- & k^* \end{pmatrix}, \quad C\gamma^3 \not{k} \gamma^5 = \begin{pmatrix} k & k_- & 0 & 0 \\ k_+ & k^* & 0 & 0 \\ 0 & 0 & k & -k_+ \\ 0 & 0 & -k_- & k^* \end{pmatrix} \quad (\text{X.77d})$$

and

$$C\not{k} \gamma^0 = \begin{pmatrix} -k & k^+ & 0 & 0 \\ -k_- & k^* & 0 & 0 \\ 0 & 0 & -k & -k_- \\ 0 & 0 & k_+ & k^* \end{pmatrix}, \quad C\not{k} \gamma^0 \gamma^5 = \begin{pmatrix} k & -k_+ & 0 & 0 \\ k_- & -k^* & 0 & 0 \\ 0 & 0 & -k & -k_- \\ 0 & 0 & k_+ & k^* \end{pmatrix} \quad (\text{X.78a})$$

$$C\not{k} \gamma^1 = \begin{pmatrix} -k_+ & k & 0 & 0 \\ -k^* & k_- & 0 & 0 \\ 0 & 0 & -k_- & -k \\ 0 & 0 & k^* & k_+ \end{pmatrix}, \quad C\not{k} \gamma^1 \gamma^5 = \begin{pmatrix} k_+ & -k & 0 & 0 \\ k^* & -k_- & 0 & 0 \\ 0 & 0 & -k_- & -k \\ 0 & 0 & k^* & k_+ \end{pmatrix} \quad (\text{X.78b})$$

$$C\not{k} \gamma^2 = \begin{pmatrix} -ik_+ & -ik & 0 & 0 \\ -ik^* & -ik_- & 0 & 0 \\ 0 & 0 & -ik_- & ik \\ 0 & 0 & ik^* & -ik_+ \end{pmatrix}, \quad C\not{k} \gamma^2 \gamma^5 = \begin{pmatrix} ik_+ & ik & 0 & 0 \\ ik^* & ik_- & 0 & 0 \\ 0 & 0 & -ik_- & ik \\ 0 & 0 & ik^* & -ik_+ \end{pmatrix} \quad (\text{X.78c})$$

$$C\not{k} \gamma^3 = \begin{pmatrix} k & k_+ & 0 & 0 \\ k_- & k^* & 0 & 0 \\ 0 & 0 & -k & k_- \\ 0 & 0 & k_+ & -k^* \end{pmatrix}, \quad C\not{k} \gamma^3 \gamma^5 = \begin{pmatrix} -k & -k_+ & 0 & 0 \\ -k_- & -k^* & 0 & 0 \\ 0 & 0 & -k & k_- \\ 0 & 0 & k_+ & -k^* \end{pmatrix} \quad (\text{X.78d})$$

*(Implementation of bispinor currents)+≡*

```
pure function fgvr (psi, k) result (kpsi)
  type(bispinor) :: kpsi
  complex(kind=default) :: kp, km, k12, k12s
  type(vector), intent(in) :: k
  type(vectorspinor), intent(in) :: psi
  kp = k%t + k%x(3)
  km = k%t - k%x(3)
  k12 = k%x(1) + (0,1)*k%x(2)
  k12s = k%x(1) - (0,1)*k%x(2)
  kpsi%a(1) = kp * psi%psi(1)%a(1) + k12s * psi%psi(1)%a(2) &
```

```

- k12 * psi%psi(2)%a(1) - km * psi%psi(2)%a(2) &
+ (0,1) * k12 * psi%psi(3)%a(1) + (0,1) * km * psi%psi(3)%a(2) &
- kp * psi%psi(4)%a(1) - k12s * psi%psi(4)%a(2)
kpsi%a(2) = k12 * psi%psi(1)%a(1) + km * psi%psi(1)%a(2) &
- kp * psi%psi(2)%a(1) - k12s * psi%psi(2)%a(2) &
- (0,1) * kp * psi%psi(3)%a(1) - (0,1) * k12s * psi%psi(3)%a(2) &
+ k12 * psi%psi(4)%a(1) + km * psi%psi(4)%a(2)
kpsi%a(3) = km * psi%psi(1)%a(3) - k12s * psi%psi(1)%a(4) &
- k12 * psi%psi(2)%a(3) + kp * psi%psi(2)%a(4) &
+ (0,1) * k12 * psi%psi(3)%a(3) - (0,1) * kp * psi%psi(3)%a(4) &
+ km * psi%psi(4)%a(3) - k12s * psi%psi(4)%a(4)
kpsi%a(4) = - k12 * psi%psi(1)%a(3) + kp * psi%psi(1)%a(4) &
+ km * psi%psi(2)%a(3) - k12s * psi%psi(2)%a(4) &
+ (0,1) * km * psi%psi(3)%a(3) - (0,1) * k12s * psi%psi(3)%a(4) &
+ k12 * psi%psi(4)%a(3) - kp * psi%psi(4)%a(4)
end function fgvgr

<Implementation of bispinor currents>+=
pure function f_sgr (g, phi, psi, k) result (phipsi)
    type(bispinor) :: phipsi
    complex(kind=default), intent(in) :: g
    complex(kind=default), intent(in) :: phi
    type(momentum), intent(in) :: k
    type(vectorspinor), intent(in) :: psi
    type(vector) :: vk
    vk = k
    phipsi = (g * phi) * fgvgr (psi, vk)
end function f_sgr

<Implementation of bispinor currents>+=
pure function f_slgr (gl, phi, psi, k) result (phipsi)
    type(bispinor) :: phipsi
    complex(kind=default), intent(in) :: gl
    complex(kind=default), intent(in) :: phi
    type(momentum), intent(in) :: k
    type(vectorspinor), intent(in) :: psi
    phipsi = f_sgr (gl, phi, psi, k)
    phipsi%a(3:4) = 0
end function f_slgr

<Implementation of bispinor currents>+=
pure function f_srgr (gr, phi, psi, k) result (phipsi)
    type(bispinor) :: phipsi
    complex(kind=default), intent(in) :: gr
    complex(kind=default), intent(in) :: phi
    type(momentum), intent(in) :: k
    type(vectorspinor), intent(in) :: psi
    phipsi = f_sgr (gr, phi, psi, k)
    phipsi%a(1:2) = 0
end function f_srgr

<Implementation of bispinor currents>+=
pure function f_slrgr (gl, gr, phi, psi, k) result (phipsi)
    type(bispinor) :: phipsi, phipsi_l, phipsi_r
    complex(kind=default), intent(in) :: gl, gr
    complex(kind=default), intent(in) :: phi

```

```

    type(momentum), intent(in) :: k
    type(vectorspinor), intent(in) :: psi
    phipsi_l = f_slgr (gl, phi, psi, k)
    phipsi_r = f_srgr (gr, phi, psi, k)
    phipsi%a(1:2) = phipsi_l%a(1:2)
    phipsi%a(3:4) = phipsi_r%a(3:4)
end function f_slgr

<Implementation of bispinor currents>+≡
pure function fgv5gr (psi, k) result (kpsi)
    type(bispinor) :: kpsi
    type(vector), intent(in) :: k
    type(vectorspinor), intent(in) :: psi
    type(bispinor) :: kpsi_dum
    kpsi_dum = fgvgr (psi, k)
    kpsi%a(1:2) = - kpsi_dum%a(1:2)
    kpsi%a(3:4) = kpsi_dum%a(3:4)
end function fgv5gr

<Implementation of bispinor currents>+≡
pure function f_pgr (g, phi, psi, k) result (phipsi)
    type(bispinor) :: phipsi
    complex(kind=default), intent(in) :: g
    complex(kind=default), intent(in) :: phi
    type(momentum), intent(in) :: k
    type(vectorspinor), intent(in) :: psi
    type(vector) :: vk
    vk = k
    phipsi = (g * phi) * fgv5gr (psi, vk)
end function f_pgr

```

The needed construction of gamma matrices involving the commutator of two gamma matrices. For the slashed terms we use as usual the abbreviations  $k_{\pm} = k_0 \pm k_3$ ,  $k = k_1 + ik_2$ ,  $k^* = k_1 - ik_2$  and analogous expressions for the vector  $v^{\mu}$ . We remind you that  $*$  is *not* complex conjugation for complex  $k_{\mu}$ . Furthermore we introduce (in what follows the brackets around the vector indices have the usual meaning of antisymmetrizing with respect to the indices inside the brackets, here without a factor two in the denominator)

$$a_+ = k_+v_- + kv^* - k_-v_+ - k^*v = 2(k_{[3}v_{0]} + ik_{[2}v_{1]}) \quad (\text{X.79a})$$

$$a_- = k_-v_+ + kv^* - k_+v_- - k^*v = 2(-k_{[3}v_{0]} + ik_{[2}v_{1]}) \quad (\text{X.79b})$$

$$b_+ = 2(k_+v - kv_+) = 2(k_{[0}v_{1]} + k_{[3}v_{1]} + ik_{[0}v_{2]} + ik_{[3}v_{2]}) \quad (\text{X.79c})$$

$$b_- = 2(k_-v - kv_-) = 2(k_{[0}v_{1]} - k_{[3}v_{1]} + ik_{[0}v_{2]} - ik_{[3}v_{2]}) \quad (\text{X.79d})$$

$$b_{+*} = 2(k_+v^* - k^*v_+) = 2(k_{[0}v_{1]} + k_{[3}v_{1]} - ik_{[0}v_{2]} - ik_{[3}v_{2]}) \quad (\text{X.79e})$$

$$b_{-*} = 2(k_-v^* - k^*v_-) = 2(k_{[0}v_{1]} - k_{[3}v_{1]} - ik_{[0}v_{2]} + ik_{[3}v_{2]}) \quad (\text{X.79f})$$

Of course, one could introduce a more advanced notation, but we don't want to

become confused.

$$[k, \gamma^0] = \begin{pmatrix} -2k_3 & -2k^* & 0 & 0 \\ -2k & 2k_3 & 0 & 0 \\ 0 & 0 & 2k_3 & 2k^* \\ 0 & 0 & 2k & -2k_3 \end{pmatrix} \quad (\text{X.80a})$$

$$[k, \gamma^1] = \begin{pmatrix} -2ik_2 & -2k_- & 0 & 0 \\ -2k_+ & 2ik_2 & 0 & 0 \\ 0 & 0 & -2ik_2 & 2k_+ \\ 0 & 0 & 2k_- & 2ik_2 \end{pmatrix} \quad (\text{X.80b})$$

$$[k, \gamma^2] = \begin{pmatrix} 2ik_1 & 2ik_- & 0 & 0 \\ -2ik_+ & -2ik_1 & 0 & 0 \\ 0 & 0 & 2ik_1 & -2ik_+ \\ 0 & 0 & 2ik_- & -2ik_1 \end{pmatrix} \quad (\text{X.80c})$$

$$[k, \gamma^3] = \begin{pmatrix} -2k_0 & -2k^* & 0 & 0 \\ 2k & 2k_0 & 0 & 0 \\ 0 & 0 & 2k_0 & -2k^* \\ 0 & 0 & 2k & -2k_0 \end{pmatrix} \quad (\text{X.80d})$$

$$[k, V] = \begin{pmatrix} a_- & b_{-*} & 0 & 0 \\ b_+ & -a_- & 0 & 0 \\ 0 & 0 & a_+ & -b_{+*} \\ 0 & 0 & -b_- & -a_+ \end{pmatrix} \quad (\text{X.80e})$$

$$\gamma^5 \gamma^0 [k, V] = \begin{pmatrix} 0 & 0 & -a_+ & b_{+*} \\ 0 & 0 & b_- & a_+ \\ a_- & b_{-*} & 0 & 0 \\ b_+ & -a_- & 0 & 0 \end{pmatrix} \quad (\text{X.80f})$$

$$\gamma^5 \gamma^1 [k, V] = \begin{pmatrix} 0 & 0 & b_- & a_+ \\ 0 & 0 & -a_+ & b_{+*} \\ -b_+ & a_- & 0 & 0 \\ -a_- & -b_{-*} & 0 & 0 \end{pmatrix} \quad (\text{X.80g})$$

$$\gamma^5 \gamma^2 [k, V] = \begin{pmatrix} 0 & 0 & -ib_- & -ia_+ \\ 0 & 0 & -ia_+ & ib_{+*} \\ ib_+ & -ia_- & 0 & 0 \\ -ia_- & -ib_{-*} & 0 & 0 \end{pmatrix} \quad (\text{X.80h})$$

$$\gamma^5 \gamma^3 [k, V] = \begin{pmatrix} 0 & 0 & -a_+ & b_{+*} \\ 0 & 0 & -b_- & -a_+ \\ -a_- & -b_{-*} & 0 & 0 \\ b_+ & -a_- & 0 & 0 \end{pmatrix} \quad (\text{X.80i})$$

and

$$[k, V] \gamma^0 \gamma^5 = \begin{pmatrix} 0 & 0 & a_- & b_{-*} \\ 0 & 0 & b_+ & -a_- \\ -a_+ & b_{+*} & 0 & 0 \\ b_- & a_+ & 0 & 0 \end{pmatrix} \quad (\text{X.81a})$$

$$[k, V] \gamma^1 \gamma^5 = \begin{pmatrix} 0 & 0 & b_{-*} & a_- \\ 0 & 0 & -a_- & b_+ \\ -b_{+*} & a_+ & 0 & 0 \\ -a_+ & -b_- & 0 & 0 \end{pmatrix} \quad (\text{X.81b})$$

$$[k, V]\gamma^2\gamma^5 = \begin{pmatrix} 0 & 0 & ib_{-*} & -ia_- \\ 0 & 0 & -ia_- & -ib_+ \\ -ib_{+*} & -ia_+ & 0 & 0 \\ -ia_+ & ib_- & 0 & 0 \end{pmatrix} \quad (\text{X.81c})$$

$$[k, V]\gamma^3\gamma^5 = \begin{pmatrix} 0 & 0 & a_- & -b_{-*} \\ 0 & 0 & b_+ & a_- \\ a_+ & b_{+*} & 0 & 0 \\ -b_- & a_+ & 0 & 0 \end{pmatrix} \quad (\text{X.81d})$$

In what follows  $l$  always means twice the value of  $k$ , e.g.  $l_+ = 2k_+$ . We use the abbreviation  $C^{\mu\nu} \equiv C[k, \gamma^\mu]\gamma^\nu\gamma^5$ .

$$C^{00} = \begin{pmatrix} 0 & 0 & -l & -l_3 \\ 0 & 0 & l_3 & l^* \\ l & -l_3 & 0 & 0 \\ -l_3 & -l^* & 0 & 0 \end{pmatrix}, \quad C^{20} = \begin{pmatrix} 0 & 0 & -il_+ & -il_1 \\ 0 & 0 & -il_1 & -il_- \\ il_- & -il_1 & 0 & 0 \\ -il_1 & il_+ & 0 & 0 \end{pmatrix} \quad (\text{X.82a})$$

$$C^{01} = \begin{pmatrix} 0 & 0 & l_3 & -l \\ 0 & 0 & l^* & l_3 \\ l_3 & -l & 0 & 0 \\ l^* & l_3 & 0 & 0 \end{pmatrix}, \quad C^{21} = \begin{pmatrix} 0 & 0 & -il_1 & -il_+ \\ 0 & 0 & -il_- & -il_1 \\ il_1 & -il_- & 0 & 0 \\ -il_+ & il_1 & 0 & 0 \end{pmatrix} \quad (\text{X.82b})$$

$$C^{02} = \begin{pmatrix} 0 & 0 & il_3 & il \\ 0 & 0 & il^* & -il_3 \\ il_3 & il & 0 & 0 \\ il^* & -il_3 & 0 & 0 \end{pmatrix}, \quad C^{22} = \begin{pmatrix} 0 & 0 & l_1 & -l_+ \\ 0 & 0 & l_- & -l_1 \\ -l_1 & -l_- & 0 & 0 \\ l_+ & l_1 & 0 & 0 \end{pmatrix} \quad (\text{X.82c})$$

$$C^{03} = \begin{pmatrix} 0 & 0 & -l & -l_3 \\ 0 & 0 & l_3 & -l^* \\ -l & -l_3 & 0 & 0 \\ l_3 & -l^* & 0 & 0 \end{pmatrix}, \quad C^{23} = \begin{pmatrix} 0 & 0 & -il_+ & il_1 \\ 0 & 0 & -il_1 & il_- \\ -il_- & -il_1 & 0 & 0 \\ il_1 & il_+ & 0 & 0 \end{pmatrix} \quad (\text{X.82d})$$

$$C^{10} = \begin{pmatrix} 0 & 0 & -l_+ & il_2 \\ 0 & 0 & il_2 & l_- \\ l_- & il_2 & 0 & 0 \\ il_2 & -l_+ & 0 & 0 \end{pmatrix}, \quad C^{30} = \begin{pmatrix} 0 & 0 & l & l_0 \\ 0 & 0 & l_0 & l^* \\ l & -l_0 & 0 & 0 \\ -l_0 & l^* & 0 & 0 \end{pmatrix} \quad (\text{X.82e})$$

$$C^{11} = \begin{pmatrix} 0 & 0 & il_2 & -l_+ \\ 0 & 0 & l_- & il_2 \\ -il_2 & -l_- & 0 & 0 \\ l_+ & -il_2 & 0 & 0 \end{pmatrix}, \quad C^{31} = \begin{pmatrix} 0 & 0 & l_0 & l \\ 0 & 0 & l^* & l_0 \\ l_0 & -l & 0 & 0 \\ -l^* & l_0 & 0 & 0 \end{pmatrix} \quad (\text{X.82f})$$

$$C^{12} = \begin{pmatrix} 0 & 0 & -l_2 & il_+ \\ 0 & 0 & il_- & l_2 \\ l_2 & il_- & 0 & 0 \\ il_+ & -l_2 & 0 & 0 \end{pmatrix}, \quad C^{32} = \begin{pmatrix} 0 & 0 & il_0 & -il \\ 0 & 0 & il^* & -il_0 \\ il_0 & il & 0 & 0 \\ -il^* & -il_0 & 0 & 0 \end{pmatrix} \quad (\text{X.82g})$$

$$C^{13} = \begin{pmatrix} 0 & 0 & -l_+ & -il_2 \\ 0 & 0 & il_2 & -l_- \\ -l_- & il_2 & 0 & 0 \\ -il_2 & -l_+ & 0 & 0 \end{pmatrix}, \quad C^{33} = \begin{pmatrix} 0 & 0 & l & -l_0 \\ 0 & 0 & l_0 & -l^* \\ -l & -l_0 & 0 & 0 \\ l_0 & l^* & 0 & 0 \end{pmatrix} \quad (\text{X.82h})$$

and, with the abbreviation  $\tilde{C}^{\mu\nu} \equiv C\gamma^5\gamma^\nu[k, \gamma^\mu]$  (note the reversed order of the indices!)

$$\tilde{C}^{00} = \begin{pmatrix} 0 & 0 & -l & l_3 \\ 0 & 0 & l_3 & l^* \\ l & -l_3 & 0 & 0 \\ -l_3 & -l^* & 0 & 0 \end{pmatrix}, \quad \tilde{C}^{20} = \begin{pmatrix} 0 & 0 & -il_- & il_1 \\ 0 & 0 & il_1 & -il_+ \\ il_+ & il_1 & 0 & 0 \\ il_1 & il_- & 0 & 0 \end{pmatrix} \quad (\text{X.83a})$$

$$\tilde{C}^{01} = \begin{pmatrix} 0 & 0 & -l_3 & -l^* \\ 0 & 0 & l & -l_3 \\ -l_3 & -l^* & 0 & 0 \\ l & -l_3 & 0 & 0 \end{pmatrix}, \quad \tilde{C}^{21} = \begin{pmatrix} 0 & 0 & -il_1 & il_+ \\ 0 & 0 & il_- & -il_1 \\ il_1 & il_- & 0 & 0 \\ il_+ & il_1 & 0 & 0 \end{pmatrix} \quad (\text{X.83b})$$

$$\tilde{C}^{02} = \begin{pmatrix} 0 & 0 & -il_3 & -il^* \\ 0 & 0 & -il & il_3 \\ -il_3 & -il^* & 0 & 0 \\ -il & il_3 & 0 & 0 \end{pmatrix}, \quad \tilde{C}^{22} = \begin{pmatrix} 0 & 0 & l_1 & -l_+ \\ 0 & 0 & l_- & -l_1 \\ -l_1 & -l_- & 0 & 0 \\ l_+ & l_1 & 0 & 0 \end{pmatrix} \quad (\text{X.83c})$$

$$\tilde{C}^{03} = \begin{pmatrix} 0 & 0 & l & -l_3 \\ 0 & 0 & l_3 & l^* \\ l & -l_3 & 0 & 0 \\ l_3 & l^* & 0 & 0 \end{pmatrix}, \quad \tilde{C}^{23} = \begin{pmatrix} 0 & 0 & il_- & -il_1 \\ 0 & 0 & il_1 & -il_+ \\ il_+ & il_1 & 0 & 0 \\ -il_1 & -il_- & 0 & 0 \end{pmatrix} \quad (\text{X.83d})$$

$$\tilde{C}^{10} = \begin{pmatrix} 0 & 0 & -l_- & -il_2 \\ 0 & 0 & -il_2 & l_+ \\ l_+ & -il_2 & 0 & 0 \\ -il_2 & -l_- & 0 & 0 \end{pmatrix}, \quad \tilde{C}^{30} = \begin{pmatrix} 0 & 0 & -l & l_0 \\ 0 & 0 & l_0 & -l^* \\ -l & -l_0 & 0 & 0 \\ -l_0 & -l^* & 0 & 0 \end{pmatrix} \quad (\text{X.83e})$$

$$\tilde{C}^{11} = \begin{pmatrix} 0 & 0 & il_2 & -l_+ \\ 0 & 0 & l_- & il_2 \\ -il_2 & -l_- & 0 & 0 \\ l_+ & -il_2 & 0 & 0 \end{pmatrix}, \quad \tilde{C}^{31} = \begin{pmatrix} 0 & 0 & -l_0 & l^* \\ 0 & 0 & l & -l_0 \\ -l_0 & -l^* & 0 & 0 \\ -l & -l_0 & 0 & 0 \end{pmatrix} \quad (\text{X.83f})$$

$$\tilde{C}^{12} = \begin{pmatrix} 0 & 0 & -l_2 & -il_+ \\ 0 & 0 & -il_- & l_2 \\ l_2 & -il_- & 0 & 0 \\ -il_+ & -l_2 & 0 & 0 \end{pmatrix}, \quad \tilde{C}^{32} = \begin{pmatrix} 0 & 0 & -il_0 & il^* \\ 0 & 0 & -il & il_0 \\ -il_0 & -il^* & 0 & 0 \\ il & il_0 & 0 & 0 \end{pmatrix} \quad (\text{X.83g})$$

$$\tilde{C}^{13} = \begin{pmatrix} 0 & 0 & l_- & il_2 \\ 0 & 0 & -il_2 & l_+ \\ l_+ & -il_2 & 0 & 0 \\ il_2 & l_- & 0 & 0 \end{pmatrix}, \quad \tilde{C}^{33} = \begin{pmatrix} 0 & 0 & l & -l_0 \\ 0 & 0 & l_0 & -l^* \\ -l & -l_0 & 0 & 0 \\ l_0 & l^* & 0 & 0 \end{pmatrix} \quad (\text{X.83h})$$



*(Implementation of bispinor currents)+≡*

```

pure function fggvvgr (v, psi, k) result (psikv)
  type(bispinor) :: psikv
  type(vectorspinor), intent(in) :: psi
  type(vector), intent(in) :: v, k
  complex(kind=default) :: kv30, kv21, kv01, kv31, kv02, kv32
  complex(kind=default) :: ap, am, bp, bm, bps, bms
  kv30 = k%x(3) * v%t - k%t * v%x(3)
  kv21 = (0,1) * (k%x(2) * v%x(1) - k%x(1) * v%x(2))
  kv01 = k%t * v%x(1) - k%x(1) * v%t
  kv31 = k%x(3) * v%x(1) - k%x(1) * v%x(3)
  kv02 = (0,1) * (k%t * v%x(2) - k%x(2) * v%t)
  kv32 = (0,1) * (k%x(3) * v%x(2) - k%x(2) * v%x(3))
  ap = 2 * (kv30 + kv21)
  am = 2 * (-kv30 + kv21)
  bp = 2 * (kv01 + kv31 + kv02 + kv32)
  bm = 2 * (kv01 - kv31 + kv02 - kv32)
  bps = 2 * (kv01 + kv31 - kv02 - kv32)
  bms = 2 * (kv01 - kv31 - kv02 + kv32)
  psikv%a(1) = (-ap) * psi%psi(1)%a(3) + bps * psi%psi(1)%a(4) &
    + (-bm) * psi%psi(2)%a(3) + (-ap) * psi%psi(2)%a(4) &
    + (0,1) * (bm * psi%psi(3)%a(3) + ap * psi%psi(3)%a(4)) &
    + ap * psi%psi(4)%a(3) + (-bps) * psi%psi(4)%a(4)
  psikv%a(2) = bm * psi%psi(1)%a(3) + ap * psi%psi(1)%a(4) &
    + ap * psi%psi(2)%a(3) + (-bps) * psi%psi(2)%a(4) &
    + (0,1) * (ap * psi%psi(3)%a(3) - bps * psi%psi(3)%a(4)) &
    + bm * psi%psi(4)%a(3) + ap * psi%psi(4)%a(4)
  psikv%a(3) = am * psi%psi(1)%a(1) + bms * psi%psi(1)%a(2) &
    + bp * psi%psi(2)%a(1) + (-am) * psi%psi(2)%a(2) &
    + (0,-1) * (bp * psi%psi(3)%a(1) + (-am) * psi%psi(3)%a(2)) &
    + am * psi%psi(4)%a(1) + bms * psi%psi(4)%a(2)
  psikv%a(4) = bp * psi%psi(1)%a(1) + (-am) * psi%psi(1)%a(2) &
    + am * psi%psi(2)%a(1) + bms * psi%psi(2)%a(2) &
    + (0,1) * (am * psi%psi(3)%a(1) + bms * psi%psi(3)%a(2)) &
    + (-bp) * psi%psi(4)%a(1) + am * psi%psi(4)%a(2)
end function fggvvgr

```

*(Implementation of bispinor currents)+≡*

```

pure function f_vgr (g, v, psi, k) result (psikkkv)
  type(bispinor) :: psikkkv
  type(vectorspinor), intent(in) :: psi
  type(vector), intent(in) :: v
  type(momentum), intent(in) :: k
  complex(kind=default), intent(in) :: g
  type(vector) :: vk
  vk = k
  psikkkv = g * (fggvvgr (v, psi, vk))
end function f_vgr

```

*(Implementation of bispinor currents)+≡*

```

pure function f_vlrg (gl, gr, v, psi, k) result (psikv)
  type(bispinor) :: psikv
  type(vectorspinor), intent(in) :: psi
  type(vector), intent(in) :: v
  type(momentum), intent(in) :: k

```

```

    complex(kind=default), intent(in) :: gl, gr
    type(vector) :: vk
    vk = k
    psikv = fggvvgr (v, psi, vk)
    psikv%a(1:2) = gl * psikv%a(1:2)
    psikv%a(3:4) = gr * psikv%a(3:4)
end function f_vlgr

<Declaration of bispinor currents>+=
    public :: gr_potf, gr_sf, gr_pf, gr_vf, gr_vlrf, gr_slf, gr_srf, gr_slrf

<Implementation of bispinor currents>+=
    pure function gr_potf (g, phi, psi) result (phipsi)
    type(vectorspinor) :: phipsi
    complex(kind=default), intent(in) :: g
    complex(kind=default), intent(in) :: phi
    type(bispinor), intent(in) :: psi
    phipsi%psi(1)%a(1) = (g * phi) * psi%a(3)
    phipsi%psi(1)%a(2) = (g * phi) * psi%a(4)
    phipsi%psi(1)%a(3) = (g * phi) * psi%a(1)
    phipsi%psi(1)%a(4) = (g * phi) * psi%a(2)
    phipsi%psi(2)%a(1) = (g * phi) * psi%a(4)
    phipsi%psi(2)%a(2) = (g * phi) * psi%a(3)
    phipsi%psi(2)%a(3) = ((-g) * phi) * psi%a(2)
    phipsi%psi(2)%a(4) = ((-g) * phi) * psi%a(1)
    phipsi%psi(3)%a(1) = ((0,-1) * g * phi) * psi%a(4)
    phipsi%psi(3)%a(2) = ((0,1) * g * phi) * psi%a(3)
    phipsi%psi(3)%a(3) = ((0,1) * g * phi) * psi%a(2)
    phipsi%psi(3)%a(4) = ((0,-1) * g * phi) * psi%a(1)
    phipsi%psi(4)%a(1) = (g * phi) * psi%a(3)
    phipsi%psi(4)%a(2) = ((-g) * phi) * psi%a(4)
    phipsi%psi(4)%a(3) = ((-g) * phi) * psi%a(1)
    phipsi%psi(4)%a(4) = (g * phi) * psi%a(2)
end function gr_potf

<Implementation of bispinor currents>+=
    pure function grkgf (psi, k) result (kpsi)
    type(vectorspinor) :: kpsi
    complex(kind=default) :: kp, km, k12, k12s
    type(bispinor), intent(in) :: psi
    type(vector), intent(in) :: k
    kp = k%t + k%x(3)
    km = k%t - k%x(3)
    k12 = k%x(1) + (0,1)*k%x(2)
    k12s = k%x(1) - (0,1)*k%x(2)
    kpsi%psi(1)%a(1) = km * psi%a(1) - k12s * psi%a(2)
    kpsi%psi(1)%a(2) = (-k12) * psi%a(1) + kp * psi%a(2)
    kpsi%psi(1)%a(3) = kp * psi%a(3) + k12s * psi%a(4)
    kpsi%psi(1)%a(4) = k12 * psi%a(3) + km * psi%a(4)
    kpsi%psi(2)%a(1) = k12s * psi%a(1) - km * psi%a(2)
    kpsi%psi(2)%a(2) = (-kp) * psi%a(1) + k12 * psi%a(2)
    kpsi%psi(2)%a(3) = k12s * psi%a(3) + kp * psi%a(4)
    kpsi%psi(2)%a(4) = km * psi%a(3) + k12 * psi%a(4)
    kpsi%psi(3)%a(1) = (0,1) * (k12s * psi%a(1) + km * psi%a(2))
    kpsi%psi(3)%a(2) = (0,-1) * (kp * psi%a(1) + k12 * psi%a(2))
    kpsi%psi(3)%a(3) = (0,1) * (k12s * psi%a(3) - kp * psi%a(4))

```

```

kpsi%psi(3)%a(4) = (0,1) * (km * psi%a(3) - k12 * psi%a(4))
kpsi%psi(4)%a(1) = -(km * psi%a(1) + k12s * psi%a(2))
kpsi%psi(4)%a(2) = k12 * psi%a(1) + kp * psi%a(2)
kpsi%psi(4)%a(3) = kp * psi%a(3) - k12s * psi%a(4)
kpsi%psi(4)%a(4) = k12 * psi%a(3) - km * psi%a(4)
end function grkgf

(Implementation of bispinor currents)+≡
pure function gr_sf (g, phi, psi, k) result (phipsi)
    type(vectorspinor) :: phipsi
    complex(kind=default), intent(in) :: g
    complex(kind=default), intent(in) :: phi
    type(bispinor), intent(in) :: psi
    type(momentum), intent(in) :: k
    type(vector) :: vk
    vk = k
    phipsi = (g * phi) * grkgf (psi, vk)
end function gr_sf

(Implementation of bispinor currents)+≡
pure function gr_slf (gl, phi, psi, k) result (phipsi)
    type(vectorspinor) :: phipsi
    complex(kind=default), intent(in) :: gl
    complex(kind=default), intent(in) :: phi
    type(bispinor), intent(in) :: psi
    type(bispinor) :: psi_l
    type(momentum), intent(in) :: k
    psi_l%a(1:2) = psi%a(1:2)
    psi_l%a(3:4) = 0
    phipsi = gr_sf (gl, phi, psi_l, k)
end function gr_slf

(Implementation of bispinor currents)+≡
pure function gr_srf (gr, phi, psi, k) result (phipsi)
    type(vectorspinor) :: phipsi
    complex(kind=default), intent(in) :: gr
    complex(kind=default), intent(in) :: phi
    type(bispinor), intent(in) :: psi
    type(bispinor) :: psi_r
    type(momentum), intent(in) :: k
    psi_r%a(1:2) = 0
    psi_r%a(3:4) = psi%a(3:4)
    phipsi = gr_sf (gr, phi, psi_r, k)
end function gr_srf

(Implementation of bispinor currents)+≡
pure function gr_slrf (gl, gr, phi, psi, k) result (phipsi)
    type(vectorspinor) :: phipsi
    complex(kind=default), intent(in) :: gl, gr
    complex(kind=default), intent(in) :: phi
    type(bispinor), intent(in) :: psi
    type(momentum), intent(in) :: k
    phipsi = gr_slf (gl, phi, psi, k) + gr_srf (gr, phi, psi, k)
end function gr_slrf

(Implementation of bispinor currents)+≡
pure function grkggf (psi, k) result (kpsi)

```

```

type(vectorspinor) :: kpsi
complex(kind=default) :: kp, km, k12, k12s
type(bispinor), intent(in) :: psi
type(vector), intent(in) :: k
kp = k%t + k%x(3)
km = k%t - k%x(3)
k12 = k%x(1) + (0,1)*k%x(2)
k12s = k%x(1) - (0,1)*k%x(2)
kpsi%psi(1)%a(1) = (-km) * psi%a(1) + k12s * psi%a(2)
kpsi%psi(1)%a(2) = k12 * psi%a(1) - kp * psi%a(2)
kpsi%psi(1)%a(3) = kp * psi%a(3) + k12s * psi%a(4)
kpsi%psi(1)%a(4) = k12 * psi%a(3) + km * psi%a(4)
kpsi%psi(2)%a(1) = (-k12s) * psi%a(1) + km * psi%a(2)
kpsi%psi(2)%a(2) = kp * psi%a(1) - k12 * psi%a(2)
kpsi%psi(2)%a(3) = k12s * psi%a(3) + kp * psi%a(4)
kpsi%psi(2)%a(4) = km * psi%a(3) + k12 * psi%a(4)
kpsi%psi(3)%a(1) = (0,-1) * (k12s * psi%a(1) + km * psi%a(2))
kpsi%psi(3)%a(2) = (0,1) * (kp * psi%a(1) + k12 * psi%a(2))
kpsi%psi(3)%a(3) = (0,1) * (k12s * psi%a(3) - kp * psi%a(4))
kpsi%psi(3)%a(4) = (0,1) * (km * psi%a(3) - k12 * psi%a(4))
kpsi%psi(4)%a(1) = km * psi%a(1) + k12s * psi%a(2)
kpsi%psi(4)%a(2) = -(k12 * psi%a(1) + kp * psi%a(2))
kpsi%psi(4)%a(3) = kp * psi%a(3) - k12s * psi%a(4)
kpsi%psi(4)%a(4) = k12 * psi%a(3) - km * psi%a(4)
end function grkggf

(Implementation of bispinor currents)+≡
pure function gr_pf (g, phi, psi, k) result (phipsi)
type(vectorspinor) :: phipsi
complex(kind=default), intent(in) :: g
complex(kind=default), intent(in) :: phi
type(bispinor), intent(in) :: psi
type(momentum), intent(in) :: k
type(vector) :: vk
vk = k
phipsi = (g * phi) * grkggf (psi, vk)
end function gr_pf

(Implementation of bispinor currents)+≡
pure function grkkggf (v, psi, k) result (psikv)
type(vectorspinor) :: psikv
type(bispinor), intent(in) :: psi
type(vector), intent(in) :: v, k
complex(kind=default) :: kv30, kv21, kv01, kv31, kv02, kv32
complex(kind=default) :: ap, am, bp, bm, bps, bms, imago
imago = (0.0_default, 1.0_default)
kv30 = k%x(3) * v%t - k%t * v%x(3)
kv21 = imago * (k%x(2) * v%x(1) - k%x(1) * v%x(2))
kv01 = k%t * v%x(1) - k%x(1) * v%t
kv31 = k%x(3) * v%x(1) - k%x(1) * v%x(3)
kv02 = imago * (k%t * v%x(2) - k%x(2) * v%t)
kv32 = imago * (k%x(3) * v%x(2) - k%x(2) * v%x(3))
ap = 2 * (kv30 + kv21)
am = 2 * ((-kv30) + kv21)
bp = 2 * (kv01 + kv31 + kv02 + kv32)

```

```

bm = 2 * (kv01 - kv31 + kv02 - kv32)
bps = 2 * (kv01 + kv31 - kv02 - kv32)
bms = 2 * (kv01 - kv31 - kv02 + kv32)
psikv%psi(1)%a(1) = am * psi%a(3) + bms * psi%a(4)
psikv%psi(1)%a(2) = bp * psi%a(3) + (-am) * psi%a(4)
psikv%psi(1)%a(3) = (-ap) * psi%a(1) + bps * psi%a(2)
psikv%psi(1)%a(4) = bm * psi%a(1) + ap * psi%a(2)
psikv%psi(2)%a(1) = bms * psi%a(3) + am * psi%a(4)
psikv%psi(2)%a(2) = (-am) * psi%a(3) + bp * psi%a(4)
psikv%psi(2)%a(3) = (-bps) * psi%a(1) + ap * psi%a(2)
psikv%psi(2)%a(4) = (-ap) * psi%a(1) + (-bm) * psi%a(2)
psikv%psi(3)%a(1) = imago * (bms * psi%a(3) - am * psi%a(4))
psikv%psi(3)%a(2) = (-imago) * (am * psi%a(3) + bp * psi%a(4))
psikv%psi(3)%a(3) = (-imago) * (bps * psi%a(1) + ap * psi%a(2))
psikv%psi(3)%a(4) = imago * ((-ap) * psi%a(1) + bm * psi%a(2))
psikv%psi(4)%a(1) = am * psi%a(3) + (-bms) * psi%a(4)
psikv%psi(4)%a(2) = bp * psi%a(3) + am * psi%a(4)
psikv%psi(4)%a(3) = ap * psi%a(1) + bps * psi%a(2)
psikv%psi(4)%a(4) = (-bm) * psi%a(1) + ap * psi%a(2)
end function grkkggf

(Implementation of bispinor currents)+≡
pure function gr_vf (g, v, psi, k) result (psikv)
  type(vectorspinor) :: psikv
  type(bispinor), intent(in) :: psi
  type(vector), intent(in) :: v
  type(momentum), intent(in) :: k
  complex(kind=default), intent(in) :: g
  type(vector) :: vk
  vk = k
  psikv = g * (grkkggf (v, psi, vk))
end function gr_vf

(Implementation of bispinor currents)+≡
pure function gr_vlrf (gl, gr, v, psi, k) result (psikv)
  type(vectorspinor) :: psikv
  type(bispinor), intent(in) :: psi
  type(bispinor) :: psi_l, psi_r
  type(vector), intent(in) :: v
  type(momentum), intent(in) :: k
  complex(kind=default), intent(in) :: gl, gr
  type(vector) :: vk
  vk = k
  psi_l%a(1:2) = psi%a(1:2)
  psi_l%a(3:4) = 0
  psi_r%a(1:2) = 0
  psi_r%a(3:4) = psi%a(3:4)
  psikv = gl * grkkggf (v, psi_l, vk) + gr * grkkggf (v, psi_r, vk)
end function gr_vlrf

(Declaration of bispinor currents)+≡
public :: v_grf, v_fgr

(Declaration of bispinor currents)+≡
public :: vlr_grf, vlr_fgr

```

$$V^\mu = \psi_\rho^T C^{\mu\rho} \psi$$

(Implementation of bispinor currents)+≡

```

pure function grkggff (psil, psir, k) result (j)
  type(vector) :: j
  type(vectorspinor), intent(in) :: psil
  type(bispinor), intent(in) :: psir
  type(vector), intent(in) :: k
  type(vectorspinor) :: c_psil0, c_psil1, c_psil2, c_psil3
  complex(kind=default) :: kp, km, k12, k12s, ik2
  kp = k%t + k%x(3)
  km = k%t - k%x(3)
  k12 = (k%x(1) + (0,1)*k%x(2))
  k12s = (k%x(1) - (0,1)*k%x(2))
  ik2 = (0,1) * k%x(2)
  !!! New version:
  c_psil0%psi(1)%a(1) = (-k%x(3)) * psir%a(3) + (-k12s) * psir%a(4)
  c_psil0%psi(1)%a(2) = (-k12) * psir%a(3) + k%x(3) * psir%a(4)
  c_psil0%psi(1)%a(3) = (-k%x(3)) * psir%a(1) + (-k12s) * psir%a(2)
  c_psil0%psi(1)%a(4) = (-k12) * psir%a(1) + k%x(3) * psir%a(2)
  c_psil0%psi(2)%a(1) = (-k12s) * psir%a(3) + (-k%x(3)) * psir%a(4)
  c_psil0%psi(2)%a(2) = k%x(3) * psir%a(3) + (-k12) * psir%a(4)
  c_psil0%psi(2)%a(3) = k12s * psir%a(1) + k%x(3) * psir%a(2)
  c_psil0%psi(2)%a(4) = (-k%x(3)) * psir%a(1) + k12 * psir%a(2)
  c_psil0%psi(3)%a(1) = (0,1) * ((-k12s) * psir%a(3) + k%x(3) * psir%a(4))
  c_psil0%psi(3)%a(2) = (0,1) * (k%x(3) * psir%a(3) + k12 * psir%a(4))
  c_psil0%psi(3)%a(3) = (0,1) * (k12s * psir%a(1) + (-k%x(3)) * psir%a(2))
  c_psil0%psi(3)%a(4) = (0,1) * ((-k%x(3)) * psir%a(1) + (-k12) * psir%a(2))
  c_psil0%psi(4)%a(1) = (-k%x(3)) * psir%a(3) + k12s * psir%a(4)
  c_psil0%psi(4)%a(2) = (-k12) * psir%a(3) + (-k%x(3)) * psir%a(4)
  c_psil0%psi(4)%a(3) = k%x(3) * psir%a(1) + (-k12s) * psir%a(2)
  c_psil0%psi(4)%a(4) = k12 * psir%a(1) + k%x(3) * psir%a(2)
  !!!
  c_psil1%psi(1)%a(1) = (-ik2) * psir%a(3) + (-km) * psir%a(4)
  c_psil1%psi(1)%a(2) = (-kp) * psir%a(3) + ik2 * psir%a(4)
  c_psil1%psi(1)%a(3) = ik2 * psir%a(1) + (-kp) * psir%a(2)
  c_psil1%psi(1)%a(4) = (-km) * psir%a(1) + (-ik2) * psir%a(2)
  c_psil1%psi(2)%a(1) = (-km) * psir%a(3) + (-ik2) * psir%a(4)
  c_psil1%psi(2)%a(2) = ik2 * psir%a(3) + (-kp) * psir%a(4)
  c_psil1%psi(2)%a(3) = kp * psir%a(1) + (-ik2) * psir%a(2)
  c_psil1%psi(2)%a(4) = ik2 * psir%a(1) + km * psir%a(2)
  c_psil1%psi(3)%a(1) = ((0,-1) * km) * psir%a(3) + (-k%x(2)) * psir%a(4)
  c_psil1%psi(3)%a(2) = (-k%x(2)) * psir%a(3) + ((0,1) * kp) * psir%a(4)
  c_psil1%psi(3)%a(3) = ((0,1) * kp) * psir%a(1) + (-k%x(2)) * psir%a(2)
  c_psil1%psi(3)%a(4) = (-k%x(2)) * psir%a(1) + ((0,-1) * km) * psir%a(2)
  c_psil1%psi(4)%a(1) = (-ik2) * psir%a(3) + km * psir%a(4)
  c_psil1%psi(4)%a(2) = (-kp) * psir%a(3) + (-ik2) * psir%a(4)
  c_psil1%psi(4)%a(3) = (-ik2) * psir%a(1) + (-kp) * psir%a(2)
  c_psil1%psi(4)%a(4) = km * psir%a(1) + (-ik2) * psir%a(2)
  !!!
  c_psil2%psi(1)%a(1) = (0,1) * (k%x(1) * psir%a(3) + km * psir%a(4))
  c_psil2%psi(1)%a(2) = (0,-1) * (kp * psir%a(3) + k%x(1) * psir%a(4))
  c_psil2%psi(1)%a(3) = (0,1) * ((-k%x(1)) * psir%a(1) + kp * psir%a(2))
  c_psil2%psi(1)%a(4) = (0,1) * ((-km) * psir%a(1) + k%x(1) * psir%a(2))
  c_psil2%psi(2)%a(1) = (0,1) * (km * psir%a(3) + k%x(1) * psir%a(4))

```

```

c_psi2%psi(2)%a(2) = (0,-1) * (k%x(1) * psir%a(3) + kp * psir%a(4))
c_psi2%psi(2)%a(3) = (0,-1) * (kp * psir%a(1) + (-k%x(1)) * psir%a(2))
c_psi2%psi(2)%a(4) = (0,-1) * (k%x(1) * psir%a(1) + (-km) * psir%a(2))
c_psi2%psi(3)%a(1) = (-km) * psir%a(3) + k%x(1) * psir%a(4)
c_psi2%psi(3)%a(2) = k%x(1) * psir%a(3) + (-kp) * psir%a(4)
c_psi2%psi(3)%a(3) = kp * psir%a(1) + k%x(1) * psir%a(2)
c_psi2%psi(3)%a(4) = k%x(1) * psir%a(1) + km * psir%a(2)
c_psi2%psi(4)%a(1) = (0,1) * (k%x(1) * psir%a(3) + (-km) * psir%a(4))
c_psi2%psi(4)%a(2) = (0,1) * ((-kp) * psir%a(3) + k%x(1) * psir%a(4))
c_psi2%psi(4)%a(3) = (0,1) * (k%x(1) * psir%a(1) + kp * psir%a(2))
c_psi2%psi(4)%a(4) = (0,1) * (km * psir%a(1) + k%x(1) * psir%a(2))
!!!
c_psi3%psi(1)%a(1) = (-k%t) * psir%a(3) - k12s * psir%a(4)
c_psi3%psi(1)%a(2) = k12 * psir%a(3) + k%t * psir%a(4)
c_psi3%psi(1)%a(3) = (-k%t) * psir%a(1) + k12s * psir%a(2)
c_psi3%psi(1)%a(4) = (-k12) * psir%a(1) + k%t * psir%a(2)
c_psi3%psi(2)%a(1) = (-k12s) * psir%a(3) + (-k%t) * psir%a(4)
c_psi3%psi(2)%a(2) = k%t * psir%a(3) + k12 * psir%a(4)
c_psi3%psi(2)%a(3) = (-k12s) * psir%a(1) + k%t * psir%a(2)
c_psi3%psi(2)%a(4) = (-k%t) * psir%a(1) + k12 * psir%a(2)
c_psi3%psi(3)%a(1) = (0,-1) * (k12s * psir%a(3) + (-k%t) * psir%a(4))
c_psi3%psi(3)%a(2) = (0,1) * (k%t * psir%a(3) + (-k12) * psir%a(4))
c_psi3%psi(3)%a(3) = (0,-1) * (k12s * psir%a(1) + k%t * psir%a(2))
c_psi3%psi(3)%a(4) = (0,-1) * (k%t * psir%a(1) + k12 * psir%a(2))
c_psi3%psi(4)%a(1) = (-k%t) * psir%a(3) + k12s * psir%a(4)
c_psi3%psi(4)%a(2) = k12 * psir%a(3) + (-k%t) * psir%a(4)
c_psi3%psi(4)%a(3) = k%t * psir%a(1) + k12s * psir%a(2)
c_psi3%psi(4)%a(4) = k12 * psir%a(1) + k%t * psir%a(2)
j%t    = 2 * (psil * c_psi0)
j%x(1) = 2 * (psil * c_psi1)
j%x(2) = 2 * (psil * c_psi2)
j%x(3) = 2 * (psil * c_psi3)
end function grkggff

```

*(Implementation of bispinor currents)+≡*

```

pure function v_grf (g, psil, psir, k) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: g
  type(vectorspinor), intent(in) :: psil
  type(bispinor), intent(in) :: psir
  type(momentum), intent(in) :: k
  type(vector) :: vk
  vk = k
  j = g * grkggff (psil, psir, vk)
end function v_grf

```

*(Implementation of bispinor currents)+≡*

```

pure function vlr_grf (gl, gr, psil, psir, k) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: gl, gr
  type(vectorspinor), intent(in) :: psil
  type(bispinor), intent(in) :: psir
  type(bispinor) :: psir_l, psir_r
  type(momentum), intent(in) :: k
  type(vector) :: vk

```

```

vk = k
psir_l%a(1:2) = psir%a(1:2)
psir_l%a(3:4) = 0
psir_r%a(1:2) = 0
psir_r%a(3:4) = psir%a(3:4)
j = gl * grkgggf (psil, psir_l, vk) + gr * grkgggf (psil, psir_r, vk)
end function vlr_grf
 $V^\mu = \psi^T \tilde{C}^{\mu\rho} \psi_\rho$ ; remember the reversed index order in  $\tilde{C}$ .
(Implementation of bispinor currents)+≡
pure function fgkgggr (psil, psir, k) result (j)
    type(vector) :: j
    type(vectorspinor), intent(in) :: psir
    type(bispinor), intent(in) :: psil
    type(vector), intent(in) :: k
    type(bispinor) :: c_psil0, c_psil1, c_psil2, c_psil3
    complex(kind=default) :: kp, km, k12, k12s, ik1, ik2
    kp = k%t + k%x(3)
    km = k%t - k%x(3)
    k12 = k%x(1) + (0,1)*k%x(2)
    k12s = k%x(1) - (0,1)*k%x(2)
    ik1 = (0,1) * k%x(1)
    ik2 = (0,1) * k%x(2)
    c_psil0%a(1) = k%x(3) * (psir%psi(1)%a(4) + psir%psi(4)%a(4) &
        + psir%psi(2)%a(3) + (0,1) * psir%psi(3)%a(3)) &
        - k12 * (psir%psi(1)%a(3) + psir%psi(4)%a(3)) &
        + k12s * (psir%psi(2)%a(4) + (0,1) * psir%psi(3)%a(4))
    c_psil0%a(2) = k%x(3) * (psir%psi(1)%a(3) - psir%psi(4)%a(3) + &
        psir%psi(2)%a(4) - (0,1) * psir%psi(3)%a(4)) + &
        k12s * (psir%psi(1)%a(4) - psir%psi(4)%a(4)) - &
        k12 * (psir%psi(2)%a(3) - (0,1) * psir%psi(3)%a(3))
    c_psil0%a(3) = k%x(3) * (-psir%psi(1)%a(2) + psir%psi(4)%a(2) + &
        psir%psi(2)%a(1) + (0,1) * psir%psi(3)%a(1)) + &
        k12 * (psir%psi(1)%a(1) - psir%psi(4)%a(1)) + &
        k12s * (psir%psi(2)%a(2) + (0,1) * psir%psi(3)%a(2))
    c_psil0%a(4) = k%x(3) * (-psir%psi(1)%a(1) - psir%psi(4)%a(1) + &
        psir%psi(2)%a(2) - (0,1) * psir%psi(3)%a(2)) - &
        k12s * (psir%psi(1)%a(2) + psir%psi(4)%a(2)) - &
        k12 * (psir%psi(2)%a(1) - (0,1) * psir%psi(3)%a(1))
    !!!
    c_psil1%a(1) = ik2 * (-psir%psi(1)%a(4) - psir%psi(4)%a(4) - &
        psir%psi(2)%a(3) - (0,1) * psir%psi(3)%a(3)) - &
        km * (psir%psi(1)%a(3) + psir%psi(4)%a(3)) + &
        kp * (psir%psi(2)%a(4) + (0,1) * psir%psi(3)%a(4))
    c_psil1%a(2) = ik2 * (-psir%psi(1)%a(3) - psir%psi(2)%a(4) + &
        psir%psi(4)%a(3) + (0,1) * psir%psi(3)%a(4)) + &
        kp * (psir%psi(1)%a(4) - psir%psi(4)%a(4)) - &
        km * (psir%psi(2)%a(3) - (0,1) * psir%psi(3)%a(3))
    c_psil1%a(3) = ik2 * (-psir%psi(1)%a(2) + psir%psi(2)%a(1) + &
        psir%psi(4)%a(2) + (0,1) * psir%psi(3)%a(1)) + &
        kp * (psir%psi(1)%a(1) - psir%psi(4)%a(1)) + &
        km * (psir%psi(2)%a(2) + (0,1) * psir%psi(3)%a(2))
    c_psil1%a(4) = ik2 * (-psir%psi(1)%a(1) + psir%psi(2)%a(2) - &
        psir%psi(4)%a(1) - (0,1) * psir%psi(3)%a(2)) - &
        km * (psir%psi(1)%a(2) + psir%psi(4)%a(2)) - &

```



```

        kp * (psir%psi(2)%a(1) - (0,1) * psir%psi(3)%a(1))
    !!!
    c_psi2%a(1) = ik1 * (psir%psi(2)%a(3) + psir%psi(1)%a(4) &
        + psir%psi(4)%a(4) + (0,1) * psir%psi(3)%a(3)) - &
        ((0,1)*km) * (psir%psi(1)%a(3) + psir%psi(4)%a(3)) &
        + kp * (psir%psi(3)%a(4) - (0,1) * psir%psi(2)%a(4))
    c_psi2%a(2) = ik1 * (psir%psi(1)%a(3) + psir%psi(2)%a(4) - &
        psir%psi(4)%a(3) - (0,1) * psir%psi(3)%a(4)) - &
        ((0,1)*kp) * (psir%psi(1)%a(4) - psir%psi(4)%a(4)) &
        - km * (psir%psi(3)%a(3) + (0,1) * psir%psi(2)%a(3))
    c_psi2%a(3) = ik1 * (psir%psi(1)%a(2) - psir%psi(2)%a(1) - &
        psir%psi(4)%a(2) - (0,1) * psir%psi(3)%a(1)) + &
        ((0,1)*kp) * (psir%psi(1)%a(1) - psir%psi(4)%a(1)) &
        + km * (psir%psi(3)%a(2) - (0,1) * psir%psi(2)%a(2))
    c_psi2%a(4) = ik1 * (psir%psi(1)%a(1) - psir%psi(2)%a(2) + &
        psir%psi(4)%a(1) + (0,1) * psir%psi(3)%a(2)) + &
        ((0,1)*km) * (psir%psi(1)%a(2) + psir%psi(4)%a(2)) - &
        kp * (psir%psi(3)%a(1) + (0,1) * psir%psi(2)%a(1))
    !!!
    c_psi3%a(1) = k%t * (psir%psi(1)%a(4) + psir%psi(4)%a(4) + &
        psir%psi(2)%a(3) + (0,1) * psir%psi(3)%a(3)) - &
        k12 * (psir%psi(1)%a(3) + psir%psi(4)%a(3)) - &
        k12s * (psir%psi(2)%a(4) + (0,1) * psir%psi(3)%a(4))
    c_psi3%a(2) = k%t * (psir%psi(1)%a(3) - psir%psi(4)%a(3) + &
        psir%psi(2)%a(4) - (0,1) * psir%psi(3)%a(4)) - &
        k12s * (psir%psi(1)%a(4) - psir%psi(4)%a(4)) - &
        k12 * (psir%psi(2)%a(3) - (0,1) * psir%psi(3)%a(3))
    c_psi3%a(3) = k%t * (-psir%psi(1)%a(2) + psir%psi(2)%a(1) + &
        psir%psi(4)%a(2) + (0,1) * psir%psi(3)%a(1)) - &
        k12 * (psir%psi(1)%a(1) - psir%psi(4)%a(1)) + &
        k12s * (psir%psi(2)%a(2) + (0,1) * psir%psi(3)%a(2))
    c_psi3%a(4) = k%t * (-psir%psi(1)%a(1) + psir%psi(2)%a(2) - &
        psir%psi(4)%a(1) - (0,1) * psir%psi(3)%a(2)) - &
        k12s * (psir%psi(1)%a(2) + psir%psi(4)%a(2)) + &
        k12 * (psir%psi(2)%a(1) - (0,1) * psir%psi(3)%a(1))
    !!! Because we explicitly multiplied the charge conjugation matrix
    !!! we have to omit it from the spinor product and take the
    !!! ordinary product!
    j%t      = 2 * dot_product (conjg (psil%a), c_psi0%a)
    j%x(1)   = 2 * dot_product (conjg (psil%a), c_psi1%a)
    j%x(2)   = 2 * dot_product (conjg (psil%a), c_psi2%a)
    j%x(3)   = 2 * dot_product (conjg (psil%a), c_psi3%a)
end function fggkggr

<Implementation of bispinor currents>+=
pure function v_fgr (g, psil, psir, k) result (j)
    type(vector) :: j
    complex(kind=default), intent(in) :: g
    type(vectorspinor), intent(in) :: psir
    type(bispinor), intent(in) :: psil
    type(momentum), intent(in) :: k
    type(vector) :: vk
    vk = k
    j = g * fggkggr (psil, psir, vk)
end function v_fgr

```

```

<Implementation of bispinor currents>+≡
pure function vlr_fgr (gl, gr, psil, psir, k) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: gl, gr
  type(vectorspinor), intent(in) :: psir
  type(bispinor), intent(in) :: psil
  type(bispinor) :: psil_l
  type(bispinor) :: psil_r
  type(momentum), intent(in) :: k
  type(vector) :: vk
  vk = k
  psil_l%a(1:2) = psil%a(1:2)
  psil_l%a(3:4) = 0
  psil_r%a(1:2) = 0
  psil_r%a(3:4) = psil%a(3:4)
  j = gl * fggkggr (psil_l, psir, vk) + gr * fggkggr (psil_r, psir, vk)
end function vlr_fgr

```

#### X.14.5 Gravitino 4-Couplings

```

<Declaration of bispinor currents>+≡
public :: f_s2gr, f_svgr, f_slvgr, f_srvgr, f_slrvgr, f_pvgr, f_v2gr, f_v2lgr

<Implementation of bispinor currents>+≡
pure function f_s2gr (g, phi1, phi2, psi) result (phipsi)
  type(bispinor) :: phipsi
  type(vectorspinor), intent(in) :: psi
  complex(kind=default), intent(in) :: g
  complex(kind=default), intent(in) :: phi1, phi2
  phipsi = phi2 * f_potgr (g, phi1, psi)
end function f_s2gr

<Implementation of bispinor currents>+≡
pure function f_svgr (g, phi, v, grav) result (phigrav)
  type(bispinor) :: phigrav
  type(vectorspinor), intent(in) :: grav
  type(vector), intent(in) :: v
  complex(kind=default), intent(in) :: g, phi
  phigrav = (g * phi) * fgvg5gr (grav, v)
end function f_svgr

<Implementation of bispinor currents>+≡
pure function f_slvgr (gl, phi, v, grav) result (phigrav)
  type(bispinor) :: phigrav, phidum
  type(vectorspinor), intent(in) :: grav
  type(vector), intent(in) :: v
  complex(kind=default), intent(in) :: gl, phi
  phidum = (gl * phi) * fgvg5gr (grav, v)
  phigrav%a(1:2) = phidum%a(1:2)
  phigrav%a(3:4) = 0
end function f_slvgr

<Implementation of bispinor currents>+≡
pure function f_srvgr (gr, phi, v, grav) result (phigrav)
  type(bispinor) :: phigrav, phidum
  type(vectorspinor), intent(in) :: grav

```

```

    type(vector), intent(in) :: v
    complex(kind=default), intent(in) :: gr, phi
    phidum = (gr * phi) * fgvg5gr (grav, v)
    phigrav%a(1:2) = 0
    phigrav%a(3:4) = phidum%a(3:4)
end function f_srvgr

<Implementation of bispinor currents>+≡
pure function f_slrvgr (gl, gr, phi, v, grav) result (phigrav)
    type(bispinor) :: phigrav
    type(vectorspinor), intent(in) :: grav
    type(vector), intent(in) :: v
    complex(kind=default), intent(in) :: gl, gr, phi
    phigrav = f_slvgr (gl, phi, v, grav) + f_srvgr (gr, phi, v, grav)
end function f_slrvgr

<Implementation of bispinor currents>+≡
pure function f_pvgr (g, phi, v, grav) result (phigrav)
    type(bispinor) :: phigrav
    type(vectorspinor), intent(in) :: grav
    type(vector), intent(in) :: v
    complex(kind=default), intent(in) :: g, phi
    phigrav = (g * phi) * fgvgr (grav, v)
end function f_pvgr

<Implementation of bispinor currents>+≡
pure function f_v2gr (g, v1, v2, grav) result (psi)
    type(bispinor) :: psi
    complex(kind=default), intent(in) :: g
    type(vectorspinor), intent(in) :: grav
    type(vector), intent(in) :: v1, v2
    psi = g * fggvvgr (v2, grav, v1)
end function f_v2gr

<Implementation of bispinor currents>+≡
pure function f_v2lrgr (gl, gr, v1, v2, grav) result (psi)
    type(bispinor) :: psi
    complex(kind=default), intent(in) :: gl, gr
    type(vectorspinor), intent(in) :: grav
    type(vector), intent(in) :: v1, v2
    psi = fggvvgr (v2, grav, v1)
    psi%a(1:2) = gl * psi%a(1:2)
    psi%a(3:4) = gr * psi%a(3:4)
end function f_v2lrgr

<Declaration of bispinor currents>+≡
public :: gr_s2f, gr_svf, gr_pvf, gr_slvf, gr_srvf, gr_slrvf, gr_v2f, gr_v2lrf

<Implementation of bispinor currents>+≡
pure function gr_s2f (g, phi1, phi2, psi) result (phipsi)
    type(vectorspinor) :: phipsi
    type(bispinor), intent(in) :: psi
    complex(kind=default), intent(in) :: g
    complex(kind=default), intent(in) :: phi1, phi2
    phipsi = phi2 * gr_potf (g, phi1, psi)
end function gr_s2f

```

```

<Implementation of bispinor currents>+≡
pure function gr_svf (g, phi, v, psi) result (phipsi)
  type(vectorspinor) :: phipsi
  type(bispinor), intent(in) :: psi
  type(vector), intent(in) :: v
  complex(kind=default), intent(in) :: g, phi
  phipsi = (g * phi) * grkggf (psi, v)
end function gr_svf

<Implementation of bispinor currents>+≡
pure function gr_slvf (gl, phi, v, psi) result (phipsi)
  type(vectorspinor) :: phipsi
  type(bispinor), intent(in) :: psi
  type(bispinor) :: psi_l
  type(vector), intent(in) :: v
  complex(kind=default), intent(in) :: gl, phi
  psi_l%a(1:2) = psi%a(1:2)
  psi_l%a(3:4) = 0
  phipsi = (gl * phi) * grkggf (psi_l, v)
end function gr_slvf

<Implementation of bispinor currents>+≡
pure function gr_srvf (gr, phi, v, psi) result (phipsi)
  type(vectorspinor) :: phipsi
  type(bispinor), intent(in) :: psi
  type(bispinor) :: psi_r
  type(vector), intent(in) :: v
  complex(kind=default), intent(in) :: gr, phi
  psi_r%a(1:2) = 0
  psi_r%a(3:4) = psi%a(3:4)
  phipsi = (gr * phi) * grkggf (psi_r, v)
end function gr_srvf

<Implementation of bispinor currents>+≡
pure function gr_slrvf (gl, gr, phi, v, psi) result (phipsi)
  type(vectorspinor) :: phipsi
  type(bispinor), intent(in) :: psi
  type(vector), intent(in) :: v
  complex(kind=default), intent(in) :: gl, gr, phi
  phipsi = gr_slvf (gl, phi, v, psi) + gr_srvf (gr, phi, v, psi)
end function gr_slrvf

<Implementation of bispinor currents>+≡
pure function gr_pvf (g, phi, v, psi) result (phipsi)
  type(vectorspinor) :: phipsi
  type(bispinor), intent(in) :: psi
  type(vector), intent(in) :: v
  complex(kind=default), intent(in) :: g, phi
  phipsi = (g * phi) * grkggf (psi, v)
end function gr_pvf

<Implementation of bispinor currents>+≡
pure function gr_v2f (g, v1, v2, psi) result (vvpsi)
  type(vectorspinor) :: vvpsi
  complex(kind=default), intent(in) :: g
  type(bispinor), intent(in) :: psi
  type(vector), intent(in) :: v1, v2

```

```

    vvpsi = g * grkkggf (v2, psi, v1)
end function gr_v2f

<Implementation of bispinor currents>+≡
pure function gr_v2lrf (gl, gr, v1, v2, psi) result (vvpsi)
  type(vectorspinor) :: vvpsi
  complex(kind=default), intent(in) :: gl, gr
  type(bispinor), intent(in) :: psi
  type(bispinor) :: psi_l, psi_r
  type(vector), intent(in) :: v1, v2
  psi_l%a(1:2) = psi%a(1:2)
  psi_l%a(3:4) = 0
  psi_r%a(1:2) = 0
  psi_r%a(3:4) = psi%a(3:4)
  vvpsi = gl * grkkggf (v2, psi_l, v1) + gr * grkkggf (v2, psi_r, v1)
end function gr_v2lrf

<Declaration of bispinor currents>+≡
public :: s2_grf, s2_fgr, sv1_grf, sv2_grf, sv1_fgr, sv2_fgr, &
  slv1_grf, slv2_grf, slv1_fgr, slv2_fgr, &
  srv1_grf, srv2_grf, srv1_fgr, srv2_fgr, &
  slrv1_grf, slrv2_grf, slrv1_fgr, slrv2_fgr, &
  pv1_grf, pv2_grf, pv1_fgr, pv2_fgr, v2_grf, v2_fgr, &
  v2lr_grf, v2lr_fgr

<Implementation of bispinor currents>+≡
pure function s2_grf (g, gravbar, phi, psi) result (j)
  complex(kind=default) :: j
  complex(kind=default), intent(in) :: g, phi
  type(vectorspinor), intent(in) :: gravbar
  type(bispinor), intent(in) :: psi
  j = phi * pot_grf (g, gravbar, psi)
end function s2_grf

<Implementation of bispinor currents>+≡
pure function s2_fgr (g, psibar, phi, grav) result (j)
  complex(kind=default) :: j
  complex(kind=default), intent(in) :: g, phi
  type(bispinor), intent(in) :: psibar
  type(vectorspinor), intent(in) :: grav
  j = phi * pot_fgr (g, psibar, grav)
end function s2_fgr

<Implementation of bispinor currents>+≡
pure function sv1_grf (g, gravbar, v, psi) result (j)
  complex(kind=default) :: j
  complex(kind=default), intent(in) :: g
  type(vectorspinor), intent(in) :: gravbar
  type(bispinor), intent(in) :: psi
  type(vector), intent(in) :: v
  j = g * grg5vgf (gravbar, psi, v)
end function sv1_grf

<Implementation of bispinor currents>+≡
pure function slv1_grf (gl, gravbar, v, psi) result (j)
  complex(kind=default) :: j
  complex(kind=default), intent(in) :: gl

```

```

    type(vectorspinor), intent(in) :: gravbar
    type(bispinor), intent(in) :: psi
    type(bispinor) :: psi_l
    type(vector), intent(in) :: v
    psi_l%a(1:2) = psi%a(1:2)
    psi_l%a(3:4) = 0
    j = gl * grg5vgf (gravbar, psi_l, v)
end function slv1_grf

<Implementation of bispinor currents>+≡
pure function srv1_grf (gr, gravbar, v, psi) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: gr
    type(vectorspinor), intent(in) :: gravbar
    type(bispinor), intent(in) :: psi
    type(bispinor) :: psi_r
    type(vector), intent(in) :: v
    psi_r%a(1:2) = 0
    psi_r%a(3:4) = psi%a(3:4)
    j = gr * grg5vgf (gravbar, psi_r, v)
end function srv1_grf

<Implementation of bispinor currents>+≡
pure function slrv1_grf (gl, gr, gravbar, v, psi) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: gl, gr
    type(vectorspinor), intent(in) :: gravbar
    type(bispinor), intent(in) :: psi
    type(bispinor) :: psi_l, psi_r
    type(vector), intent(in) :: v
    psi_l%a(1:2) = psi%a(1:2)
    psi_l%a(3:4) = 0
    psi_r%a(1:2) = 0
    psi_r%a(3:4) = psi%a(3:4)
    j = gl * grg5vgf (gravbar, psi_l, v) + gr * grg5vgf (gravbar, psi_r, v)
end function slrv1_grf

```

$$C\gamma^0\gamma^0 = -C\gamma^1\gamma^1 = -C\gamma^2\gamma^2 = C\gamma^3\gamma^3 = C = \begin{pmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \quad (\text{X.84a})$$

$$C\gamma^0\gamma^1 = -C\gamma^1\gamma^0 = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (\text{X.84b})$$

$$C\gamma^0\gamma^2 = -C\gamma^2\gamma^0 = \begin{pmatrix} -i & 0 & 0 & 0 \\ 0 & -i & 0 & 0 \\ 0 & 0 & -i & 0 \\ 0 & 0 & 0 & -i \end{pmatrix} \quad (\text{X.84c})$$

$$C\gamma^0\gamma^3 = -C\gamma^3\gamma^0 = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \quad (\text{X.84d})$$

$$C\gamma^1\gamma^2 = -C\gamma^2\gamma^1 = \begin{pmatrix} 0 & i & 0 & 0 \\ i & 0 & 0 & 0 \\ 0 & 0 & 0 & -i \\ 0 & 0 & -i & 0 \end{pmatrix} \quad (\text{X.84e})$$

$$C\gamma^1\gamma^3 = -C\gamma^3\gamma^1 = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (\text{X.84f})$$

$$C\gamma^2\gamma^3 = -C\gamma^3\gamma^2 = \begin{pmatrix} -i & 0 & 0 & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & i & 0 \\ 0 & 0 & 0 & -i \end{pmatrix} \quad (\text{X.84g})$$

*(Implementation of bispinor currents)+≡*

```
pure function sv2_grf (g, gravbar, phi, psi) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: g, phi
  type(vectorspinor), intent(in) :: gravbar
  type(bispinor), intent(in) :: psi
  type(vectorspinor) :: g0_psi, g1_psi, g2_psi, g3_psi
  g0_psi%psi(1)%a(1:2) = - psi%a(1:2)
  g0_psi%psi(1)%a(3:4) = psi%a(3:4)
  g0_psi%psi(2)%a(1) = psi%a(2)
  g0_psi%psi(2)%a(2) = psi%a(1)
  g0_psi%psi(2)%a(3) = psi%a(4)
  g0_psi%psi(2)%a(4) = psi%a(3)
  g0_psi%psi(3)%a(1) = (0,-1) * psi%a(2)
  g0_psi%psi(3)%a(2) = (0,1) * psi%a(1)
  g0_psi%psi(3)%a(3) = (0,-1) * psi%a(4)
  g0_psi%psi(3)%a(4) = (0,1) * psi%a(3)
  g0_psi%psi(4)%a(1) = psi%a(1)
  g0_psi%psi(4)%a(2) = - psi%a(2)
  g0_psi%psi(4)%a(3) = psi%a(3)
  g0_psi%psi(4)%a(4) = - psi%a(4)
  g1_psi%psi(1)%a(1:4) = - g0_psi%psi(2)%a(1:4)
  g1_psi%psi(2)%a(1:4) = - g0_psi%psi(1)%a(1:4)
  g1_psi%psi(3)%a(1) = (0,1) * psi%a(1)
  g1_psi%psi(3)%a(2) = (0,-1) * psi%a(2)
  g1_psi%psi(3)%a(3) = (0,-1) * psi%a(3)
  g1_psi%psi(3)%a(4) = (0,1) * psi%a(4)
  g1_psi%psi(4)%a(1) = - psi%a(2)
  g1_psi%psi(4)%a(2) = psi%a(1)
  g1_psi%psi(4)%a(3) = psi%a(4)
  g1_psi%psi(4)%a(4) = - psi%a(3)
  g2_psi%psi(1)%a(1:4) = - g0_psi%psi(3)%a(1:4)
  g2_psi%psi(2)%a(1:4) = - g1_psi%psi(3)%a(1:4)
  g2_psi%psi(3)%a(1:4) = - g0_psi%psi(1)%a(1:4)
  g2_psi%psi(4)%a(1) = (0,1) * psi%a(2)
```

```

g2_psi%psi(4)%a(2) = (0,1) * psi%a(1)
g2_psi%psi(4)%a(3) = (0,-1) * psi%a(4)
g2_psi%psi(4)%a(4) = (0,-1) * psi%a(3)
g3_psi%psi(1)%a(1:4) = - g0_psi%psi(4)%a(1:4)
g3_psi%psi(2)%a(1:4) = - g1_psi%psi(4)%a(1:4)
g3_psi%psi(3)%a(1:4) = - g2_psi%psi(4)%a(1:4)
g3_psi%psi(4)%a(1:4) = - g0_psi%psi(1)%a(1:4)
j%t      = (g * phi) * (gravbar * g0_psi)
j%x(1)   = (g * phi) * (gravbar * g1_psi)
j%x(2)   = (g * phi) * (gravbar * g2_psi)
j%x(3)   = (g * phi) * (gravbar * g3_psi)
end function sv2_grf

```

*(Implementation of bispinor currents)+≡*

```

pure function slv2_grf (gl, gravbar, phi, psi) result (j)
    type(vector) :: j
    complex(kind=default), intent(in) :: gl, phi
    type(vectorspinor), intent(in) :: gravbar
    type(bispinor), intent(in) :: psi
    type(bispinor) :: psi_l
    psi_l%a(1:2) = psi%a(1:2)
    psi_l%a(3:4) = 0
    j = sv2_grf (gl, gravbar, phi, psi_l)
end function slv2_grf

```

*(Implementation of bispinor currents)+≡*

```

pure function srv2_grf (gr, gravbar, phi, psi) result (j)
    type(vector) :: j
    complex(kind=default), intent(in) :: gr, phi
    type(vectorspinor), intent(in) :: gravbar
    type(bispinor), intent(in) :: psi
    type(bispinor) :: psi_r
    psi_r%a(1:2) = 0
    psi_r%a(3:4) = psi%a(3:4)
    j = sv2_grf (gr, gravbar, phi, psi_r)
end function srv2_grf

```

*(Implementation of bispinor currents)+≡*

```

pure function slrv2_grf (gl, gr, gravbar, phi, psi) result (j)
    type(vector) :: j
    complex(kind=default), intent(in) :: gl, gr, phi
    type(vectorspinor), intent(in) :: gravbar
    type(bispinor), intent(in) :: psi
    type(bispinor) :: psi_l, psi_r
    psi_l%a(1:2) = psi%a(1:2)
    psi_l%a(3:4) = 0
    psi_r%a(1:2) = 0
    psi_r%a(3:4) = psi%a(3:4)
    j = sv2_grf (gl, gravbar, phi, psi_l) + sv2_grf (gr, gravbar, phi, psi_r)
end function slrv2_grf

```

*(Implementation of bispinor currents)+≡*

```

pure function sv1_fgr (g, psibar, v, grav) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: g
    type(bispinor), intent(in) :: psibar

```



```

    type(vectorspinor), intent(in) :: grav
    type(vector), intent(in) :: v
    j = g * fg5gkgr (psibar, grav, v)
end function sv1_fgr

<Implementation of bispinor currents>+≡
pure function slv1_fgr (gl, psibar, v, grav) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: gl
    type(bispinor), intent(in) :: psibar
    type(bispinor) :: psibar_l
    type(vectorspinor), intent(in) :: grav
    type(vector), intent(in) :: v
    psibar_l%a(1:2) = psibar%a(1:2)
    psibar_l%a(3:4) = 0
    j = gl * fg5gkgr (psibar_l, grav, v)
end function slv1_fgr

<Implementation of bispinor currents>+≡
pure function srv1_fgr (gr, psibar, v, grav) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: gr
    type(bispinor), intent(in) :: psibar
    type(bispinor) :: psibar_r
    type(vectorspinor), intent(in) :: grav
    type(vector), intent(in) :: v
    psibar_r%a(1:2) = 0
    psibar_r%a(3:4) = psibar%a(3:4)
    j = gr * fg5gkgr (psibar_r, grav, v)
end function srv1_fgr

<Implementation of bispinor currents>+≡
pure function slrv1_fgr (gl, gr, psibar, v, grav) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: gl, gr
    type(bispinor), intent(in) :: psibar
    type(bispinor) :: psibar_l, psibar_r
    type(vectorspinor), intent(in) :: grav
    type(vector), intent(in) :: v
    psibar_l%a(1:2) = psibar%a(1:2)
    psibar_l%a(3:4) = 0
    psibar_r%a(1:2) = 0
    psibar_r%a(3:4) = psibar%a(3:4)
    j = gl * fg5gkgr (psibar_l, grav, v) + gr * fg5gkgr (psibar_r, grav, v)
end function slrv1_fgr

<Implementation of bispinor currents>+≡
pure function sv2_fgr (g, psibar, phi, grav) result (j)
    type(vector) :: j
    complex(kind=default), intent(in) :: g, phi
    type(bispinor), intent(in) :: psibar
    type(vectorspinor), intent(in) :: grav
    type(bispinor) :: g0_grav, g1_grav, g2_grav, g3_grav
    g0_grav%a(1) = -grav%psi(1)%a(1) + grav%psi(2)%a(2) - &
        (0,1) * grav%psi(3)%a(2) + grav%psi(4)%a(1)
    g0_grav%a(2) = -grav%psi(1)%a(2) + grav%psi(2)%a(1) + &

```

```

      (0,1) * grav%psi(3)%a(1) - grav%psi(4)%a(2)
g0_grav%a(3) = grav%psi(1)%a(3) + grav%psi(2)%a(4) - &
      (0,1) * grav%psi(3)%a(4) + grav%psi(4)%a(3)
g0_grav%a(4) = grav%psi(1)%a(4) + grav%psi(2)%a(3) + &
      (0,1) * grav%psi(3)%a(3) - grav%psi(4)%a(4)
!!!
g1_grav%a(1) = grav%psi(1)%a(2) - grav%psi(2)%a(1) + &
      (0,1) * grav%psi(3)%a(1) - grav%psi(4)%a(2)
g1_grav%a(2) = grav%psi(1)%a(1) - grav%psi(2)%a(2) - &
      (0,1) * grav%psi(3)%a(2) + grav%psi(4)%a(1)
g1_grav%a(3) = grav%psi(1)%a(4) + grav%psi(2)%a(3) - &
      (0,1) * grav%psi(3)%a(3) + grav%psi(4)%a(4)
g1_grav%a(4) = grav%psi(1)%a(3) + grav%psi(2)%a(4) + &
      (0,1) * grav%psi(3)%a(4) - grav%psi(4)%a(3)
!!!
g2_grav%a(1) = (0,1) * (-grav%psi(1)%a(2) - grav%psi(2)%a(1) + &
      grav%psi(4)%a(2)) - grav%psi(3)%a(1)
g2_grav%a(2) = (0,1) * (grav%psi(1)%a(1) + grav%psi(2)%a(2) + &
      grav%psi(4)%a(1)) - grav%psi(3)%a(2)
g2_grav%a(3) = (0,1) * (-grav%psi(1)%a(4) + grav%psi(2)%a(3) - &
      grav%psi(4)%a(4)) + grav%psi(3)%a(3)
g2_grav%a(4) = (0,1) * (grav%psi(1)%a(3) - grav%psi(2)%a(4) - &
      grav%psi(4)%a(3)) + grav%psi(3)%a(4)
!!!
g3_grav%a(1) = -grav%psi(1)%a(2) + grav%psi(2)%a(2) - &
      (0,1) * grav%psi(3)%a(2) - grav%psi(4)%a(1)
g3_grav%a(2) = grav%psi(1)%a(1) - grav%psi(2)%a(1) - &
      (0,1) * grav%psi(3)%a(1) - grav%psi(4)%a(2)
g3_grav%a(3) = -grav%psi(1)%a(2) - grav%psi(2)%a(4) + &
      (0,1) * grav%psi(3)%a(4) + grav%psi(4)%a(3)
g3_grav%a(4) = -grav%psi(1)%a(4) + grav%psi(2)%a(3) + &
      (0,1) * grav%psi(3)%a(3) + grav%psi(4)%a(4)
j%t      = (g * phi) * (psibar * g0_grav)
j%x(1)   = (g * phi) * (psibar * g1_grav)
j%x(2)   = (g * phi) * (psibar * g2_grav)
j%x(3)   = (g * phi) * (psibar * g3_grav)
end function sv2_fgr

```

(Implementation of bispinor currents)+≡

```

pure function slv2_fgr (gl, psibar, phi, grav) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: gl, phi
  type(bispinor), intent(in) :: psibar
  type(bispinor) :: psibar_l
  type(vectorspinor), intent(in) :: grav
  psibar_l%a(1:2) = psibar%a(1:2)
  psibar_l%a(3:4) = 0
  j = sv2_fgr (gl, psibar_l, phi, grav)
end function slv2_fgr

```

(Implementation of bispinor currents)+≡

```

pure function srv2_fgr (gr, psibar, phi, grav) result (j)
  type(vector) :: j
  complex(kind=default), intent(in) :: gr, phi
  type(bispinor), intent(in) :: psibar

```

```

    type(bispinor) :: psibar_r
    type(vectorspinor), intent(in) :: grav
    psibar_r%a(1:2) = 0
    psibar_r%a(3:4) = psibar%a(3:4)
    j = sv2_fgr (gr, psibar_r, phi, grav)
end function srv2_fgr

<Implementation of bispinor currents>+≡
pure function slrv2_fgr (gl, gr, psibar, phi, grav) result (j)
    type(vector) :: j
    complex(kind=default), intent(in) :: gl, gr, phi
    type(bispinor), intent(in) :: psibar
    type(bispinor) :: psibar_l, psibar_r
    type(vectorspinor), intent(in) :: grav
    psibar_l%a(1:2) = psibar%a(1:2)
    psibar_l%a(3:4) = 0
    psibar_r%a(1:2) = 0
    psibar_r%a(3:4) = psibar%a(3:4)
    j = sv2_fgr (gl, psibar_l, phi, grav) + sv2_fgr (gr, psibar_r, phi, grav)
end function slrv2_fgr

<Implementation of bispinor currents>+≡
pure function pv1_grf (g, gravbar, v, psi) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: g
    type(vectorspinor), intent(in) :: gravbar
    type(bispinor), intent(in) :: psi
    type(vector), intent(in) :: v
    j = g * grvgf (gravbar, psi, v)
end function pv1_grf

<Implementation of bispinor currents>+≡
pure function pv2_grf (g, gravbar, phi, psi) result (j)
    type(vector) :: j
    complex(kind=default), intent(in) :: g, phi
    type(vectorspinor), intent(in) :: gravbar
    type(bispinor), intent(in) :: psi
    type(bispinor) :: g5_psi
    g5_psi%a(1:2) = - psi%a(1:2)
    g5_psi%a(3:4) = psi%a(3:4)
    j = sv2_grf (g, gravbar, phi, g5_psi)
end function pv2_grf

<Implementation of bispinor currents>+≡
pure function pv1_fgr (g, psibar, v, grav) result (j)
    complex(kind=default) :: j
    complex(kind=default), intent(in) :: g
    type(bispinor), intent(in) :: psibar
    type(vectorspinor), intent(in) :: grav
    type(vector), intent(in) :: v
    j = g * fgkgr (psibar, grav, v)
end function pv1_fgr

<Implementation of bispinor currents>+≡
pure function pv2_fgr (g, psibar, phi, grav) result (j)
    type(vector) :: j
    complex(kind=default), intent(in) :: g, phi

```

```

    type(vectorspinor), intent(in) :: grav
    type(bispinor), intent(in) :: psibar
    type(bispinor) :: psibar_g5
    psibar_g5%a(1:2) = - psibar%a(1:2)
    psibar_g5%a(3:4) = psibar%a(3:4)
    j = sv2_fgr (g, psibar_g5, phi, grav)
end function pv2_fgr

<Implementation of bispinor currents>+≡
pure function v2_grf (g, gravbar, v, psi) result (j)
    type(vector) :: j
    complex(kind=default), intent(in) :: g
    type(vectorspinor), intent(in) :: gravbar
    type(bispinor), intent(in) :: psi
    type(vector), intent(in) :: v
    j = -g * grkgggf (gravbar, psi, v)
end function v2_grf

<Implementation of bispinor currents>+≡
pure function v2lr_grf (gl, gr, gravbar, v, psi) result (j)
    type(vector) :: j
    complex(kind=default), intent(in) :: gl, gr
    type(vectorspinor), intent(in) :: gravbar
    type(bispinor), intent(in) :: psi
    type(bispinor) :: psi_l, psi_r
    type(vector), intent(in) :: v
    psi_l%a(1:2) = psi%a(1:2)
    psi_l%a(3:4) = 0
    psi_r%a(1:2) = 0
    psi_r%a(3:4) = psi%a(3:4)
    j = -(gl * grkgggf (gravbar, psi_l, v) + gr * grkgggf (gravbar, psi_r, v))
end function v2lr_grf

<Implementation of bispinor currents>+≡
pure function v2_fgr (g, psibar, v, grav) result (j)
    type(vector) :: j
    complex(kind=default), intent(in) :: g
    type(vectorspinor), intent(in) :: grav
    type(bispinor), intent(in) :: psibar
    type(vector), intent(in) :: v
    j = -g * fgkgggr (psibar, grav, v)
end function v2_fgr

<Implementation of bispinor currents>+≡
pure function v2lr_fgr (gl, gr, psibar, v, grav) result (j)
    type(vector) :: j
    complex(kind=default), intent(in) :: gl, gr
    type(vectorspinor), intent(in) :: grav
    type(bispinor), intent(in) :: psibar
    type(bispinor) :: psibar_l, psibar_r
    type(vector), intent(in) :: v
    psibar_l%a(1:2) = psibar%a(1:2)
    psibar_l%a(3:4) = 0
    psibar_r%a(1:2) = 0
    psibar_r%a(3:4) = psibar%a(3:4)
    j = -(gl * fgkgggr (psibar_l, grav, v) + gr * fgkgggr (psibar_r, grav, v))
end function v2lr_fgr

```

### X.14.6 On Shell Wave Functions

*(Declaration of bispinor on shell wave functions)*≡

```
public :: u, v, ghost
```

$$\chi_+(\vec{p}) = \frac{1}{\sqrt{2|\vec{p}|(|\vec{p}| + p_3)}} \begin{pmatrix} |\vec{p}| + p_3 \\ p_1 + ip_2 \end{pmatrix} \quad (\text{X.85a})$$

$$\chi_-(\vec{p}) = \frac{1}{\sqrt{2|\vec{p}|(|\vec{p}| + p_3)}} \begin{pmatrix} -p_1 + ip_2 \\ |\vec{p}| + p_3 \end{pmatrix} \quad (\text{X.85b})$$

$$u_{\pm}(p) = \begin{pmatrix} \sqrt{p_0 \mp |\vec{p}|} \cdot \chi_{\pm}(\vec{p}) \\ \sqrt{p_0 \pm |\vec{p}|} \cdot \chi_{\pm}(\vec{p}) \end{pmatrix} \quad (\text{X.86})$$

*(Implementation of bispinor on shell wave functions)*≡

```
pure function u (mass, p, s) result (psi)
  type(bispinor) :: psi
  real(kind=default), intent(in) :: mass
  type(momentum), intent(in) :: p
  integer, intent(in) :: s
  complex(kind=default), dimension(2) :: chip, chim
  real(kind=default) :: pabs, norm, delta, m
  m = abs(mass)
  pabs = sqrt (dot_product (p%x, p%x))
  if (m < epsilon (m) * pabs) then
    delta = 0
  else
    delta = sqrt (max (p%t - pabs, 0._default))
  end if
  if (pabs + p%x(3) <= 1000 * epsilon (pabs) * pabs) then
    chip = (/ cmplx ( 0.0, 0.0, kind=default), &
             cmplx ( 1.0, 0.0, kind=default) /)
    chim = (/ cmplx (-1.0, 0.0, kind=default), &
             cmplx ( 0.0, 0.0, kind=default) /)
  else
    norm = 1 / sqrt (2*pabs*(pabs + p%x(3)))
    chip = norm * (/ cmplx (pabs + p%x(3), kind=default), &
                    cmplx (p%x(1), p%x(2), kind=default) /)
    chim = norm * (/ cmplx (-p%x(1), p%x(2), kind=default), &
                    cmplx (pabs + p%x(3), kind=default) /)
  end if
  if (s > 0) then
    psi%a(1:2) = delta * chip
    psi%a(3:4) = sqrt (p%t + pabs) * chip
  else
    psi%a(1:2) = sqrt (p%t + pabs) * chim
    psi%a(3:4) = delta * chim
  end if
  pabs = m ! make the compiler happy and use m
  if (mass < 0) then
    psi%a(1:2) = - imago * psi%a(1:2)
    psi%a(3:4) = + imago * psi%a(3:4)
  end if
end function u
```

$$v_{\pm}(p) = \begin{pmatrix} \mp \sqrt{p_0 \pm |\vec{p}|} \cdot \chi_{\mp}(\vec{p}) \\ \pm \sqrt{p_0 \mp |\vec{p}|} \cdot \chi_{\mp}(\vec{p}) \end{pmatrix} \quad (\text{X.87})$$

*(Implementation of bispinor on shell wave functions)* +=

```
pure function v (mass, p, s) result (psi)
  type(bispinor) :: psi
  real(kind=default), intent(in) :: mass
  type(momentum), intent(in) :: p
  integer, intent(in) :: s
  complex(kind=default), dimension(2) :: chip, chim
  real(kind=default) :: pabs, norm, delta, m
  pabs = sqrt (dot_product (p%x, p%x))
  m = abs(mass)
  if (m < epsilon (m) * pabs) then
    delta = 0
  else
    delta = sqrt (max (p%t - pabs, 0._default))
  end if
  if (pabs + p%x(3) <= 1000 * epsilon (pabs) * pabs) then
    chip = (/ cmplx ( 0.0, 0.0, kind=default), &
             cmplx ( 1.0, 0.0, kind=default) /)
    chim = (/ cmplx (-1.0, 0.0, kind=default), &
             cmplx ( 0.0, 0.0, kind=default) /)
  else
    norm = 1 / sqrt (2*pabs*(pabs + p%x(3)))
    chip = norm * (/ cmplx (pabs + p%x(3), kind=default), &
                    cmplx (p%x(1), p%x(2), kind=default) /)
    chim = norm * (/ cmplx (-p%x(1), p%x(2), kind=default), &
                    cmplx (pabs + p%x(3), kind=default) /)
  end if
  if (s > 0) then
    psi%a(1:2) = - sqrt (p%t + pabs) * chim
    psi%a(3:4) = delta * chim
  else
    psi%a(1:2) = delta * chip
    psi%a(3:4) = - sqrt (p%t + pabs) * chip
  end if
  pabs = m ! make the compiler happy and use m
  if (mass < 0) then
    psi%a(1:2) = - imago * psi%a(1:2)
    psi%a(3:4) = + imago * psi%a(3:4)
  end if
end function v
```

*(Implementation of bispinor on shell wave functions)* +=

```
pure function ghost (m, p, s) result (psi)
  type(bispinor) :: psi
  real(kind=default), intent(in) :: m
  type(momentum), intent(in) :: p
  integer, intent(in) :: s
  psi%a(:) = 0
  select case (s)
  case (1)
    psi%a(1) = 1
```

```

        psi%a(2:4) = 0
    case (2)
        psi%a(1)   = 0
        psi%a(2)   = 1
        psi%a(3:4) = 0
    case (3)
        psi%a(1:2) = 0
        psi%a(3)   = 1
        psi%a(4)   = 0
    case (4)
        psi%a(1:3) = 0
        psi%a(4)   = 1
    case (5)
        psi%a(1) = 1.4
        psi%a(2) = - 2.3
        psi%a(3) = - 71.5
        psi%a(4) = 0.1
    end select
end function ghost

```

#### X.14.7 Off Shell Wave Functions

This is the same as for the Dirac fermions except that the expressions for [ubar] and [vbar] are missing.

(Declaration of bispinor off shell wave functions)≡

```
public :: brs_u, brs_v
```

In momentum space we have:

$$brsu(p) = (-i)(\not{p} - m)u(p) \quad (\text{X.88})$$

(Implementation of bispinor off shell wave functions)≡

```

pure function brs_u (m, p, s) result (dpsi)
    type(bispinor) :: dpsi, psi
    real(kind=default), intent(in) :: m
    type(momentum), intent(in) :: p
    integer, intent(in) :: s
    type (vector)::vp
    complex(kind=default), parameter :: one = (1, 0)
    vp=p
    psi=u(m,p,s)
    dpsi=cmlpx(0.0,-1.0)*(f_vf(one,vp,psi)-m*psi)
end function brs_u

```

$$brsv(p) = i(\not{p} + m)v(p) \quad (\text{X.89})$$

(Implementation of bispinor off shell wave functions)+≡

```

pure function brs_v (m, p, s) result (dpsi)
    type(bispinor) :: dpsi, psi
    real(kind=default), intent(in) :: m
    type(momentum), intent(in) :: p
    integer, intent(in) :: s
    type (vector)::vp
    complex(kind=default), parameter :: one = (1, 0)

```

```

vp=p
psi=v(m,p,s)
dpsi=cplx(0.0,1.0)*(f_vf(one,vp,psi)+m*psi)
end function brs_v

```

#### X.14.8 Propagators

*(Declaration of bispinor propagators)*≡

```

public :: pr_psi, pr_grav
public :: pj_psi, pg_psi

```

$$\frac{i(-\not{p} + m)}{p^2 - m^2 + im\Gamma}\psi \quad (\text{X.90})$$

NB: the sign of the momentum comes about because all momenta are treated as *outgoing* and the particle charge flow is therefore opposite to the momentum.

*(Implementation of bispinor propagators)*≡

```

pure function pr_psi (p, m, w, psi) result (ppsi)
  type(bispinor) :: ppsi
  type(momentum), intent(in) :: p
  real(kind=default), intent(in) :: m, w
  type(bispinor), intent(in) :: psi
  type(vector) :: vp
  complex(kind=default), parameter :: one = (1, 0)
  vp = p
  ppsi = (1 / cplx (p*p - m**2, m*w, kind=default)) &
    * (- f_vf (one, vp, psi) + m * psi)
end function pr_psi

```

$$\sqrt{\frac{\pi}{M\Gamma}}(-\not{p} + m)\psi \quad (\text{X.91})$$

*(Implementation of bispinor propagators)*+≡

```

pure function pj_psi (p, m, w, psi) result (ppsi)
  type(bispinor) :: ppsi
  type(momentum), intent(in) :: p
  real(kind=default), intent(in) :: m, w
  type(bispinor), intent(in) :: psi
  type(vector) :: vp
  complex(kind=default), parameter :: one = (1, 0)
  vp = p
  ppsi = (0, -1) * sqrt (PI / m / w) * (- f_vf (one, vp, psi) + m * psi)
end function pj_psi

```

*(Implementation of bispinor propagators)*+≡

```

pure function pg_psi (p, m, w, psi) result (ppsi)
  type(bispinor) :: ppsi
  type(momentum), intent(in) :: p
  real(kind=default), intent(in) :: m, w
  type(bispinor), intent(in) :: psi
  type(vector) :: vp
  complex(kind=default), parameter :: one = (1, 0)
  vp = p
  ppsi = gauss (p*p, m, w) * (- f_vf (one, vp, psi) + m * psi)
end function pg_psi

```



$$i \left\{ (-\not{p} + m) \left( -\eta_{\mu\nu} + \frac{p_\mu p_\nu}{m^2} \right) + \frac{1}{3} \left( \gamma_\mu - \frac{p_\mu}{m} \right) (\not{p} + m) \left( \gamma_\nu - \frac{p_\nu}{m} \right) \right\} \frac{\psi^\nu}{p^2 - m^2 + im\Gamma} \quad (\text{X.92})$$

*(Implementation of bispinor propagators)* +=

```

pure function pr_grav (p, m, w, grav) result (propgrav)
  type(vectorspinor) :: propgrav
  type(momentum), intent(in) :: p
  real(kind=default), intent(in) :: m, w
  type(vectorspinor), intent(in) :: grav
  type(vector) :: vp
  type(bispinor) :: pgrav, ggrav, ggrav1, ggrav2, ppgrav
  type(vectorspinor) :: etagrav_dum, etagrav, pppgrav, &
    gg_grav_dum, gg_grav
  complex(kind=default), parameter :: one = (1, 0)
  real(kind=default) :: minv
  integer :: i
  vp = p
  minv = 1/m
  pgrav = p%t * grav%psi(1) - p%x(1) * grav%psi(2) - &
    p%x(2) * grav%psi(3) - p%x(3) * grav%psi(4)
  ggrav%a(1) = grav%psi(1)%a(3) - grav%psi(2)%a(4) + (0,1) * &
    grav%psi(3)%a(4) - grav%psi(4)%a(3)
  ggrav%a(2) = grav%psi(1)%a(4) - grav%psi(2)%a(3) - (0,1) * &
    grav%psi(3)%a(3) + grav%psi(4)%a(4)
  ggrav%a(3) = grav%psi(1)%a(1) + grav%psi(2)%a(2) - (0,1) * &
    grav%psi(3)%a(2) + grav%psi(4)%a(1)
  ggrav%a(4) = grav%psi(1)%a(2) + grav%psi(2)%a(1) + (0,1) * &
    grav%psi(3)%a(1) - grav%psi(4)%a(2)
  ggrav1 = ggrav - minv * pgrav
  ggrav2 = f_vf (one, vp, ggrav1) + m * ggrav - pgrav
  ppgrav = (-minv**2) * f_vf (one, vp, pgrav) + minv * pgrav
  do i = 1, 4
    etagrav_dum%psi(i) = f_vf (one, vp, grav%psi(i))
  end do
  etagrav = etagrav_dum - m * grav
  pppgrav%psi(1) = p%t * ppgrav
  pppgrav%psi(2) = p%x(1) * ppgrav
  pppgrav%psi(3) = p%x(2) * ppgrav
  pppgrav%psi(4) = p%x(3) * ppgrav
  gg_grav_dum%psi(1) = p%t * ggrav2
  gg_grav_dum%psi(2) = p%x(1) * ggrav2
  gg_grav_dum%psi(3) = p%x(2) * ggrav2
  gg_grav_dum%psi(4) = p%x(3) * ggrav2
  gg_grav = gr_potf (one, one, ggrav2) - minv * gg_grav_dum
  propgrav = (1 / cmplx (p*p - m**2, m*w, kind=default)) * &
    (etagrav + pppgrav + (1/3.0_default) * gg_grav)
end function pr_grav

```

### X.15 Polarization vectorspinors

Here we construct the wavefunctions for (massive) gravitinos out of the wavefunctions of (massive) vectorbosons and (massive) Majorana fermions.

$$\psi_{(u;3/2)}^\mu(k) = \epsilon_+^\mu(k) \cdot u(k, +) \quad (\text{X.93a})$$

$$\psi_{(u;1/2)}^\mu(k) = \sqrt{\frac{1}{3}} \epsilon_+^\mu(k) \cdot u(k, -) + \sqrt{\frac{2}{3}} \epsilon_0^\mu(k) \cdot u(k, +) \quad (\text{X.93b})$$

$$\psi_{(u;-1/2)}^\mu(k) = \sqrt{\frac{2}{3}} \epsilon_0^\mu(k) \cdot u(k, -) + \sqrt{\frac{1}{3}} \epsilon_-^\mu(k) \cdot u(k, +) \quad (\text{X.93c})$$

$$\psi_{(u;-3/2)}^\mu(k) = \epsilon_-^\mu(k) \cdot u(k, -) \quad (\text{X.93d})$$

and in the same manner for  $\psi_{(v;s)}^\mu$  with  $u$  replaced by  $v$  and with the conjugated polarization vectors. These gravitino wavefunctions obey the Dirac equation, they are transverse and they fulfill the irreducibility condition

$$\gamma_\mu \psi_{(u/v;s)}^\mu = 0. \quad (\text{X.94})$$

```

⟨omega_vspinor_polarizations.f90⟩≡
⟨Cotypeleft⟩
module omega_vspinor_polarizations
  use kinds
  use constants
  use omega_vectors
  use omega_bispinors
  use omega_bispinor_couplings
  use omega_vectorspinors
  implicit none
  ⟨Declaration of polarization vectorspinors⟩
  integer, parameter, public :: omega_vspinor_pols_2010_01_A = 0
contains
  ⟨Implementation of polarization vectorspinors⟩
end module omega_vspinor_polarizations

⟨Declaration of polarization vectorspinors⟩≡
public :: ueps, veps
private :: eps
private :: outer_product

```

Here we implement the polarization vectors for vectorbosons with trigonometric functions, without the rotating of components done in HELAS [5]. These are only used for generating the polarization vectorspinors.

$$\epsilon_+^\mu(k) = \frac{-e^{+i\phi}}{\sqrt{2}} (0; \cos \theta \cos \phi - i \sin \phi, \cos \theta \sin \phi + i \cos \phi, -\sin \theta) \quad (\text{X.95a})$$

$$\epsilon_-^\mu(k) = \frac{e^{-i\phi}}{\sqrt{2}} (0; \cos \theta \cos \phi + i \sin \phi, \cos \theta \sin \phi - i \cos \phi, -\sin \theta) \quad (\text{X.95b})$$

$$\epsilon_0^\mu(k) = \frac{1}{m} \left( |\vec{k}|; k^0 \sin \theta \cos \phi, k^0 \sin \theta \sin \phi, k^0 \cos \theta \right) \quad (\text{X.95c})$$

Determining the mass from the momenta is a numerically haphazardous for light particles. Therefore, we accept some redundancy and pass the mass explicitly.

For the case that the momentum lies totally in the  $z$ -direction we take the convention  $\cos \phi = 1$  and  $\sin \phi = 0$ .

*(Implementation of polarization vectorspinors)*≡

```

pure function eps (mass, k, s) result (e)
  type(vector) :: e
  real(kind=default), intent(in) :: mass
  type(momentum), intent(in) :: k
  integer, intent(in) :: s
  real(kind=default) :: kabs, kabs2, sqrt2, m
  real(kind=default) :: cos_phi, sin_phi, cos_th, sin_th
  complex(kind=default) :: epiphi, emiphi
  sqrt2 = sqrt (2.0_default)
  kabs2 = dot_product (k%x, k%x)
  m = abs(mass)
  if (kabs2 > 0) then
    kabs = sqrt (kabs2)
    if ((k%x(1) == 0) .and. (k%x(2) == 0)) then
      cos_phi = 1
      sin_phi = 0
    else
      cos_phi = k%x(1) / sqrt(k%x(1)**2 + k%x(2)**2)
      sin_phi = k%x(2) / sqrt(k%x(1)**2 + k%x(2)**2)
    end if
    cos_th = k%x(3) / kabs
    sin_th = sqrt(1 - cos_th**2)
    epiphi = cos_phi + (0,1) * sin_phi
    emiphi = cos_phi - (0,1) * sin_phi
    e%t = 0
    e%x = 0
    select case (s)
    case (1)
      e%x(1) = epiphi * (-cos_th * cos_phi + (0,1) * sin_phi) / sqrt2
      e%x(2) = epiphi * (-cos_th * sin_phi - (0,1) * cos_phi) / sqrt2
      e%x(3) = epiphi * ( sin_th / sqrt2)
    case (-1)
      e%x(1) = emiphi * ( cos_th * cos_phi + (0,1) * sin_phi) / sqrt2
      e%x(2) = emiphi * ( cos_th * sin_phi - (0,1) * cos_phi) / sqrt2
      e%x(3) = emiphi * (-sin_th / sqrt2)
    case (0)
      if (m > 0) then
        e%t = kabs / m
        e%x = k%t / (m*kabs) * k%x
      end if
    case (4)
      if (m > 0) then
        e = (1 / m) * k
      else
        e = (1 / k%t) * k
      end if
    end select
  else
    !!! for particles in their rest frame defined to be
    !!! polarized along the 3-direction
    e%t = 0
    e%x = 0
  end if
end function eps

```

```

select case (s)
case (1)
  e%x(1) = cmplx ( - 1, 0, kind=default) / sqrt2
  e%x(2) = cmplx ( 0, 1, kind=default) / sqrt2
case (-1)
  e%x(1) = cmplx ( 1, 0, kind=default) / sqrt2
  e%x(2) = cmplx ( 0, 1, kind=default) / sqrt2
case (0)
  if (m > 0) then
    e%x(3) = 1
  end if
case (4)
  if (m > 0) then
    e = (1 / m) * k
  else
    e = (1 / k%t) * k
  end if
end select
end if
end function eps

```

*(Implementation of polarization vectorspinors)*  $\equiv$

```

pure function ueps (m, k, s) result (t)
  type(vectorspinor) :: t
  real(kind=default), intent(in) :: m
  type(momentum), intent(in) :: k
  integer, intent(in) :: s
  integer :: i
  type(vector) :: ep, e0, em
  type(bispinor) :: up, um
  do i = 1, 4
    t%psi(i)%a = 0
  end do
  select case (s)
  case (2)
    ep = eps (m, k, 1)
    up = u (m, k, 1)
    t = outer_product (ep, up)
  case (1)
    ep = eps (m, k, 1)
    e0 = eps (m, k, 0)
    up = u (m, k, 1)
    um = u (m, k, -1)
    t = (1 / sqrt (3.0_default)) * (outer_product (ep, um) &
      + sqrt (2.0_default) * outer_product (e0, up))
  case (-1)
    e0 = eps (m, k, 0)
    em = eps (m, k, -1)
    up = u (m, k, 1)
    um = u (m, k, -1)
    t = (1 / sqrt (3.0_default)) * (sqrt (2.0_default) * &
      outer_product (e0, um) + outer_product (em, up))
  case (-2)
    em = eps (m, k, -1)
    um = u (m, k, -1)
  end select
end function ueps

```

```

        t = outer_product (em, um)
    end select
end function ueps

<Implementation of polarization vectorspinors>+≡
pure function veps (m, k, s) result (t)
    type(vectorspinor) :: t
    real(kind=default), intent(in) :: m
    type(momentum), intent(in) :: k
    integer, intent(in) :: s
    integer :: i
    type(vector) :: ep, e0, em
    type(bispinor) :: vp, vm
    do i = 1, 4
        t%psi(i)%a = 0
    end do
    select case (s)
    case (2)
        ep = conjg(eps (m, k, 1))
        vp = v (m, k, 1)
        t = outer_product (ep, vp)
    case (1)
        ep = conjg(eps (m, k, 1))
        e0 = conjg(eps (m, k, 0))
        vp = v (m, k, 1)
        vm = v (m, k, -1)
        t = (1 / sqrt (3.0_default)) * (outer_product (ep, vm) &
            + sqrt (2.0_default) * outer_product (e0, vp))
    case (-1)
        e0 = conjg(eps (m, k, 0))
        em = conjg(eps (m, k, -1))
        vp = v (m, k, 1)
        vm = v (m, k, -1)
        t = (1 / sqrt (3.0_default)) * (sqrt (2.0_default) &
            * outer_product (e0, vm) + outer_product (em, vp))
    case (-2)
        em = conjg(eps (m, k, -1))
        vm = v (m, k, -1)
        t = outer_product (em, vm)
    end select
end function veps

<Implementation of polarization vectorspinors>+≡
pure function outer_product (ve, sp) result (vs)
    type(vectorspinor) :: vs
    type(vector), intent(in) :: ve
    type(bispinor), intent(in) :: sp
    integer :: i
    vs%psi(1)%a(1:4) = ve%t * sp%a(1:4)
    do i = 1, 3
        vs%psi((i+1))%a(1:4) = ve%x(i) * sp%a(1:4)
    end do
end function outer_product

```

## X.16 Color

```

(omega_color.f90)≡
  <Cpyleft>
  module omega_color
    use kinds
    implicit none
    private
    <Declaration of color types>
    <Declaration of color functions>
    integer, parameter, public :: omega_color_2010_01_A = 0
  contains
    <Implementation of color functions>
  end module omega_color

```

### X.16.1 Color Sum

```

<Declaration of color types>≡
  public :: omega_color_factor
  type omega_color_factor
    integer :: i1, i2
    real(kind=default) :: factor
  end type omega_color_factor

```

```

<Declaration of color functions>≡
  public :: omega_color_sum

```

The !\$omp instruction will result in parallel code if compiled with support for OpenMP otherwise it is ignored.

```

<Implementation of color functions>≡
  <pure unless OpenMP>
  function omega_color_sum (flv, hel, amp, cf) result (amp2)
    complex(kind=default) :: amp2
    integer, intent(in) :: flv, hel
    complex(kind=default), dimension(:,:), intent(in) :: amp
    type(omega_color_factor), dimension(:), intent(in) :: cf
    integer :: n
    amp2 = 0
    !$omp parallel do reduction(+:amp2)
    do n = 1, size (cf)
      amp2 = amp2 + cf(n)%factor * &
        amp(flv,cf(n)%i1,hel) * conjg (amp(flv,cf(n)%i2,hel))
    end do
    !$omp end parallel do
  end function omega_color_sum

```

In the bytecode for the OVM, we only save the symmetric part of the color factor table. This almost halves the size of  $n$  gluon amplitudes for  $n > 6$ . For  $2 \rightarrow (5,6)g$  the reduced color factor table still amounts for  $\sim (75,93)\%$  of the bytecode, making it desirable to omit it completely by computing it dynamically to reduce memory requirements. Note that  $2\text{Re}(A_{i_1}A_{i_2}^*) = A_{i_1}A_{i_2}^* + A_{i_2}A_{i_1}^*$ .

```

<Declaration of color functions>+=
  public :: ovm_color_sum

```

```

<Implementation of color functions>+≡
  <pure unless OpenMP>
  function ovm_color_sum (flv, hel, amp, cf) result (amp2)
    real(kind=default) :: amp2
    integer, intent(in) :: flv, hel
    complex(kind=default), dimension(:,:,:), intent(in) :: amp
    type(omega_color_factor), dimension(:), intent(in) :: cf
    integer :: n
    amp2 = 0
    !$omp parallel do reduction(+:amp2)
    do n = 1, size (cf)
      if (cf(n)%i1 == cf(n)%i2) then
        amp2 = amp2 + cf(n)%factor * &
          real(amp(flv,cf(n)%i1,hel) * conjg(amp(flv,cf(n)%i2,hel)))
      else
        amp2 = amp2 + cf(n)%factor * 2 * &
          real(amp(flv,cf(n)%i1,hel) * conjg(amp(flv,cf(n)%i2,hel)))
      end if
    end do
    !$omp end parallel do
  end function ovm_color_sum

```

## X.17 Utilities

```

<omega_utils.f90>≡
  <Copleft>
  module omega_utils
    use kinds
    use omega_vectors
    use omega_polarizations
    implicit none
    private
    <Declaration of utility functions>
    <Numerical tolerances>
    integer, parameter, public :: omega_utils_2010_01_A = 0
  contains
    <Implementation of utility functions>
  end module omega_utils

```

### X.17.1 Helicity Selection Rule Heuristics

```

<Declaration of utility functions>≡
  public :: omega_update_helicity_selection

<Implementation of utility functions>≡
  pure subroutine omega_update_helicity_selection &
    (count, amp, max_abs, sum_abs, mask, threshold, cutoff, mask_dirty)
    integer, intent(inout) :: count
    complex(kind=default), dimension(:,:,:), intent(in) :: amp
    real(kind=default), dimension(:), intent(inout) :: max_abs
    real(kind=default), intent(inout) :: sum_abs
    logical, dimension(:), intent(inout) :: mask
    real(kind=default), intent(in) :: threshold

```

```

integer, intent(in) :: cutoff
logical, intent(out) :: mask_dirty
integer :: h
real(kind=default) :: avg
mask_dirty = .false.
if (threshold > 0) then
  count = count + 1
  if (count <= cutoff) then
    forall (h = lbound (amp, 3) : ubound (amp, 3))
      max_abs(h) = max (max_abs(h), maxval (abs (amp(:, :, h))))
    end forall
    sum_abs = sum_abs + sum (abs (amp))
    if (count == cutoff) then
      avg = sum_abs / size (amp) / cutoff
      mask = max_abs >= threshold * epsilon (avg) * avg
      mask_dirty = .true.
    end if
  end if
end if
end subroutine omega_update_helicity_selection

```

### X.17.2 Diagnostics

*(Declaration of utility functions)+≡*

```
public :: omega_report_helicity_selection
```

We should try to use `msg_message` from WHIZARD's diagnostics module, but this would spoil independent builds.

*(Implementation of utility functions)+≡*

```

subroutine omega_report_helicity_selection (mask, spin_states, threshold, unit)
  logical, dimension(:), intent(in) :: mask
  integer, dimension(:, :), intent(in) :: spin_states
  real(kind=default), intent(in) :: threshold
  integer, intent(in), optional :: unit
  integer :: u
  integer :: h, i
  if (present(unit)) then
    u = unit
  else
    u = 6
  end if
  if (u >= 0) then
    write (unit = u, &
      fmt = "('| ', 'Contributing Helicity Combinations: ', I5, ' of ', I5)") &
      count (mask), size (mask)
    write (unit = u, &
      fmt = "('| ', 'Threshold: amp / avg > ', E9.2, ' = ', E9.2, ' * epsilon())') &
      threshold * epsilon (threshold), threshold
    i = 0
    do h = 1, size (mask)
      if (mask(h)) then
        i = i + 1
        write (unit = u, fmt = "('| ', I4, ': ', 20I4)") i, spin_states (:, h)
      end if
    end do
  end if
end subroutine

```



```

        end do
    end if
end subroutine omega_report_helicity_selection

```

*(Declaration of utility functions)+≡*

```

public :: omega_ward_warn, omega_ward_panic

```

The O'Mega amplitudes have only one particle off shell and are the sum of *all* possible diagrams with the other particles on-shell.



The problem with these gauge checks is that are numerically very small amplitudes that vanish analytically and that violate transversality. The hard part is to determine the thresholds that make these tests usable.

*(Implementation of utility functions)+≡*

```

subroutine omega_ward_warn (name, m, k, e)
    character(len=*), intent(in) :: name
    real(kind=default), intent(in) :: m
    type(momentum), intent(in) :: k
    type(vector), intent(in) :: e
    type(vector) :: ek
    real(kind=default) :: abs_eke, abs_ek_abs_e
    ek = eps (m, k, 4)
    abs_eke = abs (ek * e)
    abs_ek_abs_e = abs (ek) * abs (e)
    print *, name, ":", abs_eke / abs_ek_abs_e, abs (ek), abs (e)
    if (abs_eke > 1000 * epsilon (abs_ek_abs_e)) then
        print *, "O'Mega: warning: non-transverse vector field: ", &
            name, ":", abs_eke / abs_ek_abs_e, abs (e)
    end if
end subroutine omega_ward_warn

```

*(Implementation of utility functions)+≡*

```

subroutine omega_ward_panic (name, m, k, e)
    character(len=*), intent(in) :: name
    real(kind=default), intent(in) :: m
    type(momentum), intent(in) :: k
    type(vector), intent(in) :: e
    type(vector) :: ek
    real(kind=default) :: abs_eke, abs_ek_abs_e
    ek = eps (m, k, 4)
    abs_eke = abs (ek * e)
    abs_ek_abs_e = abs (ek) * abs (e)
    if (abs_eke > 1000 * epsilon (abs_ek_abs_e)) then
        print *, "O'Mega: panic: non-transverse vector field: ", &
            name, ":", abs_eke / abs_ek_abs_e, abs (e)
        stop
    end if
end subroutine omega_ward_panic

```

*(Declaration of utility functions)+≡*

```

public :: omega_slavnov_warn, omega_slavnov_panic

```

*(Implementation of utility functions)+≡*

```

subroutine omega_slavnov_warn (name, m, k, e, phi)
    character(len=*), intent(in) :: name
    real(kind=default), intent(in) :: m

```

```

    type(momentum), intent(in) :: k
    type(vector), intent(in) :: e
    complex(kind=default), intent(in) :: phi
    type(vector) :: ek
    real(kind=default) :: abs_eke, abs_ek_abs_e
    ek = eps (m, k, 4)
    abs_eke = abs (ek * e - phi)
    abs_ek_abs_e = abs (ek) * abs (e)
    print *, name, ":", abs_eke / abs_ek_abs_e, abs (ek), abs (e)
    if (abs_eke > 1000 * epsilon (abs_ek_abs_e)) then
        print *, "0'Mega: warning: non-transverse vector field: ", &
            name, ":", abs_eke / abs_ek_abs_e, abs (e)
    end if
end subroutine omega_slavnov_warn

<Implementation of utility functions>+≡
subroutine omega_slavnov_panic (name, m, k, e, phi)
    character(len=*), intent(in) :: name
    real(kind=default), intent(in) :: m
    type(momentum), intent(in) :: k
    type(vector), intent(in) :: e
    complex(kind=default), intent(in) :: phi
    type(vector) :: ek
    real(kind=default) :: abs_eke, abs_ek_abs_e
    ek = eps (m, k, 4)
    abs_eke = abs (ek * e - phi)
    abs_ek_abs_e = abs (ek) * abs (e)
    if (abs_eke > 1000 * epsilon (abs_ek_abs_e)) then
        print *, "0'Mega: panic: non-transverse vector field: ", &
            name, ":", abs_eke / abs_ek_abs_e, abs (e)
        stop
    end if
end subroutine omega_slavnov_panic

<Declaration of utility functions>+≡
public :: omega_check_arguments_warn, omega_check_arguments_panic

<Implementation of utility functions>+≡
subroutine omega_check_arguments_warn (n, k)
    integer, intent(in) :: n
    real(kind=default), dimension(0:,:), intent(in) :: k
    integer :: i
    i = size(k,dim=1)
    if (i /= 4) then
        print *, "0'Mega: warning: wrong # of dimensions:", i
    end if
    i = size(k,dim=2)
    if (i /= n) then
        print *, "0'Mega: warning: wrong # of momenta:", i, &
            ", expected", n
    end if
end subroutine omega_check_arguments_warn

<Implementation of utility functions>+≡
subroutine omega_check_arguments_panic (n, k)
    integer, intent(in) :: n

```

```

    real(kind=default), dimension(0:,:), intent(in) :: k
    logical :: error
    integer :: i
    error = .false.
    i = size(k,dim=1)
    if (i /= n) then
        print *, "0'Mega: warning: wrong # of dimensions:", i
        error = .true.
    end if
    i = size(k,dim=2)
    if (i /= n) then
        print *, "0'Mega: warning: wrong # of momenta:", i, &
            ", expected", n
        error = .true.
    end if
    if (error) then
        stop
    end if
end subroutine omega_check_arguments_panic

<Declaration of utility functions>+≡
public :: omega_check_helicities_warn, omega_check_helicities_panic
private :: omega_check_helicity

<Implementation of utility functions>+≡
function omega_check_helicity (m, smax, s) result (error)
    real(kind=default), intent(in) :: m
    integer, intent(in) :: smax, s
    logical :: error
    select case (smax)
    case (0)
        error = (s /= 0)
    case (1)
        error = (abs (s) /= 1)
    case (2)
        if (m == 0.0_default) then
            error = .not. (abs (s) == 1 .or. abs (s) == 4)
        else
            error = .not. (abs (s) <= 1 .or. abs (s) == 4)
        end if
    case (4)
        error = .true.
    case default
        error = .true.
    end select
end function omega_check_helicity

<Implementation of utility functions>+≡
subroutine omega_check_helicities_warn (m, smax, s)
    real(kind=default), dimension(:), intent(in) :: m
    integer, dimension(:), intent(in) :: smax, s
    integer :: i
    do i = 1, size (m)
        if (omega_check_helicity (m(i), smax(i), s(i))) then
            print *, "0'Mega: warning: invalid helicity", s(i)
        end if
    end do
end subroutine

```

```

        end do
    end subroutine omega_check_helicities_warn

<Implementation of utility functions>+≡
    subroutine omega_check_helicities_panic (m, smax, s)
        real(kind=default), dimension(:), intent(in) :: m
        integer, dimension(:), intent(in) :: smax, s
        logical :: error
        logical :: error1
        integer :: i
        error = .false.
        do i = 1, size (m)
            error1 = omega_check_helicity (m(i), smax(i), s(i))
            if (error1) then
                print *, "O'Mega: panic: invalid helicity", s(i)
                error = .true.
            end if
        end do
        if (error) then
            stop
        end if
    end subroutine omega_check_helicities_panic

<Declaration of utility functions>+≡
    public :: omega_check_momenta_warn, omega_check_momenta_panic
    private :: check_momentum_conservation, check_mass_shell

<Numerical tolerances>≡
    integer, parameter, private :: MOMENTUM_TOLERANCE = 10000

<Implementation of utility functions>+≡
    function check_momentum_conservation (k) result (error)
        real(kind=default), dimension(0:,:), intent(in) :: k
        logical :: error
        error = any (abs (sum (k(:,3:), dim = 2) - k(:,1) - k(:,2)) > &
            MOMENTUM_TOLERANCE * epsilon (maxval (abs (k), dim = 2)))
        if (error) then
            print *, sum (k(:,3:), dim = 2) - k(:,1) - k(:,2)
            print *, MOMENTUM_TOLERANCE * epsilon (maxval (abs (k), dim = 2)), &
                maxval (abs (k), dim = 2)
        end if
    end function check_momentum_conservation

<Numerical tolerances>+≡
    integer, parameter, private :: ON_SHELL_TOLERANCE = 1000000

<Implementation of utility functions>+≡
    function check_mass_shell (m, k) result (error)
        real(kind=default), intent(in) :: m
        real(kind=default), dimension(0:), intent(in) :: k
        real(kind=default) :: e2
        logical :: error
        e2 = k(1)**2 + k(2)**2 + k(3)**2 + m**2
        error = abs (k(0)**2 - e2) > ON_SHELL_TOLERANCE * epsilon (max (k(0)**2, e2))
        if (error) then
            print *, k(0)**2 - e2
            print *, ON_SHELL_TOLERANCE * epsilon (max (k(0)**2, e2)), max (k(0)**2, e2)
        end if
    end function check_mass_shell

```

```

        end if
    end function check_mass_shell

<Implementation of utility functions>+≡
subroutine omega_check_momenta_warn (m, k)
    real(kind=default), dimension(:), intent(in) :: m
    real(kind=default), dimension(0:,:), intent(in) :: k
    integer :: i
    if (check_momentum_conservation (k)) then
        print *, "O'Mega: warning: momentum not conserved"
    end if
    do i = 1, size(m)
        if (check_mass_shell (m(i), k(:,i))) then
            print *, "O'Mega: warning: particle #", i, "not on-shell"
        end if
    end do
end subroutine omega_check_momenta_warn

<Implementation of utility functions>+≡
subroutine omega_check_momenta_panic (m, k)
    real(kind=default), dimension(:), intent(in) :: m
    real(kind=default), dimension(0:,:), intent(in) :: k
    logical :: error
    logical :: error1
    integer :: i
    error = check_momentum_conservation (k)
    if (error) then
        print *, "O'Mega: panic: momentum not conserved"
    end if
    do i = 1, size(m)
        error1 = check_mass_shell (m(i), k(0:,i))
        if (error1) then
            print *, "O'Mega: panic: particle #", i, "not on-shell"
            error = .true.
        end if
    end do
    if (error) then
        stop
    end if
end subroutine omega_check_momenta_panic

```

### X.17.3 Obsolete Summation

#### Spin/Helicity Summation

```

<Declaration of obsolete utility functions>≡
public :: omega_sum, omega_sum_nonzero, omega_nonzero
private :: state_index

<Implementation of obsolete utility functions>≡
pure function omega_sum (omega, p, states, fixed) result (sigma)
    real(kind=default) :: sigma
    real(kind=default), dimension(0:,:), intent(in) :: p
    integer, dimension(:), intent(in), optional :: states, fixed
    <interface for O'Mega Amplitude>

```

```

integer, dimension(size(p,dim=2)) :: s, nstates
integer :: j
complex(kind=default) :: a
if (present (states)) then
    nstates = states
else
    nstates = 2
end if
sigma = 0
s = -1
sum_spins: do
    if (present (fixed)) then
        !!! print *, 's = ', s, ', fixed = ', fixed, ', nstates = ', nstates, &
        !!!      ', fixed|s = ', merge (fixed, s, mask = nstates == 0)
        a = omega (p, merge (fixed, s, mask = nstates == 0))
    else
        a = omega (p, s)
    end if
    sigma = sigma + a * conjg(a)
    <Step s like a n-ary number and terminate when all (s == -1)>
end do sum_spins
sigma = sigma / num_states (2, nstates(1:2))
end function omega_sum

```

We're looping over all spins like a  $n$ -ary numbers  $(-1, \dots, -1, -1), (-1, \dots, -1, 0), (-1, \dots, -1, 1), (-1, \dots, 0, -1), \dots, (1, \dots, 1, 0), (1, \dots, 1, 1)$ :

*<Step s like a n-ary number and terminate when all (s == -1)>*  $\equiv$

```

do j = size (p, dim = 2), 1, -1
    select case (nstates (j))
    case (3) ! massive vectors
        s(j) = modulo (s(j) + 2, 3) - 1
    case (2) ! spinors, massless vectors
        s(j) = - s(j)
    case (1) ! scalars
        s(j) = -1
    case (0) ! fixed spin
        s(j) = -1
    case default ! ???
        s(j) = -1
    end select
    if (s(j) /= -1) then
        cycle sum_spins
    end if
end do
exit sum_spins

```

The dual operation evaluates an  $n$ -number:

*<Implementation of obsolete utility functions>*  $+\equiv$

```

pure function state_index (s, states) result (n)
integer, dimension(:), intent(in) :: s
integer, dimension(:), intent(in), optional :: states
integer :: n
integer :: j, p
n = 1
p = 1

```

```

    if (present (states)) then
      do j = size (s), 1, -1
        select case (states(j))
          case (3)
            n = n + p * (s(j) + 1)
          case (2)
            n = n + p * (s(j) + 1) / 2
          end select
        p = p * states(j)
      end do
    else
      do j = size (s), 1, -1
        n = n + p * (s(j) + 1) / 2
        p = p * 2
      end do
    end if
  end function state_index
<interface for O'Mega Amplitude>≡
interface
  pure function omega (p, s) result (me)
    use kinds
    implicit none
    complex(kind=default) :: me
    real(kind=default), dimension(0:,:), intent(in) :: p
    integer, dimension(:), intent(in) :: s
  end function omega
end interface
<Declaration of obsolete utility functions>+≡
public :: num_states
<Implementation of obsolete utility functions>+≡
pure function num_states (n, states) result (ns)
  integer, intent(in) :: n
  integer, dimension(:), intent(in), optional :: states
  integer :: ns
  if (present (states)) then
    ns = product (states, mask = states == 2 .or. states == 3)
  else
    ns = 2*n
  end if
end function num_states

```

## X.18 omega95

```

<omega95.f90>≡
<Cotypeleft>
module omega95
  use constants
  use omega_spinors
  use omega_vectors
  use omega_polarizations
  use omega_tensors
  use omega_tensor_polarizations

```

```

    use omega_couplings
    use omega_spinor_couplings
    use omega_color
    use omega_utils
    public
end module omega95

```

### *X.19 omega95 Revisited*

```

⟨omega95_bispinors.f90⟩≡
⟨Cotypeleft⟩
module omega95_bispinors
  use constants
  use omega_bispinors
  use omega_vectors
  use omega_vectorspinors
  use omega_polarizations
  use omega_vspinor_polarizations
  use omega_couplings
  use omega_bispinor_couplings
  use omega_color
  use omega_utils
  public
end module omega95_bispinors

```

### *X.20 Testing*

```

⟨omega_testtools.f90⟩≡
⟨Cotypeleft⟩
module omega_testtools
  use kinds
  implicit none
  private
  real(kind=default), parameter, private :: ABS_THRESHOLD_DEFAULT = 1E-17
  real(kind=default), parameter, private :: THRESHOLD_DEFAULT = 0.6
  real(kind=default), parameter, private :: THRESHOLD_WARN = 0.8
  ⟨Declaration of test support functions⟩
contains
  ⟨Implementation of test support functions⟩
end module omega_testtools

```

Quantify the agreement of two real or complex numbers

$$\text{agreement}(x, y) = \frac{\ln \Delta(x, y)}{\ln \epsilon} \in [0, 1] \quad (\text{X.96})$$

with

$$\Delta(x, y) = \frac{|x - y|}{\max(|x|, |y|)} \quad (\text{X.97})$$

and values outside  $[0, 1]$  replaced the closed value in the interval. In other words

- 1 for  $x - y = \max(|x|, |y|) \cdot \mathcal{O}(\epsilon)$  and



- 0 for  $x - y = \max(|x|, |y|) \cdot \mathcal{O}(1)$

with logarithmic interpolation. The cases  $x = 0$  and  $y = 0$  must be treated separately.

*(Declaration of test support functions)*≡

```
public :: agreement
interface agreement
  module procedure agreement_real, agreement_complex, &
    agreement_real_complex, agreement_complex_real, &
    agreement_integer_complex, agreement_complex_integer, &
    agreement_integer_real, agreement_real_integer
end interface
private :: agreement_real, agreement_complex, &
  agreement_real_complex, agreement_complex_real, &
  agreement_integer_complex, agreement_complex_integer, &
  agreement_integer_real, agreement_real_integer
```

*(Implementation of test support functions)*≡

```
elemental function agreement_real (x, y, base) result (a)
  real(kind=default) :: a
  real(kind=default), intent(in) :: x, y
  real(kind=default), intent(in), optional :: base
  real(kind=default) :: scale, dxy
  if (present (base)) then
    scale = max (abs (x), abs (y), abs (base))
  else
    scale = max (abs (x), abs (y))
  end if
  if (ieee_is_nan (x) .or. ieee_is_nan (y)) then
    a = 0
  else if (scale <= 0) then
    a = -1
  else
    dxy = abs (x - y) / scale
    if (dxy <= 0.0_default) then
      a = 1
    else
      a = log (dxy) / log (epsilon (scale))
      a = max (0.0_default, min (1.0_default, a))
      if (ieee_is_nan (a)) then
        a = 0
      end if
    end if
  end if
  if (ieee_is_nan (a)) then
    a = 0
  end if
end function agreement_real
```

Poor man's replacement

*(Implementation of test support functions)*+≡

```
elemental function ieee_is_nan (x) result (yorn)
  logical :: yorn
  real (kind=default), intent(in) :: x
  yorn = (x /= x)
```

```
end function ieee_is_nan
```

*(Implementation of test support functions)+≡*

```
elemental function agreement_complex (x, y, base) result (a)
  real(kind=default) :: a
  complex(kind=default), intent(in) :: x, y
  real(kind=default), intent(in), optional :: base
  real(kind=default) :: scale, dxy
  if (present (base)) then
    scale = max (abs (x), abs (y), abs (base))
  else
    scale = max (abs (x), abs (y))
  end if
  if (
    ieee_is_nan (real (x, kind=default)) .or. ieee_is_nan (aimag (x)) &
    .or. ieee_is_nan (real (y, kind=default)) .or. ieee_is_nan (aimag (y))) then
    a = 0
  else if (scale <= 0) then
    a = -1
  else
    dxy = abs (x - y) / scale
    if (dxy <= 0.0_default) then
      a = 1
    else
      a = log (dxy) / log (epsilon (scale))
      a = max (0.0_default, min (1.0_default, a))
      if (ieee_is_nan (a)) then
        a = 0
      end if
    end if
  end if
  if (ieee_is_nan (a)) then
    a = 0
  end if
end function agreement_complex
```

*(Implementation of test support functions)+≡*

```
elemental function agreement_real_complex (x, y, base) result (a)
  real(kind=default) :: a
  real(kind=default), intent(in) :: x
  complex(kind=default), intent(in) :: y
  real(kind=default), intent(in), optional :: base
  a = agreement_complex (cmplx (x, kind=default), y, base)
end function agreement_real_complex
```

*(Implementation of test support functions)+≡*

```
elemental function agreement_complex_real (x, y, base) result (a)
  real(kind=default) :: a
  complex(kind=default), intent(in) :: x
  real(kind=default), intent(in) :: y
  real(kind=default), intent(in), optional :: base
  a = agreement_complex (x, cmplx (y, kind=default), base)
end function agreement_complex_real
```

*(Implementation of test support functions)+≡*

```
elemental function agreement_integer_complex (x, y, base) result (a)
  real(kind=default) :: a
```

```

integer, intent(in) :: x
complex(kind=default), intent(in) :: y
real(kind=default), intent(in), optional :: base
a = agreement_complex (cmplx (x, kind=default), y, base)
end function agreement_integer_complex

<Implementation of test support functions>+≡
elemental function agreement_complex_integer (x, y, base) result (a)
real(kind=default) :: a
complex(kind=default), intent(in) :: x
integer, intent(in) :: y
real(kind=default), intent(in), optional :: base
a = agreement_complex (x, cmplx (y, kind=default), base)
end function agreement_complex_integer

<Implementation of test support functions>+≡
elemental function agreement_integer_real (x, y, base) result (a)
real(kind=default) :: a
integer, intent(in) :: x
real(kind=default), intent(in) :: y
real(kind=default), intent(in), optional :: base
a = agreement_real (real(x, kind=default), y, base)
end function agreement_integer_real

<Implementation of test support functions>+≡
elemental function agreement_real_integer (x, y, base) result (a)
real(kind=default) :: a
real(kind=default), intent(in) :: x
integer, intent(in) :: y
real(kind=default), intent(in), optional :: base
a = agreement_real (x, real (y, kind=default), base)
end function agreement_real_integer

<Declaration of test support functions>+≡
public:: vanishes
interface vanishes
module procedure vanishes_real, vanishes_complex
end interface
private :: vanishes_real, vanishes_complex

<Implementation of test support functions>+≡
elemental function vanishes_real (x, scale) result (a)
real(kind=default) :: a
real(kind=default), intent(in) :: x
real(kind=default), intent(in), optional :: scale
real(kind=default) :: scaled_x
if (x == 0.0_default) then
a = 1
return
else if (ieee_is_nan (x)) then
a = 0
return
end if
scaled_x = x
if (present (scale)) then
if (scale /= 0) then
scaled_x = x / abs (scale)

```

```

        else
            a = 0
            return
        end if
    else
    end if
    a = log (abs (scaled_x)) / log (epsilon (scaled_x))
    a = max (0.0_default, min (1.0_default, a))
    if (ieee_is_nan (a)) then
        a = 0
    end if
end function vanishes_real

<Implementation of test support functions>+≡
elemental function vanishes_complex (x, scale) result (a)
    real(kind=default) :: a
    complex(kind=default), intent(in) :: x
    real(kind=default), intent(in), optional :: scale
    a = vanishes_real (abs (x), scale)
end function vanishes_complex

<Declaration of test support functions>+≡
public :: expect
interface expect
    module procedure expect_integer, expect_real, expect_complex, &
        expect_real_integer, expect_integer_real, &
        expect_complex_integer, expect_integer_complex, &
        expect_complex_real, expect_real_complex
end interface
private :: expect_integer, expect_real, expect_complex, &
    expect_real_integer, expect_integer_real, &
    expect_complex_integer, expect_integer_complex, &
    expect_complex_real, expect_real_complex

<Implementation of test support functions>+≡
subroutine expect_integer (x, x0, msg, passed, quiet, buffer, unit)
    integer, intent(in) :: x, x0
    character(len=*), intent(in) :: msg
    logical, intent(inout), optional :: passed
    logical, intent(in), optional :: quiet
    character(len=*), intent(inout), optional :: buffer
    integer, intent(in), optional :: unit
    logical :: failed, verbose
    character(len=*), parameter :: fmt = "(1X,A,' : ',A)"
    character(len=*), parameter :: &
        fmt_verbose = "(1X,A,' : ',A,' [expected ',I6,', got ',I6,']')"
    failed = .false.
    verbose = .true.
    if (present (quiet)) then
        verbose = .not.quiet
    end if
    if (x == x0) then
        if (verbose) then
            if (.not. (present (buffer) .or. present (unit))) then
                write (unit = *, fmt = fmt) msg, "passed"
            end if
        end if
    end if
end subroutine expect_integer

```

```

        if (present (unit)) then
            write (unit = unit, fmt = fmt) msg, "passed"
        end if
        if (present (buffer)) then
            write (unit = buffer, fmt = fmt) msg, "passed"
        end if
    end if
else
    if (.not. (present (buffer) .or. present (unit))) then
        write (unit = *, fmt = fmt_verbose) msg, "failed", x0, x
    end if
    if (present (unit)) then
        write (unit = unit, fmt = fmt_verbose) msg, "failed", x0, x
    end if
    if (present (buffer)) then
        write (unit = buffer, fmt = fmt_verbose) msg, "failed", x0, x
    end if
    failed = .true.
end if
if (present (passed)) then
    passed = passed .and. .not.failed
end if
end subroutine expect_integer

```

*(Implementation of test support functions)+≡*

```

subroutine expect_real (x, x0, msg, passed, threshold, quiet, abs_threshold)
    real(kind=default), intent(in) :: x, x0
    character(len=*), intent(in) :: msg
    logical, intent(inout), optional :: passed
    real(kind=default), intent(in), optional :: threshold
    real(kind=default), intent(in), optional :: abs_threshold
    logical, intent(in), optional :: quiet
    logical :: failed, verbose
    real(kind=default) :: agreement_threshold, abs_agreement_threshold
    character(len=*), parameter :: fmt = "(1X,A,' : ',A,' at ',I4,'%')'"
    character(len=*), parameter :: fmt_verbose = "(1X,A,' : ',A,' at ',I4,'%'," // &
        "' [expected ',E10.3,', got ',E10.3,']')'"
    real(kind=default) :: a
    failed = .false.
    verbose = .true.
    if (present (quiet)) then
        verbose = .not.quiet
    end if
    if (x == x0) then
        if (verbose) then
            write (unit = *, fmt = fmt) msg, "passed", 100
        end if
    else
        if (x0 == 0) then
            a = vanishes (x)
        else
            a = agreement (x, x0)
        end if
        if (present (threshold)) then
            agreement_threshold = threshold
        end if
    end if
end subroutine expect_real

```

```

else
  agreement_threshold = THRESHOLD_DEFAULT
end if
if (present (abs_threshold)) then
  abs_agreement_threshold = abs_threshold
else
  abs_agreement_threshold = ABS_THRESHOLD_DEFAULT
end if
if (a >= agreement_threshold .or. &
    max(abs(x), abs(x0)) <= abs_agreement_threshold) then
  if (verbose) then
    if (a >= THRESHOLD_WARN) then
      write (unit = *, fmt = fmt) msg, "passed", int (a * 100)
    else
      write (unit = *, fmt = fmt_verbose) msg, "passed", int (a * 100), x0, x
    end if
  end if
else
  failed = .true.
  write (unit = *, fmt = fmt_verbose) msg, "failed", int (a * 100), x0, x
end if
end if
if (present (passed)) then
  passed = passed .and. .not.failed
end if
end subroutine expect_real

```

*(Implementation of test support functions)*+≡

```

subroutine expect_complex (x, x0, msg, passed, threshold, quiet, abs_threshold)
  complex(kind=default), intent(in) :: x, x0
  character(len=*), intent(in) :: msg
  logical, intent(inout), optional :: passed
  real(kind=default), intent(in), optional :: threshold
  real(kind=default), intent(in), optional :: abs_threshold
  logical, intent(in), optional :: quiet
  logical :: failed, verbose
  real(kind=default) :: agreement_threshold, abs_agreement_threshold
  character(len=*), parameter :: fmt = "(1X,A,' : ',A,' at ',I4,'%')'"
  character(len=*), parameter :: fmt_verbose = "(1X,A,' : ',A,' at ',I4,'%'," // &
    "' [expected (' ,E10.3,' ,',E10.3,'), got (' ,E10.3,' ,',E10.3,')]'"
  character(len=*), parameter :: fmt_phase = "(1X,A,' : ',A,' at ',I4,'%'," // &
    "' [modulus passed at ',I4,'%',' , phases ',F5.3,' vs. ',F5.3,'])'"
  real(kind=default) :: a, a_modulus
  failed = .false.
  verbose = .true.
  if (present (quiet)) then
    verbose = .not.quiet
  end if
  if (x == x0) then
    if (verbose) then
      write (unit = *, fmt = fmt) msg, "passed", 100
    end if
  else
    if (x0 == 0) then
      a = vanishes (x)

```

```

else
    a = agreement (x, x0)
end if
if (present (threshold)) then
    agreement_threshold = threshold
else
    agreement_threshold = THRESHOLD_DEFAULT
end if
if (present (abs_threshold)) then
    abs_agreement_threshold = abs_threshold
else
    abs_agreement_threshold = ABS_THRESHOLD_DEFAULT
end if
if (a >= agreement_threshold .or. &
    max(abs(x), abs(x0)) <= abs_agreement_threshold) then
    if (verbose) then
        if (a >= THRESHOLD_WARN) then
            write (unit = *, fmt = fmt) msg, "passed", int (a * 100)
        else
            write (unit = *, fmt = fmt_verbose) msg, "passed", int (a * 100), x0, x
        end if
    end if
else
    a_modulus = agreement (abs (x), abs (x0))
    if (a_modulus >= agreement_threshold) then
        write (unit = *, fmt = fmt_phase) msg, "failed", int (a * 100), &
            int (a_modulus * 100), &
            atan2 (real (x, kind=default), aimag (x)), &
            atan2 (real (x0, kind=default), aimag (x0))
    else
        write (unit = *, fmt = fmt_verbose) msg, "failed", int (a * 100), x0, x
    end if
    failed = .true.
end if
end if
if (present (passed)) then
    passed = passed .and. .not.failed
end if
end subroutine expect_complex

```

*(Implementation of test support functions)+≡*

```

subroutine expect_real_integer (x, x0, msg, passed, threshold, quiet)
    real(kind=default), intent(in) :: x
    integer, intent(in) :: x0
    character(len=*), intent(in) :: msg
    real(kind=default), intent(in), optional :: threshold
    logical, intent(inout), optional :: passed
    logical, intent(in), optional :: quiet
    call expect_real (x, real (x0, kind=default), msg, passed, threshold, quiet)
end subroutine expect_real_integer

```

*(Implementation of test support functions)+≡*

```

subroutine expect_integer_real (x, x0, msg, passed, threshold, quiet)
    integer, intent(in) :: x
    real(kind=default), intent(in) :: x0

```

```

character(len=*), intent(in) :: msg
real(kind=default), intent(in), optional :: threshold
logical, intent(inout), optional :: passed
logical, intent(in), optional :: quiet
call expect_real (real (x, kind=default), x0, msg, passed, threshold, quiet)
end subroutine expect_integer_real

```

*(Implementation of test support functions)+≡*

```

subroutine expect_complex_integer (x, x0, msg, passed, threshold, quiet)
  complex(kind=default), intent(in) :: x
  integer, intent(in) :: x0
  character(len=*), intent(in) :: msg
  logical, intent(inout), optional :: passed
  real(kind=default), intent(in), optional :: threshold
  logical, intent(in), optional :: quiet
  call expect_complex (x, cmplx (x0, kind=default), msg, passed, threshold, quiet)
end subroutine expect_complex_integer

```

*(Implementation of test support functions)+≡*

```

subroutine expect_integer_complex (x, x0, msg, passed, threshold, quiet)
  integer, intent(in) :: x
  complex(kind=default), intent(in) :: x0
  character(len=*), intent(in) :: msg
  logical, intent(inout), optional :: passed
  real(kind=default), intent(in), optional :: threshold
  logical, intent(in), optional :: quiet
  call expect_complex (cmplx (x, kind=default), x0, msg, passed, threshold, quiet)
end subroutine expect_integer_complex

```

*(Implementation of test support functions)+≡*

```

subroutine expect_complex_real (x, x0, msg, passed, threshold, quiet)
  complex(kind=default), intent(in) :: x
  real(kind=default), intent(in) :: x0
  character(len=*), intent(in) :: msg
  logical, intent(inout), optional :: passed
  real(kind=default), intent(in), optional :: threshold
  logical, intent(in), optional :: quiet
  call expect_complex (x, cmplx (x0, kind=default), msg, passed, threshold, quiet)
end subroutine expect_complex_real

```

*(Implementation of test support functions)+≡*

```

subroutine expect_real_complex (x, x0, msg, passed, threshold, quiet)
  real(kind=default), intent(in) :: x
  complex(kind=default), intent(in) :: x0
  character(len=*), intent(in) :: msg
  logical, intent(inout), optional :: passed
  real(kind=default), intent(in), optional :: threshold
  logical, intent(in), optional :: quiet
  call expect_complex (cmplx (x, kind=default), x0, msg, passed, threshold, quiet)
end subroutine expect_real_complex

```

*(Declaration of test support functions)+≡*

```

public :: expect_zero
interface expect_zero
  module procedure expect_zero_integer, expect_zero_real, expect_zero_complex
end interface
private :: expect_zero_integer, expect_zero_real, expect_zero_complex

```



*(Implementation of test support functions)+≡*

```
subroutine expect_zero_integer (x, msg, passed)
  integer, intent(in) :: x
  character(len=*), intent(in) :: msg
  logical, intent(inout), optional :: passed
  call expect_integer (x, 0, msg, passed)
end subroutine expect_zero_integer
```

*(Implementation of test support functions)+≡*

```
subroutine expect_zero_real (x, scale, msg, passed, threshold, quiet)
  real(kind=default), intent(in) :: x, scale
  character(len=*), intent(in) :: msg
  logical, intent(inout), optional :: passed
  real(kind=default), intent(in), optional :: threshold
  logical, intent(in), optional :: quiet
  logical :: failed, verbose
  real(kind=default) :: agreement_threshold
  character(len=*), parameter :: fmt = "(1X,A,': ',A,' at ',I4,'%')'"
  character(len=*), parameter :: fmt_verbose = "(1X,A,': ',A,' at ',I4,'%'," // &
    "' [expected 0 (relative to ',E10.3,') got ',E10.3,']')'"
  real(kind=default) :: a
  failed = .false.
  verbose = .true.
  if (present (quiet)) then
    verbose = .not.quiet
  end if
  if (x == 0) then
    if (verbose) then
      write (unit = *, fmt = fmt) msg, "passed", 100
    end if
  else
    a = vanishes (x, scale = scale)
    if (present (threshold)) then
      agreement_threshold = threshold
    else
      agreement_threshold = THRESHOLD_DEFAULT
    end if
    if (a >= agreement_threshold) then
      if (verbose) then
        if (a >= THRESHOLD_WARN) then
          write (unit = *, fmt = fmt) msg, "passed", int (a * 100)
        else
          write (unit = *, fmt = fmt_verbose) msg, "passed", int (a * 100), scale, x
        end if
      end if
    else
      failed = .true.
      write (unit = *, fmt = fmt_verbose) msg, "failed", int (a * 100), scale, x
    end if
  end if
  if (present (passed)) then
    passed = passed .and. .not.failed
  end if
end subroutine expect_zero_real
```

*(Implementation of test support functions)*+≡

```
subroutine expect_zero_complex (x, scale, msg, passed, threshold, quiet)
  complex(kind=default), intent(in) :: x
  real(kind=default), intent(in) :: scale
  character(len=*), intent(in) :: msg
  logical, intent(inout), optional :: passed
  real(kind=default), intent(in), optional :: threshold
  logical, intent(in), optional :: quiet
  call expect_zero_real (abs (x), scale, msg, passed, threshold, quiet)
end subroutine expect_zero_complex
```

*(Implementation of test support functions)*+≡

```
subroutine print_matrix (a)
  complex(kind=default), dimension(:, :), intent(in) :: a
  integer :: row
  do row = 1, size (a, dim=1)
    write (unit = *, fmt = "(10(tr2, f5.2, ' ', f5.2, 'I'))") a(row,:)
  end do
end subroutine print_matrix
```

*(Declaration of test support functions)*+≡

```
public :: print_matrix
```

*(test\_omega95.f90)*≡

*(Copleft)*

```
program test_omega95
  use kinds
  use omega95
  use omega_testtools
  implicit none
  real(kind=default) :: m, pabs, qabs, w
  real(kind=default), dimension(0:3) :: r
  complex(kind=default) :: c_one, c_nil
  type(momentum) :: p, q, p0
  type(vector) :: vp, vq, vtest, v0
  type(tensor) :: ttest
  integer, dimension(8) :: date_time
  integer :: rsize
  logical :: passed
  call date_and_time (values = date_time)
  call random_seed (size = rsize)
  call random_seed (put = spread (product (date_time), dim = 1, ncopies = rsize))
  w = 1.4142
  c_one = 1.0_default
  c_nil = 0.0_default
  m = 13
  pabs = 42
  qabs = 137
  call random_number (r)
  vtest%t = cmplx (10.0_default * r(0), kind=default)
  vtest%x(1:3) = cmplx (10.0_default * r(1:3), kind=default)
  ttest = vtest.tprod.vtest
  call random_momentum (p, pabs, m)
  call random_momentum (q, qabs, m)
  call random_momentum (p0, 0.0_default, m)
  vp = p
```

```

vq = q
v0 = p0
passed = .true.
<Test omega95>
if (.not. passed) then
  stop 1
end if
end program test_omega95

<Test omega95>≡
print *, "*** Checking the equations of motion ***:"
call expect (abs(f_vf(c_one, vp, u(m, p, +1)) - m * u(m, p, +1)), 0, "[p-m]u(+)=0", passed)
call expect (abs(f_vf(c_one, vp, u(m, p, -1)) - m * u(m, p, -1)), 0, "[p-m]u(-)=0", passed)
call expect (abs(f_vf(c_one, vp, v(m, p, +1)) + m * v(m, p, +1)), 0, "[p+m]v(+)=0", passed)
call expect (abs(f_vf(c_one, vp, v(m, p, -1)) + m * v(m, p, -1)), 0, "[p+m]v(-)=0", passed)
call expect (abs(f_fv(c_one, ubar(m, p, +1), vp) - m * ubar(m, p, +1)), 0, "ubar(+)[p-m]=0", passed)
call expect (abs(f_fv(c_one, ubar(m, p, -1), vp) - m * ubar(m, p, -1)), 0, "ubar(-)[p-m]=0", passed)
call expect (abs(f_fv(c_one, vbar(m, p, +1), vp) + m * vbar(m, p, +1)), 0, "vbar(+)[p+m]=0", passed)
call expect (abs(f_fv(c_one, vbar(m, p, -1), vp) + m * vbar(m, p, -1)), 0, "vbar(-)[p+m]=0", passed)
print *, "*** Checking the equations of motion for negative mass***:"
call expect (abs(f_vf(c_one, vp, u(-m, p, +1)) + m * u(-m, p, +1)), 0, "[p+m]u(+)=0", passed)
call expect (abs(f_vf(c_one, vp, u(-m, p, -1)) + m * u(-m, p, -1)), 0, "[p+m]u(-)=0", passed)
call expect (abs(f_vf(c_one, vp, v(-m, p, +1)) - m * v(-m, p, +1)), 0, "[p-m]v(+)=0", passed)
call expect (abs(f_vf(c_one, vp, v(-m, p, -1)) - m * v(-m, p, -1)), 0, "[p-m]v(-)=0", passed)
call expect (abs(f_fv(c_one, ubar(-m, p, +1), vp) + m * ubar(-m, p, +1)), 0, "ubar(+)[p+m]=0", passed)
call expect (abs(f_fv(c_one, ubar(-m, p, -1), vp) + m * ubar(-m, p, -1)), 0, "ubar(-)[p+m]=0", passed)
call expect (abs(f_fv(c_one, vbar(-m, p, +1), vp) - m * vbar(-m, p, +1)), 0, "vbar(+)[p-m]=0", passed)
call expect (abs(f_fv(c_one, vbar(-m, p, -1), vp) - m * vbar(-m, p, -1)), 0, "vbar(-)[p-m]=0", passed)

<Test omega95>+≡
print *, "*** Checking the normalization ***:"
call expect (ubar(m, p, +1) * u(m, p, +1), +2 * m, "ubar(+)*u(+)=+2m", passed)
call expect (ubar(m, p, -1) * u(m, p, -1), +2 * m, "ubar(-)*u(-)=+2m", passed)
call expect (vbar(m, p, +1) * v(m, p, +1), -2 * m, "vbar(+)*v(+)= -2m", passed)
call expect (vbar(m, p, -1) * v(m, p, -1), -2 * m, "vbar(-)*v(-)= -2m", passed)
call expect (ubar(m, p, +1) * v(m, p, +1), 0, "ubar(+)*v(+)=0", passed)
call expect (ubar(m, p, -1) * v(m, p, -1), 0, "ubar(-)*v(-)=0", passed)
call expect (vbar(m, p, +1) * u(m, p, +1), 0, "vbar(+)*u(+)=0", passed)
call expect (vbar(m, p, -1) * u(m, p, -1), 0, "vbar(-)*u(-)=0", passed)
print *, "*** Checking the normalization for negative masses***:"
call expect (ubar(-m, p, +1) * u(-m, p, +1), -2 * m, "ubar(+)*u(+)= -2m", passed)
call expect (ubar(-m, p, -1) * u(-m, p, -1), -2 * m, "ubar(-)*u(-)= -2m", passed)
call expect (vbar(-m, p, +1) * v(-m, p, +1), +2 * m, "vbar(+)*v(+)=+2m", passed)
call expect (vbar(-m, p, -1) * v(-m, p, -1), +2 * m, "vbar(-)*v(-)=+2m", passed)
call expect (ubar(-m, p, +1) * v(-m, p, +1), 0, "ubar(+)*v(+)=0", passed)
call expect (ubar(-m, p, -1) * v(-m, p, -1), 0, "ubar(-)*v(-)=0", passed)
call expect (vbar(-m, p, +1) * u(-m, p, +1), 0, "vbar(+)*u(+)=0", passed)
call expect (vbar(-m, p, -1) * u(-m, p, -1), 0, "vbar(-)*u(-)=0", passed)

<Test omega95>+≡
print *, "*** Checking the currents ***:"
call expect (abs(v_ff(c_one, ubar(m, p, +1), u(m, p, +1)) - 2 * vp), 0, "ubar(+).V.u(+)=2p", passed)
call expect (abs(v_ff(c_one, ubar(m, p, -1), u(m, p, -1)) - 2 * vp), 0, "ubar(-).V.u(-)=2p", passed)
call expect (abs(v_ff(c_one, vbar(m, p, +1), v(m, p, +1)) - 2 * vp), 0, "vbar(+).V.v(+)=2p", passed)
call expect (abs(v_ff(c_one, vbar(m, p, -1), v(m, p, -1)) - 2 * vp), 0, "vbar(-).V.v(-)=2p", passed)
print *, "*** Checking the currents for negative masses***:"

```

```

call expect (abs(v_ff(c_one,ubar(-m,p,+1),u(-m,p,+1))-2*vp), 0, "ubar(+).V.u(+)=2p", passed)
call expect (abs(v_ff(c_one,ubar(-m,p,-1),u(-m,p,-1))-2*vp), 0, "ubar(-).V.u(-)=2p", passed)
call expect (abs(v_ff(c_one,vbar(-m,p,+1),v(-m,p,+1))-2*vp), 0, "vbar(+).V.v(+)=2p", passed)
call expect (abs(v_ff(c_one,vbar(-m,p,-1),v(-m,p,-1))-2*vp), 0, "vbar(-).V.v(-)=2p", passed)

<Test omega95>+=
print *, "*** Checking current conservation ***:"
call expect ((vp-vq)*v_ff(c_one,ubar(m,p,+1),u(m,q,+1)), 0, "d(ubar(+).V.u(+))=0", passed)
call expect ((vp-vq)*v_ff(c_one,ubar(m,p,-1),u(m,q,-1)), 0, "d(ubar(-).V.u(-))=0", passed)
call expect ((vp-vq)*v_ff(c_one,vbar(m,p,+1),v(m,q,+1)), 0, "d(vbar(+).V.v(+))=0", passed)
call expect ((vp-vq)*v_ff(c_one,vbar(m,p,-1),v(m,q,-1)), 0, "d(vbar(-).V.v(-))=0", passed)
print *, "*** Checking current conservation for negative masses***:"
call expect ((vp-vq)*v_ff(c_one,ubar(-m,p,+1),u(-m,q,+1)), 0, "d(ubar(+).V.u(+))=0", passed)
call expect ((vp-vq)*v_ff(c_one,ubar(-m,p,-1),u(-m,q,-1)), 0, "d(ubar(-).V.u(-))=0", passed)
call expect ((vp-vq)*v_ff(c_one,vbar(-m,p,+1),v(-m,q,+1)), 0, "d(vbar(+).V.v(+))=0", passed)
call expect ((vp-vq)*v_ff(c_one,vbar(-m,p,-1),v(-m,q,-1)), 0, "d(vbar(-).V.v(-))=0", passed)

<Test omega95>+=
if (m == 0) then
  print *, "*** Checking axial current conservation ***:"
  call expect ((vp-vq)*a_ff(c_one,ubar(m,p,+1),u(m,q,+1)), 0, "d(ubar(+).A.u(+))=0", passed)
  call expect ((vp-vq)*a_ff(c_one,ubar(m,p,-1),u(m,q,-1)), 0, "d(ubar(-).A.u(-))=0", passed)
  call expect ((vp-vq)*a_ff(c_one,vbar(m,p,+1),v(m,q,+1)), 0, "d(vbar(+).A.v(+))=0", passed)
  call expect ((vp-vq)*a_ff(c_one,vbar(m,p,-1),v(m,q,-1)), 0, "d(vbar(-).A.v(-))=0", passed)
end if

<Test omega95>+=
print *, "*** Checking implementation of the sigma vertex funktions ***:"
call expect ((vp*tvam_ff(c_one,c_nil,ubar(m,p,+1),u(m,q,+1),q) - (p*q-m**2)*(ubar(m,p,+1)*u(m,q,+1)
  "p*[ubar(p,+).(Isigma*q).u(q,+)] - (p*q-m^2)*ubar(p,+).u(q,+)", passed)
call expect ((vp*tvam_ff(c_one,c_nil,ubar(m,p,-1),u(m,q,-1),q) - (p*q-m**2)*(ubar(m,p,-1)*u(m,q,-1)
  "p*[ubar(p,-).(Isigma*q).u(q,-)] - (p*q-m^2)*ubar(p,-).u(q,-)", passed)
call expect ((vp*tvam_ff(c_one,c_nil,vbar(m,p,+1),v(m,q,+1),q) - (p*q-m**2)*(vbar(m,p,+1)*v(m,q,+1)
  "p*[vbar(p,+).(Isigma*q).v(q,+)] - (p*q-m^2)*vbar(p,+).v(q,+)", passed)
call expect ((vp*tvam_ff(c_one,c_nil,vbar(m,p,-1),v(m,q,-1),q) - (p*q-m**2)*(vbar(m,p,-1)*v(m,q,-1)
  "p*[vbar(p,-).(Isigma*q).v(q,-)] - (p*q-m^2)*vbar(p,-).v(q,-)", passed)
call expect ((ubar(m,p,+1)*f_tvamf(c_one,c_nil,vp,u(m,q,+1),q) - (p*q-m**2)*(ubar(m,p,+1)*u(m,q,+1)
  "ubar(p,+).[p*(Isigma*q).u(q,+)] - (p*q-m^2)*ubar(p,+).u(q,+)", passed)
call expect ((ubar(m,p,-1)*f_tvamf(c_one,c_nil,vp,u(m,q,-1),q) - (p*q-m**2)*(ubar(m,p,-1)*u(m,q,-1)
  "ubar(p,-).[p*(Isigma*q).u(q,-)] - (p*q-m^2)*ubar(p,-).u(q,-)", passed)
call expect ((vbar(m,p,+1)*f_tvamf(c_one,c_nil,vp,v(m,q,+1),q) - (p*q-m**2)*(vbar(m,p,+1)*v(m,q,+1)
  "vbar(p,+).[p*(Isigma*q).v(q,+)] - (p*q-m^2)*vbar(p,+).v(q,+)", passed)
call expect ((vbar(m,p,-1)*f_tvamf(c_one,c_nil,vp,v(m,q,-1),q) - (p*q-m**2)*(vbar(m,p,-1)*v(m,q,-1)
  "vbar(p,-).[p*(Isigma*q).v(q,-)] - (p*q-m^2)*vbar(p,-).v(q,-)", passed)
call expect ((f_ftvam(c_one,c_nil,ubar(m,p,+1),vp,q)*u(m,q,+1) - (p*q-m**2)*(ubar(m,p,+1)*u(m,q,+1)
  "[ubar(p,+).p*(Isigma*q)].u(q,+)] - (p*q-m^2)*ubar(p,+).u(q,+)", passed)
call expect ((f_ftvam(c_one,c_nil,ubar(m,p,-1),vp,q)*u(m,q,-1) - (p*q-m**2)*(ubar(m,p,-1)*u(m,q,-1)
  "[ubar(p,-).p*(Isigma*q)].u(q,-)] - (p*q-m^2)*ubar(p,-).u(q,-)", passed)
call expect ((f_ftvam(c_one,c_nil,vbar(m,p,+1),vp,q)*v(m,q,+1) - (p*q-m**2)*(vbar(m,p,+1)*v(m,q,+1)
  "[vbar(p,+).p*(Isigma*q)].v(q,+)] - (p*q-m^2)*vbar(p,+).v(q,+)", passed)
call expect ((f_ftvam(c_one,c_nil,vbar(m,p,-1),vp,q)*v(m,q,-1) - (p*q-m**2)*(vbar(m,p,-1)*v(m,q,-1)
  "[vbar(p,-).p*(Isigma*q)].v(q,-)] - (p*q-m^2)*vbar(p,-).v(q,-)", passed)

call expect ((vp*tvam_ff(c_nil,c_one,ubar(m,p,+1),u(m,q,+1),q) - (p*q+m**2)*p_ff(c_one,ubar(m,p,+1)
  "p*[ubar(p,+).(Isigma*q).g5.u(q,+)] - (p*q+m^2)*ubar(p,+).g5.u(q,+)", passed)
call expect ((vp*tvam_ff(c_nil,c_one,ubar(m,p,-1),u(m,q,-1),q) - (p*q+m**2)*p_ff(c_one,ubar(m,p,-1)

```

```

        "p*[ubar(p,-).(Isigma*q).g5.u(q,-)] - (p*q+m^2)*ubar(p,-).g5.u(q,-) = 0", passed)
call expect ((vp*tvam_ff(c_nil,c_one,vbar(m,p,+1),v(m,q,+1),q) - (p*q+m**2)*p_ff(c_one,vbar(m,p,+1)
        "p*[vbar(p,+).(Isigma*q).g5.v(q,+)] - (p*q+m^2)*vbar(p,+).g5.v(q,+) = 0", passed)
call expect ((vp*tvam_ff(c_nil,c_one,vbar(m,p,-1),v(m,q,-1),q) - (p*q+m**2)*p_ff(c_one,vbar(m,p,-1)
        "p*[vbar(p,-).(Isigma*q).g5.v(q,-)] - (p*q+m^2)*vbar(p,-).g5.v(q,-) = 0", passed)
call expect ((ubar(m,p,+1)*f_tvamf(c_nil,c_one,vp,u(m,q,+1),q) - (p*q+m**2)*p_ff(c_one,ubar(m,p,+1)
        "p*[ubar(p,+).(Isigma*q).g5.u(q,+)] - (p*q+m^2)*ubar(p,+).g5.u(q,+) = 0", passed)
call expect ((ubar(m,p,-1)*f_tvamf(c_nil,c_one,vp,u(m,q,-1),q) - (p*q+m**2)*p_ff(c_one,ubar(m,p,-1)
        "p*[ubar(p,-).(Isigma*q).g5.u(q,-)] - (p*q+m^2)*ubar(p,-).g5.u(q,-) = 0", passed)
call expect ((vbar(m,p,+1)*f_tvamf(c_nil,c_one,vp,v(m,q,+1),q) - (p*q+m**2)*p_ff(c_one,vbar(m,p,+1)
        "p*[vbar(p,+).(Isigma*q).g5.v(q,+)] - (p*q+m^2)*vbar(p,+).g5.v(q,+) = 0", passed)
call expect ((vbar(m,p,-1)*f_tvamf(c_nil,c_one,vp,v(m,q,-1),q) - (p*q+m**2)*p_ff(c_one,vbar(m,p,-1)
        "p*[vbar(p,-).(Isigma*q).g5.v(q,-)] - (p*q+m^2)*vbar(p,-).g5.v(q,-) = 0", passed)
call expect ((f_ftvam(c_nil,c_one,ubar(m,p,+1),vp,q)*u(m,q,+1) - (p*q+m**2)*p_ff(c_one,ubar(m,p,+1)
        "p*[ubar(p,+).(Isigma*q).g5.u(q,+)] - (p*q+m^2)*ubar(p,+).g5.u(q,+) = 0", passed)
call expect ((f_ftvam(c_nil,c_one,ubar(m,p,-1),vp,q)*u(m,q,-1) - (p*q+m**2)*p_ff(c_one,ubar(m,p,-1)
        "p*[ubar(p,-).(Isigma*q).g5.u(q,-)] - (p*q+m^2)*ubar(p,-).g5.u(q,-) = 0", passed)
call expect ((f_ftvam(c_nil,c_one,vbar(m,p,+1),vp,q)*v(m,q,+1) - (p*q+m**2)*p_ff(c_one,vbar(m,p,+1)
        "p*[vbar(p,+).(Isigma*q).g5.v(q,+)] - (p*q+m^2)*vbar(p,+).g5.v(q,+) = 0", passed)
call expect ((f_ftvam(c_nil,c_one,vbar(m,p,-1),vp,q)*v(m,q,-1) - (p*q+m**2)*p_ff(c_one,vbar(m,p,-1)
        "p*[vbar(p,-).(Isigma*q).g5.v(q,-)] - (p*q+m^2)*vbar(p,-).g5.v(q,-) = 0", passed)

<Test omega95)+≡
print *, "*** Checking polarisation vectors: ***"
call expect (conjg(eps(m,p, 1))*eps(m,p, 1), -1, "e( 1).e( 1)=-1", passed)
call expect (conjg(eps(m,p, 1))*eps(m,p,-1), 0, "e( 1).e(-1)= 0", passed)
call expect (conjg(eps(m,p,-1))*eps(m,p, 1), 0, "e(-1).e( 1)= 0", passed)
call expect (conjg(eps(m,p,-1))*eps(m,p,-1), -1, "e(-1).e(-1)=-1", passed)
call expect (
        p*eps(m,p, 1), 0, "    p.e( 1)= 0", passed)
call expect (
        p*eps(m,p,-1), 0, "    p.e(-1)= 0", passed)
if (m > 0) then
    call expect (conjg(eps(m,p, 1))*eps(m,p, 0), 0, "e( 1).e( 0)= 0", passed)
    call expect (conjg(eps(m,p, 0))*eps(m,p, 1), 0, "e( 0).e( 1)= 0", passed)
    call expect (conjg(eps(m,p, 0))*eps(m,p, 0), -1, "e( 0).e( 0)=-1", passed)
    call expect (conjg(eps(m,p, 0))*eps(m,p,-1), 0, "e( 0).e(-1)= 0", passed)
    call expect (conjg(eps(m,p,-1))*eps(m,p, 0), 0, "e(-1).e( 0)= 0", passed)
    call expect (
        p*eps(m,p, 0), 0, "    p.e( 0)= 0", passed)
end if

<Test omega95)+≡
print *, "*** Checking epsilon tensor: ***"
call expect ( pseudo_scalar(eps(m,p,1),eps(m,q,1),eps(m,p,0),eps(m,q,0)), &
        - pseudo_scalar(eps(m,q,1),eps(m,p,1),eps(m,p,0),eps(m,q,0)), "eps(1<->2)", passed)
call expect ( pseudo_scalar(eps(m,p,1),eps(m,q,1),eps(m,p,0),eps(m,q,0)), &
        - pseudo_scalar(eps(m,p,0),eps(m,q,1),eps(m,p,1),eps(m,q,0)), "eps(1<->3)", passed)
call expect ( pseudo_scalar(eps(m,p,1),eps(m,q,1),eps(m,p,0),eps(m,q,0)), &
        - pseudo_scalar(eps(m,q,0),eps(m,q,1),eps(m,p,0),eps(m,p,1)), "eps(1<->4)", passed)
call expect ( pseudo_scalar(eps(m,p,1),eps(m,q,1),eps(m,p,0),eps(m,q,0)), &
        - pseudo_scalar(eps(m,p,1),eps(m,p,0),eps(m,q,1),eps(m,q,0)), "eps(2<->3)", passed)
call expect ( pseudo_scalar(eps(m,p,1),eps(m,q,1),eps(m,p,0),eps(m,q,0)), &
        - pseudo_scalar(eps(m,p,1),eps(m,q,0),eps(m,p,0),eps(m,q,1)), "eps(2<->4)", passed)
call expect ( pseudo_scalar(eps(m,p,1),eps(m,q,1),eps(m,p,0),eps(m,q,0)), &
        - pseudo_scalar(eps(m,p,1),eps(m,q,1),eps(m,q,0),eps(m,p,0)), "eps(3<->4)", passed)
call expect ( pseudo_scalar(eps(m,p,1),eps(m,q,1),eps(m,p,0),eps(m,q,0)), &
        eps(m,p,1)*pseudo_vector(eps(m,q,1),eps(m,p,0),eps(m,q,0)), "eps'", passed)

```

$$\frac{1}{2}[x \wedge y]_{\mu\nu}^*[x \wedge y]^{\mu\nu} = \frac{1}{2}(x_\mu^* y_\nu^* - x_\nu^* y_\mu^*)(x^\mu y^\nu - x^\nu y^\mu) = (x^* x)(y^* y) - (x^* y)(y^* x) \quad (\text{X.98})$$

$\langle \text{Test omega95} \rangle + \equiv$

```
print *, "*** Checking tensors: ***"
call expect (conjg(p.wedge.q)*(p.wedge.q), (p*p)*(q*q)-(p*q)**2, &
  "[p,q].[q,p]=p.p*q.q-p.q^2", passed)
call expect (conjg(p.wedge.q)*(q.wedge.p), (p*q)**2-(p*p)*(q*q), &
  "[p,q].[q,p]=p.q^2-p.p*q.q", passed)
```

i. e.

$$\frac{1}{2}[p \wedge \epsilon(p, i)]_{\mu\nu}^*[p \wedge \epsilon(p, j)]^{\mu\nu} = -p^2 \delta_{ij} \quad (\text{X.99})$$

$\langle \text{Test omega95} \rangle + \equiv$

```
call expect (conjg(p.wedge.eps(m,p, 1))*(p.wedge.eps(m,p, 1)), -p*p, &
  "[p,e( 1)].[p,e( 1)]=-p.p", passed)
call expect (conjg(p.wedge.eps(m,p, 1))*(p.wedge.eps(m,p,-1)), 0, &
  "[p,e( 1)].[p,e(-1)]=0", passed)
call expect (conjg(p.wedge.eps(m,p,-1))*(p.wedge.eps(m,p, 1)), 0, &
  "[p,e(-1)].[p,e( 1)]=0", passed)
call expect (conjg(p.wedge.eps(m,p,-1))*(p.wedge.eps(m,p,-1)), -p*p, &
  "[p,e(-1)].[p,e(-1)]=-p.p", passed)
if (m > 0) then
  call expect (conjg(p.wedge.eps(m,p, 1))*(p.wedge.eps(m,p, 0)), 0, &
    "[p,e( 1)].[p,e( 0)]=0", passed)
  call expect (conjg(p.wedge.eps(m,p, 0))*(p.wedge.eps(m,p, 1)), 0, &
    "[p,e( 0)].[p,e( 1)]=0", passed)
  call expect (conjg(p.wedge.eps(m,p, 0))*(p.wedge.eps(m,p, 0)), -p*p, &
    "[p,e( 0)].[p,e( 0)]=-p.p", passed)
  call expect (conjg(p.wedge.eps(m,p, 0))*(p.wedge.eps(m,p,-1)), 0, &
    "[p,e( 1)].[p,e(-1)]=0", passed)
  call expect (conjg(p.wedge.eps(m,p,-1))*(p.wedge.eps(m,p, 0)), 0, &
    "[p,e(-1)].[p,e( 0)]=0", passed)
end if
```

also

$$[x \wedge y]_{\mu\nu} z^\nu = x_\mu (yz) - y_\mu (xz) \quad (\text{X.100})$$

$$z_\mu [x \wedge y]^{\mu\nu} = (zx)y^\nu - (zy)x^\nu \quad (\text{X.101})$$

$\langle \text{Test omega95} \rangle + \equiv$

```
call expect (abs ((p.wedge.eps(m,p, 1))*p + (p*p)*eps(m,p, 1)), 0, &
  "[p,e( 1)].p=-p.p*e( 1)", passed)
call expect (abs ((p.wedge.eps(m,p, 0))*p + (p*p)*eps(m,p, 0)), 0, &
  "[p,e( 0)].p=-p.p*e( 0)", passed)
call expect (abs ((p.wedge.eps(m,p,-1))*p + (p*p)*eps(m,p,-1)), 0, &
  "[p,e(-1)].p=-p.p*e(-1)", passed)
call expect (abs (p*(p.wedge.eps(m,p, 1)) - (p*p)*eps(m,p, 1)), 0, &
  "p.[p,e( 1)]=p.p*e( 1)", passed)
call expect (abs (p*(p.wedge.eps(m,p, 0)) - (p*p)*eps(m,p, 0)), 0, &
  "p.[p,e( 0)]=p.p*e( 0)", passed)
call expect (abs (p*(p.wedge.eps(m,p,-1)) - (p*p)*eps(m,p,-1)), 0, &
  "p.[p,e(-1)]=p.p*e(-1)", passed)
```

```

<Test omega95>+=
print *, "*** Checking polarisation tensors: ***"
call expect (conjg(eps2(m,p, 2))*eps2(m,p, 2), 1, "e2( 2).e2( 2)=1", passed)
call expect (conjg(eps2(m,p, 2))*eps2(m,p,-2), 0, "e2( 2).e2(-2)=0", passed)
call expect (conjg(eps2(m,p,-2))*eps2(m,p, 2), 0, "e2(-2).e2( 2)=0", passed)
call expect (conjg(eps2(m,p,-2))*eps2(m,p,-2), 1, "e2(-2).e2(-2)=1", passed)
if (m > 0) then
  call expect (conjg(eps2(m,p, 2))*eps2(m,p, 1), 0, "e2( 2).e2( 1)=0", passed)
  call expect (conjg(eps2(m,p, 2))*eps2(m,p, 0), 0, "e2( 2).e2( 0)=0", passed)
  call expect (conjg(eps2(m,p, 2))*eps2(m,p,-1), 0, "e2( 2).e2(-1)=0", passed)
  call expect (conjg(eps2(m,p, 1))*eps2(m,p, 2), 0, "e2( 1).e2( 2)=0", passed)
  call expect (conjg(eps2(m,p, 1))*eps2(m,p, 1), 1, "e2( 1).e2( 1)=1", passed)
  call expect (conjg(eps2(m,p, 1))*eps2(m,p, 0), 0, "e2( 1).e2( 0)=0", passed)
  call expect (conjg(eps2(m,p, 1))*eps2(m,p,-1), 0, "e2( 1).e2(-1)=0", passed)
  call expect (conjg(eps2(m,p, 1))*eps2(m,p,-2), 0, "e2( 1).e2(-2)=0", passed)
  call expect (conjg(eps2(m,p, 0))*eps2(m,p, 2), 0, "e2( 0).e2( 2)=0", passed)
  call expect (conjg(eps2(m,p, 0))*eps2(m,p, 1), 0, "e2( 0).e2( 1)=0", passed)
  call expect (conjg(eps2(m,p, 0))*eps2(m,p, 0), 1, "e2( 0).e2( 0)=1", passed)
  call expect (conjg(eps2(m,p, 0))*eps2(m,p,-1), 0, "e2( 0).e2(-1)=0", passed)
  call expect (conjg(eps2(m,p, 0))*eps2(m,p,-2), 0, "e2( 0).e2(-2)=0", passed)
  call expect (conjg(eps2(m,p,-1))*eps2(m,p, 2), 0, "e2(-1).e2( 2)=0", passed)
  call expect (conjg(eps2(m,p,-1))*eps2(m,p, 1), 0, "e2(-1).e2( 1)=0", passed)
  call expect (conjg(eps2(m,p,-1))*eps2(m,p, 0), 0, "e2(-1).e2( 0)=0", passed)
  call expect (conjg(eps2(m,p,-1))*eps2(m,p,-1), 1, "e2(-1).e2(-1)=1", passed)
  call expect (conjg(eps2(m,p,-1))*eps2(m,p,-2), 0, "e2(-1).e2(-2)=0", passed)
  call expect (conjg(eps2(m,p,-2))*eps2(m,p, 1), 0, "e2(-2).e2( 1)=0", passed)
  call expect (conjg(eps2(m,p,-2))*eps2(m,p, 0), 0, "e2(-2).e2( 0)=0", passed)
  call expect (conjg(eps2(m,p,-2))*eps2(m,p,-1), 0, "e2(-2).e2(-1)=0", passed)
end if

<Test omega95>+=
call expect (abs(p*eps2(m,p, 2) ), 0, " |p.e2( 2)| =0", passed)
call expect (abs(eps2(m,p, 2)*p), 0, " |e2( 2).p|=0", passed)
call expect (abs(p*eps2(m,p,-2) ), 0, " |p.e2(-2)| =0", passed)
call expect (abs(eps2(m,p,-2)*p), 0, " |e2(-2).p|=0", passed)
if (m > 0) then
  call expect (abs(p*eps2(m,p, 1) ), 0, " |p.e2( 1)| =0", passed)
  call expect (abs(eps2(m,p, 1)*p), 0, " |e2( 1).p|=0", passed)
  call expect (abs(p*eps2(m,p, 0) ), 0, " |p.e2( 0)| =0", passed)
  call expect (abs(eps2(m,p, 0)*p), 0, " |e2( 0).p|=0", passed)
  call expect (abs(p*eps2(m,p,-1) ), 0, " |p.e2(-1)| =0", passed)
  call expect (abs(eps2(m,p,-1)*p), 0, " |e2(-1).p|=0", passed)
end if

<XXX Test omega95>=
print *, " *** Checking the polarization tensors for massive gravitons:"
call expect (abs(p * eps2(m,p,2)), 0, "p.e(+2)=0", passed)
call expect (abs(p * eps2(m,p,1)), 0, "p.e(+1)=0", passed)
call expect (abs(p * eps2(m,p,0)), 0, "p.e( 0)=0", passed)
call expect (abs(p * eps2(m,p,-1)), 0, "p.e(-1)=0", passed)
call expect (abs(p * eps2(m,p,-2)), 0, "p.e(-2)=0", passed)
call expect (abs(trace(eps2 (m,p,2))), 0, "Tr[e(+2)]=0", passed)
call expect (abs(trace(eps2 (m,p,1))), 0, "Tr[e(+1)]=0", passed)
call expect (abs(trace(eps2 (m,p,0))), 0, "Tr[e( 0)]=0", passed)
call expect (abs(trace(eps2 (m,p,-1))), 0, "Tr[e(-1)]=0", passed)

```

```

call expect (abs(trace(eps2 (m,p,-2))), 0, "Tr[e(-2)]=0", passed)
call expect (abs(eps2(m,p,2) * eps2(m,p,2)), 1, &
  "e(2).e(2) = 1", passed)
call expect (abs(eps2(m,p,2) * eps2(m,p,1)), 0, &
  "e(2).e(1) = 0", passed)
call expect (abs(eps2(m,p,2) * eps2(m,p,0)), 0, &
  "e(2).e(0) = 0", passed)
call expect (abs(eps2(m,p,2) * eps2(m,p,-1)), 0, &
  "e(2).e(-1) = 0", passed)
call expect (abs(eps2(m,p,2) * eps2(m,p,-2)), 0, &
  "e(2).e(-2) = 0", passed)
call expect (abs(eps2(m,p,1) * eps2(m,p,1)), 1, &
  "e(1).e(1) = 1", passed)
call expect (abs(eps2(m,p,1) * eps2(m,p,0)), 0, &
  "e(1).e(0) = 0", passed)
call expect (abs(eps2(m,p,1) * eps2(m,p,-1)), 0, &
  "e(1).e(-1) = 0", passed)
call expect (abs(eps2(m,p,1) * eps2(m,p,-2)), 0, &
  "e(1).e(-2) = 0", passed)
call expect (abs(eps2(m,p,0) * eps2(m,p,0)), 1, &
  "e(0).e(0) = 1", passed)
call expect (abs(eps2(m,p,0) * eps2(m,p,-1)), 0, &
  "e(0).e(-1) = 0", passed)
call expect (abs(eps2(m,p,0) * eps2(m,p,-2)), 0, &
  "e(0).e(-2) = 0", passed)
call expect (abs(eps2(m,p,-1) * eps2(m,p,-1)), 1, &
  "e(-1).e(-1) = 1", passed)
call expect (abs(eps2(m,p,-1) * eps2(m,p,-2)), 0, &
  "e(-1).e(-2) = 0", passed)
call expect (abs(eps2(m,p,-2) * eps2(m,p,-2)), 1, &
  "e(-2).e(-2) = 1", passed)

<Test omega95)+≡
print *, " *** Checking the graviton propagator:"
call expect (abs(p * (cmplx (p*p - m**2, m*w, kind=default) * &
  pr_tensor(p,m,w,eps2(m,p,-2)))), 0, "p.pr.e(-2)", passed)
call expect (abs(p * (cmplx (p*p - m**2, m*w, kind=default) * &
  pr_tensor(p,m,w,eps2(m,p,-1)))), 0, "p.pr.e(-1)", passed)
call expect (abs(p * (cmplx (p*p - m**2, m*w, kind=default) * &
  pr_tensor(p,m,w,eps2(m,p,0)))), 0, "p.pr.e(0)", passed)
call expect (abs(p * (cmplx (p*p - m**2, m*w, kind=default) * &
  pr_tensor(p,m,w,eps2(m,p,1)))), 0, "p.pr.e(1)", passed)
call expect (abs(p * (cmplx (p*p - m**2, m*w, kind=default) * &
  pr_tensor(p,m,w,eps2(m,p,2)))), 0, "p.pr.e(2)", passed)
call expect (abs(p * (cmplx (p*p - m**2, m*w, kind=default) * &
  pr_tensor(p,m,w,ttest))), 0, "p.pr.ttest", passed)

<test_omega95_bispinors.f90)≡
<Cotypeleft>
program test_omega95_bispinors
  use kinds
  use omega95_bispinors
  use omega_vspinor_polarizations
  use omega_testtools
  implicit none

```



```

integer :: i, j
real(kind=default) :: m, pabs, qabs, tabs, zabs, w
real(kind=default), dimension(4) :: r
complex(kind=default) :: c_one, c_two
type(momentum) :: p, q, t, z, p_0
type(vector) :: vp, vq, vt, vz
type(vectorspinor) :: testv
logical :: passed
call random_seed ()
c_one = 1
c_two = 2
w = 1.4142
m = 13
pabs = 42
qabs = 137
tabs = 84
zabs = 3.1415
p_0%t = m
p_0%x = 0
call random_momentum (p, pabs, m)
call random_momentum (q, qabs, m)
call random_momentum (t, tabs, m)
call random_momentum (z, zabs, m)
call random_number (r)
do i = 1, 4
    testv%psi(1)%a(i) = (0.0_default, 0.0_default)
end do
do i = 2, 3
    do j = 1, 4
        testv%psi(i)%a(j) = cmplx (10.0_default * r(j))
    end do
end do
testv%psi(4)%a(1) = (1.0_default, 0.0_default)
testv%psi(4)%a(2) = (0.0_default, 2.0_default)
testv%psi(4)%a(3) = (1.0_default, 0.0_default)
testv%psi(4)%a(4) = (3.0_default, 0.0_default)
vp = p
vq = q
vt = t
vz = z
passed = .true.
<Test omega95_bispinors>
if (.not. passed) then
    stop 1
end if
end program test_omega95_bispinors

<Test omega95_bispinors>≡
print *, "*** Checking the equations of motion ***:"
call expect (abs(f_vf(c_one, vp, u(m, p, +1)) - m * u(m, p, +1)), 0, "[p-m]u(+)=0", passed)
call expect (abs(f_vf(c_one, vp, u(m, p, -1)) - m * u(m, p, -1)), 0, "[p-m]u(-)=0", passed)
call expect (abs(f_vf(c_one, vp, v(m, p, +1)) + m * v(m, p, +1)), 0, "[p+m]v(+)=0", passed)
call expect (abs(f_vf(c_one, vp, v(m, p, -1)) + m * v(m, p, -1)), 0, "[p+m]v(-)=0", passed)
print *, "*** Checking the equations of motion for negative masses***:"
call expect (abs(f_vf(c_one, vp, u(-m, p, +1)) + m * u(-m, p, +1)), 0, "[p+m]u(+)=0", passed)

```

```

call expect (abs(f_vf(c_one, vp, u(-m, p, -1)) + m * u(-m, p, -1)), 0, "[p+m]u(-)=0", passed)
call expect (abs(f_vf(c_one, vp, v(-m, p, +1)) - m * v(-m, p, +1)), 0, "[p-m]v(+)=0", passed)
call expect (abs(f_vf(c_one, vp, v(-m, p, -1)) - m * v(-m, p, -1)), 0, "[p-m]v(-)=0", passed)

<Test omega95_bispinors>+≡
print *, "*** Checking the normalization ***:"
call expect (s_ff(c_one, v(m, p, +1), u(m, p, +1)), +2*m, "ubar(+)*u(+)=+2m", passed)
call expect (s_ff(c_one, v(m, p, -1), u(m, p, -1)), +2*m, "ubar(-)*u(-)=+2m", passed)
call expect (s_ff(c_one, u(m, p, +1), v(m, p, +1)), -2*m, "vbar(+)*v(+)=+2m", passed)
call expect (s_ff(c_one, u(m, p, -1), v(m, p, -1)), -2*m, "vbar(-)*v(-)=+2m", passed)
call expect (s_ff(c_one, v(m, p, +1), v(m, p, +1)), 0, "ubar(+)*v(+)=0", passed)
call expect (s_ff(c_one, v(m, p, -1), v(m, p, -1)), 0, "ubar(-)*v(-)=0", passed)
call expect (s_ff(c_one, u(m, p, +1), u(m, p, +1)), 0, "vbar(+)*u(+)=0", passed)
call expect (s_ff(c_one, u(m, p, -1), u(m, p, -1)), 0, "vbar(-)*u(-)=0", passed)
print *, "*** Checking the normalization for negative masses***:"
call expect (s_ff(c_one, v(-m, p, +1), u(-m, p, +1)), -2*m, "ubar(+)*u(+)=+2m", passed)
call expect (s_ff(c_one, v(-m, p, -1), u(-m, p, -1)), -2*m, "ubar(-)*u(-)=+2m", passed)
call expect (s_ff(c_one, u(-m, p, +1), v(-m, p, +1)), +2*m, "vbar(+)*v(+)=+2m", passed)
call expect (s_ff(c_one, u(-m, p, -1), v(-m, p, -1)), +2*m, "vbar(-)*v(-)=+2m", passed)
call expect (s_ff(c_one, v(-m, p, +1), v(-m, p, +1)), 0, "ubar(+)*v(+)=0", passed)
call expect (s_ff(c_one, v(-m, p, -1), v(-m, p, -1)), 0, "ubar(-)*v(-)=0", passed)
call expect (s_ff(c_one, u(-m, p, +1), u(-m, p, +1)), 0, "vbar(+)*u(+)=0", passed)
call expect (s_ff(c_one, u(-m, p, -1), u(-m, p, -1)), 0, "vbar(-)*u(-)=0", passed)

<Test omega95_bispinors>+≡
print *, "*** Checking the currents ***:"
call expect (abs(v_ff(c_one, v(m, p, +1), u(m, p, +1)) - 2*vp), 0, "ubar(+).V.u(+)=2p", passed)
call expect (abs(v_ff(c_one, v(m, p, -1), u(m, p, -1)) - 2*vp), 0, "ubar(-).V.u(-)=2p", passed)
call expect (abs(v_ff(c_one, u(m, p, +1), v(m, p, +1)) - 2*vp), 0, "vbar(+).V.v(+)=2p", passed)
call expect (abs(v_ff(c_one, u(m, p, -1), v(m, p, -1)) - 2*vp), 0, "vbar(-).V.v(-)=2p", passed)
print *, "*** Checking the currents for negative masses***:"
call expect (abs(v_ff(c_one, v(-m, p, +1), u(-m, p, +1)) - 2*vp), 0, "ubar(+).V.u(+)=2p", passed)
call expect (abs(v_ff(c_one, v(-m, p, -1), u(-m, p, -1)) - 2*vp), 0, "ubar(-).V.u(-)=2p", passed)
call expect (abs(v_ff(c_one, u(-m, p, +1), v(-m, p, +1)) - 2*vp), 0, "vbar(+).V.v(+)=2p", passed)
call expect (abs(v_ff(c_one, u(-m, p, -1), v(-m, p, -1)) - 2*vp), 0, "vbar(-).V.v(-)=2p", passed)

<Test omega95_bispinors>+≡
print *, "*** Checking current conservation ***:"
call expect ((vp-vq)*v_ff(c_one, v(m, p, +1), u(m, q, +1)), 0, "d(ubar(+).V.u(+))=0", passed)
call expect ((vp-vq)*v_ff(c_one, v(m, p, -1), u(m, q, -1)), 0, "d(ubar(-).V.u(-))=0", passed)
call expect ((vp-vq)*v_ff(c_one, u(m, p, +1), v(m, q, +1)), 0, "d(vbar(+).V.v(+))=0", passed)
call expect ((vp-vq)*v_ff(c_one, u(m, p, -1), v(m, q, -1)), 0, "d(vbar(-).V.v(-))=0", passed)

<Test omega95_bispinors>+≡
print *, "*** Checking current conservation for negative masses***:"
call expect ((vp-vq)*v_ff(c_one, v(-m, p, +1), u(-m, q, +1)), 0, "d(ubar(+).V.u(+))=0", passed)
call expect ((vp-vq)*v_ff(c_one, v(-m, p, -1), u(-m, q, -1)), 0, "d(ubar(-).V.u(-))=0", passed)
call expect ((vp-vq)*v_ff(c_one, u(-m, p, +1), v(-m, q, +1)), 0, "d(vbar(+).V.v(+))=0", passed)
call expect ((vp-vq)*v_ff(c_one, u(-m, p, -1), v(-m, q, -1)), 0, "d(vbar(-).V.v(-))=0", passed)

<Test omega95_bispinors>+≡
if (m == 0) then
  print *, "*** Checking axial current conservation ***:"
  call expect ((vp-vq)*a_ff(c_one, v(m, p, +1), u(m, q, +1)), 0, "d(ubar(+).A.u(+))=0", passed)
  call expect ((vp-vq)*a_ff(c_one, v(m, p, -1), u(m, q, -1)), 0, "d(ubar(-).A.u(-))=0", passed)
  call expect ((vp-vq)*a_ff(c_one, u(m, p, +1), v(m, q, +1)), 0, "d(vbar(+).A.v(+))=0", passed)
  call expect ((vp-vq)*a_ff(c_one, u(m, p, -1), v(m, q, -1)), 0, "d(vbar(-).A.v(-))=0", passed)

```

```

end if

<Test omega95_bispinors>+≡
print *, "*** Checking polarization vectors: ***"
call expect (conjg(eps(m,p, 1))*eps(m,p, 1), -1, "e( 1).e( 1)=-1", passed)
call expect (conjg(eps(m,p, 1))*eps(m,p,-1), 0, "e( 1).e(-1)= 0", passed)
call expect (conjg(eps(m,p,-1))*eps(m,p, 1), 0, "e(-1).e( 1)= 0", passed)
call expect (conjg(eps(m,p,-1))*eps(m,p,-1), -1, "e(-1).e(-1)=-1", passed)
call expect (p*eps(m,p, 1), 0, "p.e( 1)= 0", passed)
call expect (p*eps(m,p,-1), 0, "p.e(-1)= 0", passed)
if (m > 0) then
  call expect (conjg(eps(m,p, 1))*eps(m,p, 0), 0, "e( 1).e( 0)= 0", passed)
  call expect (conjg(eps(m,p, 0))*eps(m,p, 1), 0, "e( 0).e( 1)= 0", passed)
  call expect (conjg(eps(m,p, 0))*eps(m,p, 0), -1, "e( 0).e( 0)=-1", passed)
  call expect (conjg(eps(m,p, 0))*eps(m,p,-1), 0, "e( 0).e(-1)= 0", passed)
  call expect (conjg(eps(m,p,-1))*eps(m,p, 0), 0, "e(-1).e( 0)= 0", passed)
  call expect (p*eps(m,p, 0), 0, "p.e( 0)= 0", passed)
end if

<Test omega95_bispinors>+≡
print *, "*** Checking polarization vectorspinors: ***"
call expect (abs(p * ueps(m, p, 2)), 0, "p.ueps ( 2)= 0", passed)
call expect (abs(p * ueps(m, p, 1)), 0, "p.ueps ( 1)= 0", passed)
call expect (abs(p * ueps(m, p, -1)), 0, "p.ueps (-1)= 0", passed)
call expect (abs(p * ueps(m, p, -2)), 0, "p.ueps (-2)= 0", passed)
call expect (abs(p * veps(m, p, 2)), 0, "p.veps ( 2)= 0", passed)
call expect (abs(p * veps(m, p, 1)), 0, "p.veps ( 1)= 0", passed)
call expect (abs(p * veps(m, p, -1)), 0, "p.veps (-1)= 0", passed)
call expect (abs(p * veps(m, p, -2)), 0, "p.veps (-2)= 0", passed)
print *, "*** Checking polarization vectorspinors (neg. masses): ***"
call expect (abs(p * ueps(-m, p, 2)), 0, "p.ueps ( 2)= 0", passed)
call expect (abs(p * ueps(-m, p, 1)), 0, "p.ueps ( 1)= 0", passed)
call expect (abs(p * ueps(-m, p, -1)), 0, "p.ueps (-1)= 0", passed)
call expect (abs(p * ueps(-m, p, -2)), 0, "p.ueps (-2)= 0", passed)
call expect (abs(p * veps(-m, p, 2)), 0, "p.veps ( 2)= 0", passed)
call expect (abs(p * veps(-m, p, 1)), 0, "p.veps ( 1)= 0", passed)
call expect (abs(p * veps(-m, p, -1)), 0, "p.veps (-1)= 0", passed)
call expect (abs(p * veps(-m, p, -2)), 0, "p.veps (-2)= 0", passed)
print *, "*** in the rest frame ***"
call expect (abs(p_0 * ueps(m, p_0, 2)), 0, "p0.ueps ( 2)= 0", passed)
call expect (abs(p_0 * ueps(m, p_0, 1)), 0, "p0.ueps ( 1)= 0", passed)
call expect (abs(p_0 * ueps(m, p_0, -1)), 0, "p0.ueps (-1)= 0", passed)
call expect (abs(p_0 * ueps(m, p_0, -2)), 0, "p0.ueps (-2)= 0", passed)
call expect (abs(p_0 * veps(m, p_0, 2)), 0, "p0.veps ( 2)= 0", passed)
call expect (abs(p_0 * veps(m, p_0, 1)), 0, "p0.veps ( 1)= 0", passed)
call expect (abs(p_0 * veps(m, p_0, -1)), 0, "p0.veps (-1)= 0", passed)
call expect (abs(p_0 * veps(m, p_0, -2)), 0, "p0.veps (-2)= 0", passed)
print *, "*** in the rest frame (neg. masses) ***"
call expect (abs(p_0 * ueps(-m, p_0, 2)), 0, "p0.ueps ( 2)= 0", passed)
call expect (abs(p_0 * ueps(-m, p_0, 1)), 0, "p0.ueps ( 1)= 0", passed)
call expect (abs(p_0 * ueps(-m, p_0, -1)), 0, "p0.ueps (-1)= 0", passed)
call expect (abs(p_0 * ueps(-m, p_0, -2)), 0, "p0.ueps (-2)= 0", passed)
call expect (abs(p_0 * veps(-m, p_0, 2)), 0, "p0.veps ( 2)= 0", passed)
call expect (abs(p_0 * veps(-m, p_0, 1)), 0, "p0.veps ( 1)= 0", passed)
call expect (abs(p_0 * veps(-m, p_0, -1)), 0, "p0.veps (-1)= 0", passed)

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call expect (abs(p_0 * veps(-m, p_0, -2)), 0, "p0.veps (-2)= 0", passed)

<Test omega95_bispinors>+≡
print *, "*** Checking the irreducibility condition: ***"
call expect (abs(f_potgr (c_one, c_one, ueps(m, p, 2))), 0, "g.ueps ( 2)", passed)
call expect (abs(f_potgr (c_one, c_one, ueps(m, p, 1))), 0, "g.ueps ( 1)", passed)
call expect (abs(f_potgr (c_one, c_one, ueps(m, p, -1))), 0, "g.ueps (-1)", passed)
call expect (abs(f_potgr (c_one, c_one, ueps(m, p, -2))), 0, "g.ueps (-2)", passed)
call expect (abs(f_potgr (c_one, c_one, veps(m, p, 2))), 0, "g.veps ( 2)", passed)
call expect (abs(f_potgr (c_one, c_one, veps(m, p, 1))), 0, "g.veps ( 1)", passed)
call expect (abs(f_potgr (c_one, c_one, veps(m, p, -1))), 0, "g.veps (-1)", passed)
call expect (abs(f_potgr (c_one, c_one, veps(m, p, -2))), 0, "g.veps (-2)", passed)
print *, "*** Checking the irreducibility condition (neg. masses): ***"
call expect (abs(f_potgr (c_one, c_one, ueps(-m, p, 2))), 0, "g.ueps ( 2)", passed)
call expect (abs(f_potgr (c_one, c_one, ueps(-m, p, 1))), 0, "g.ueps ( 1)", passed)
call expect (abs(f_potgr (c_one, c_one, ueps(-m, p, -1))), 0, "g.ueps (-1)", passed)
call expect (abs(f_potgr (c_one, c_one, ueps(-m, p, -2))), 0, "g.ueps (-2)", passed)
call expect (abs(f_potgr (c_one, c_one, veps(-m, p, 2))), 0, "g.veps ( 2)", passed)
call expect (abs(f_potgr (c_one, c_one, veps(-m, p, 1))), 0, "g.veps ( 1)", passed)
call expect (abs(f_potgr (c_one, c_one, veps(-m, p, -1))), 0, "g.veps (-1)", passed)
call expect (abs(f_potgr (c_one, c_one, veps(-m, p, -2))), 0, "g.veps (-2)", passed)
print *, "*** in the rest frame ***"
call expect (abs(f_potgr (c_one, c_one, ueps(m, p_0, 2))), 0, "g.ueps ( 2)", passed)
call expect (abs(f_potgr (c_one, c_one, ueps(m, p_0, 1))), 0, "g.ueps ( 1)", passed)
call expect (abs(f_potgr (c_one, c_one, ueps(m, p_0, -1))), 0, "g.ueps (-1)", passed)
call expect (abs(f_potgr (c_one, c_one, ueps(m, p_0, -2))), 0, "g.ueps (-2)", passed)
call expect (abs(f_potgr (c_one, c_one, veps(m, p_0, 2))), 0, "g.veps ( 2)", passed)
call expect (abs(f_potgr (c_one, c_one, veps(m, p_0, 1))), 0, "g.veps ( 1)", passed)
call expect (abs(f_potgr (c_one, c_one, veps(m, p_0, -1))), 0, "g.veps (-1)", passed)
call expect (abs(f_potgr (c_one, c_one, veps(m, p_0, -2))), 0, "g.veps (-2)", passed)
print *, "*** in the rest frame (neg. masses) ***"
call expect (abs(f_potgr (c_one, c_one, ueps(m, p_0, 2))), 0, "g.ueps ( 2)", passed)
call expect (abs(f_potgr (c_one, c_one, ueps(m, p_0, 1))), 0, "g.ueps ( 1)", passed)
call expect (abs(f_potgr (c_one, c_one, ueps(m, p_0, -1))), 0, "g.ueps (-1)", passed)
call expect (abs(f_potgr (c_one, c_one, ueps(m, p_0, -2))), 0, "g.ueps (-2)", passed)
call expect (abs(f_potgr (c_one, c_one, veps(m, p_0, 2))), 0, "g.veps ( 2)", passed)
call expect (abs(f_potgr (c_one, c_one, veps(m, p_0, 1))), 0, "g.veps ( 1)", passed)
call expect (abs(f_potgr (c_one, c_one, veps(m, p_0, -1))), 0, "g.veps (-1)", passed)
call expect (abs(f_potgr (c_one, c_one, veps(m, p_0, -2))), 0, "g.veps (-2)", passed)

<Test omega95_bispinors>+≡
print *, "*** Testing vectorspinor normalization ***"
call expect (veps(m,p, 2)*ueps(m,p, 2), -2*m, "ueps( 2).ueps( 2)= -2m", passed)
call expect (veps(m,p, 1)*ueps(m,p, 1), -2*m, "ueps( 1).ueps( 1)= -2m", passed)
call expect (veps(m,p,-1)*ueps(m,p,-1), -2*m, "ueps(-1).ueps(-1)= -2m", passed)
call expect (veps(m,p,-2)*ueps(m,p,-2), -2*m, "ueps(-2).ueps(-2)= -2m", passed)
call expect (ueps(m,p, 2)*veps(m,p, 2), 2*m, "veps( 2).veps( 2)= +2m", passed)
call expect (ueps(m,p, 1)*veps(m,p, 1), 2*m, "veps( 1).veps( 1)= +2m", passed)
call expect (ueps(m,p,-1)*veps(m,p,-1), 2*m, "veps(-1).veps(-1)= +2m", passed)
call expect (ueps(m,p,-2)*veps(m,p,-2), 2*m, "veps(-2).veps(-2)= +2m", passed)
call expect (ueps(m,p, 2)*ueps(m,p, 2), 0, "ueps( 2).veps( 2)= 0", passed)
call expect (ueps(m,p, 1)*ueps(m,p, 1), 0, "ueps( 1).veps( 1)= 0", passed)
call expect (ueps(m,p,-1)*ueps(m,p,-1), 0, "ueps(-1).veps(-1)= 0", passed)
call expect (ueps(m,p,-2)*ueps(m,p,-2), 0, "ueps(-2).veps(-2)= 0", passed)
call expect (veps(m,p, 2)*veps(m,p, 2), 0, "veps( 2).ueps( 2)= 0", passed)

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call expect (veps(m,p, 1)*veps(m,p, 1), 0, "veps( 1).ueps( 1)= 0", passed)
call expect (veps(m,p,-1)*veps(m,p,-1), 0, "veps(-1).ueps(-1)= 0", passed)
call expect (veps(m,p,-2)*veps(m,p,-2), 0, "veps(-2).ueps(-2)= 0", passed)
print *, "*** Testing vectorspinor normalization (neg. masses) ***"
call expect (veps(-m,p, 2)*ueps(-m,p, 2), +2*m, "ueps( 2).ueps( 2)= +2m", passed)
call expect (veps(-m,p, 1)*ueps(-m,p, 1), +2*m, "ueps( 1).ueps( 1)= +2m", passed)
call expect (veps(-m,p,-1)*ueps(-m,p,-1), +2*m, "ueps(-1).ueps(-1)= +2m", passed)
call expect (veps(-m,p,-2)*ueps(-m,p,-2), +2*m, "ueps(-2).ueps(-2)= +2m", passed)
call expect (ueps(-m,p, 2)*veps(-m,p, 2), -2*m, "veps( 2).veps( 2)= -2m", passed)
call expect (ueps(-m,p, 1)*veps(-m,p, 1), -2*m, "veps( 1).veps( 1)= -2m", passed)
call expect (ueps(-m,p,-1)*veps(-m,p,-1), -2*m, "veps(-1).veps(-1)= -2m", passed)
call expect (ueps(-m,p,-2)*veps(-m,p,-2), -2*m, "veps(-2).veps(-2)= -2m", passed)
call expect (ueps(-m,p, 2)*ueps(-m,p, 2), 0, "ueps( 2).veps( 2)= 0", passed)
call expect (ueps(-m,p, 1)*ueps(-m,p, 1), 0, "ueps( 1).veps( 1)= 0", passed)
call expect (ueps(-m,p,-1)*ueps(-m,p,-1), 0, "ueps(-1).veps(-1)= 0", passed)
call expect (ueps(-m,p,-2)*ueps(-m,p,-2), 0, "ueps(-2).veps(-2)= 0", passed)
call expect (veps(-m,p, 2)*veps(-m,p, 2), 0, "veps( 2).ueps( 2)= 0", passed)
call expect (veps(-m,p, 1)*veps(-m,p, 1), 0, "veps( 1).ueps( 1)= 0", passed)
call expect (veps(-m,p,-1)*veps(-m,p,-1), 0, "veps(-1).ueps(-1)= 0", passed)
call expect (veps(-m,p,-2)*veps(-m,p,-2), 0, "veps(-2).ueps(-2)= 0", passed)
print *, "*** in the rest frame ***"
call expect (veps(m,p_0, 2)*ueps(m,p_0, 2), -2*m, "ueps( 2).ueps( 2)= -2m", passed)
call expect (veps(m,p_0, 1)*ueps(m,p_0, 1), -2*m, "ueps( 1).ueps( 1)= -2m", passed)
call expect (veps(m,p_0,-1)*ueps(m,p_0,-1), -2*m, "ueps(-1).ueps(-1)= -2m", passed)
call expect (veps(m,p_0,-2)*ueps(m,p_0,-2), -2*m, "ueps(-2).ueps(-2)= -2m", passed)
call expect (ueps(m,p_0, 2)*veps(m,p_0, 2), 2*m, "veps( 2).veps( 2)= +2m", passed)
call expect (ueps(m,p_0, 1)*veps(m,p_0, 1), 2*m, "veps( 1).veps( 1)= +2m", passed)
call expect (ueps(m,p_0,-1)*veps(m,p_0,-1), 2*m, "veps(-1).veps(-1)= +2m", passed)
call expect (ueps(m,p_0,-2)*veps(m,p_0,-2), 2*m, "veps(-2).veps(-2)= +2m", passed)
call expect (ueps(m,p_0, 2)*ueps(m,p_0, 2), 0, "ueps( 2).veps( 2)= 0", passed)
call expect (ueps(m,p_0, 1)*ueps(m,p_0, 1), 0, "ueps( 1).veps( 1)= 0", passed)
call expect (ueps(m,p_0,-1)*ueps(m,p_0,-1), 0, "ueps(-1).veps(-1)= 0", passed)
call expect (ueps(m,p_0,-2)*ueps(m,p_0,-2), 0, "ueps(-2).veps(-2)= 0", passed)
call expect (veps(m,p_0, 2)*veps(m,p_0, 2), 0, "veps( 2).ueps( 2)= 0", passed)
call expect (veps(m,p_0, 1)*veps(m,p_0, 1), 0, "veps( 1).ueps( 1)= 0", passed)
call expect (veps(m,p_0,-1)*veps(m,p_0,-1), 0, "veps(-1).ueps(-1)= 0", passed)
call expect (veps(m,p_0,-2)*veps(m,p_0,-2), 0, "veps(-2).ueps(-2)= 0", passed)
print *, "*** in the rest frame (neg. masses) ***"
call expect (veps(-m,p_0, 2)*ueps(-m,p_0, 2), +2*m, "ueps( 2).ueps( 2)= +2m", passed)
call expect (veps(-m,p_0, 1)*ueps(-m,p_0, 1), +2*m, "ueps( 1).ueps( 1)= +2m", passed)
call expect (veps(-m,p_0,-1)*ueps(-m,p_0,-1), +2*m, "ueps(-1).ueps(-1)= +2m", passed)
call expect (veps(-m,p_0,-2)*ueps(-m,p_0,-2), +2*m, "ueps(-2).ueps(-2)= +2m", passed)
call expect (ueps(-m,p_0, 2)*veps(-m,p_0, 2), -2*m, "veps( 2).veps( 2)= -2m", passed)
call expect (ueps(-m,p_0, 1)*veps(-m,p_0, 1), -2*m, "veps( 1).veps( 1)= -2m", passed)
call expect (ueps(-m,p_0,-1)*veps(-m,p_0,-1), -2*m, "veps(-1).veps(-1)= -2m", passed)
call expect (ueps(-m,p_0,-2)*veps(-m,p_0,-2), -2*m, "veps(-2).veps(-2)= -2m", passed)
call expect (ueps(-m,p_0, 2)*ueps(-m,p_0, 2), 0, "ueps( 2).veps( 2)= 0", passed)
call expect (ueps(-m,p_0, 1)*ueps(-m,p_0, 1), 0, "ueps( 1).veps( 1)= 0", passed)
call expect (ueps(-m,p_0,-1)*ueps(-m,p_0,-1), 0, "ueps(-1).veps(-1)= 0", passed)
call expect (ueps(-m,p_0,-2)*ueps(-m,p_0,-2), 0, "ueps(-2).veps(-2)= 0", passed)
call expect (veps(-m,p_0, 2)*veps(-m,p_0, 2), 0, "veps( 2).ueps( 2)= 0", passed)
call expect (veps(-m,p_0, 1)*veps(-m,p_0, 1), 0, "veps( 1).ueps( 1)= 0", passed)
call expect (veps(-m,p_0,-1)*veps(-m,p_0,-1), 0, "veps(-1).ueps(-1)= 0", passed)
call expect (veps(-m,p_0,-2)*veps(-m,p_0,-2), 0, "veps(-2).ueps(-2)= 0", passed)

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<Test omega95_bispinors>+=
print *, "*** Majorana properties of gravitino vertices: ***"
call expect (abs(u (m,q,1) * f_sgr (c_one, c_one, ueps(m,p,2), t) + &
    ueps(m,p,2) * gr_sf(c_one,c_one,u(m,q,1),t))), 0, "f_sgr + gr_sf = 0", passed)
!!! call expect (abs(u (m,q,-1) * f_sgr (c_one, c_one, ueps(m,p,2), t) + &
    ueps(m,p,2) * gr_sf(c_one,c_one,u(m,q,-1),t))), 0, "f_sgr + gr_sf = 0", passed)
!!! call expect (abs(u (m,q,1) * f_sgr (c_one, c_one, ueps(m,p,1), t) + &
    ueps(m,p,1) * gr_sf(c_one,c_one,u(m,q,1),t))), 0, "f_sgr + gr_sf = 0", passed)
!!! call expect (abs(u (m,q,-1) * f_sgr (c_one, c_one, ueps(m,p,1), t) + &
    ueps(m,p,1) * gr_sf(c_one,c_one,u(m,q,-1),t))), 0, "f_sgr + gr_sf = 0", passed)
!!! call expect (abs(u (m,q,1) * f_sgr (c_one, c_one, ueps(m,p,-1), t) + &
    ueps(m,p,-1) * gr_sf(c_one,c_one,u(m,q,1),t))), 0, "f_sgr + gr_sf = 0", passed)
!!! call expect (abs(u (m,q,-1) * f_sgr (c_one, c_one, ueps(m,p,-1), t) + &
    ueps(m,p,-1) * gr_sf(c_one,c_one,u(m,q,-1),t))), 0, "f_sgr + gr_sf = 0", passed)
!!! call expect (abs(u (m,q,1) * f_sgr (c_one, c_one, ueps(m,p,-2), t) + &
    ueps(m,p,-2) * gr_sf(c_one,c_one,u(m,q,1),t))), 0, "f_sgr + gr_sf = 0", passed)
!!! call expect (abs(u (m,q,-1) * f_sgr (c_one, c_one, ueps(m,p,-2), t) + &
    ueps(m,p,-2) * gr_sf(c_one,c_one,u(m,q,-1),t))), 0, "f_sgr + gr_sf = 0", passed)
call expect (abs(u (m,q,1) * f_slgr (c_one, c_one, ueps(m,p,2), t) + &
    ueps(m,p,2) * gr_slf(c_one,c_one,u(m,q,1),t))), 0, "f_slgr + gr_slf = 0", passed)
call expect (abs(u (m,q,1) * f_srgr (c_one, c_one, ueps(m,p,2), t) + &
    ueps(m,p,2) * gr_srf(c_one,c_one,u(m,q,1),t))), 0, "f_srgr + gr_srf = 0", passed)
call expect (abs(u (m,q,1) * f_slrgr (c_one, c_two, c_one, ueps(m,p,2), t) + &
    ueps(m,p,2) * gr_slrf(c_one,c_two,c_one,u(m,q,1),t))), 0, "f_slrgr + gr_slrf = 0", passed)
call expect (abs(u (m,q,1) * f_pgr (c_one, c_one, ueps(m,p,2), t) + &
    ueps(m,p,2) * gr_pf(c_one,c_one,u(m,q,1),t))), 0, "f_pgr + gr_pf = 0", passed)
call expect (abs(u (m,q,1) * f_vgr (c_one, vt, ueps(m,p,2), p+q) + &
    ueps(m,p,2) * gr_vf(c_one,vt,u(m,q,1),p+q))), 0, "f_vgr + gr_vf = 0", passed)
call expect (abs(u (m,q,1) * f_vlrgr (c_one, c_two, vt, ueps(m,p,2), p+q) + &
    ueps(m,p,2) * gr_vlrf(c_one,c_two,vt,u(m,q,1),p+q))), 0, "f_vlrgr + gr_vlrf = 0", &
    passed, threshold = 0.5_default)
!!! call expect (abs(u (m,q,-1) * f_vgr (c_one, vt, ueps(m,p,2), p+q) + &
    ueps(m,p,2) * gr_vf(c_one,vt,u(m,q,-1),p+q))), 0, "f_vgr + gr_vf = 0", passed)
!!! call expect (abs(u (m,q,1) * f_vgr (c_one, vt, ueps(m,p,1), p+q) + &
    ueps(m,p,1) * gr_vf(c_one,vt,u(m,q,1),p+q))), 0, "f_vgr + gr_vf = 0", passed)
!!! call expect (abs(u (m,q,-1) * f_vgr (c_one, vt, ueps(m,p,1), p+q) + &
    ueps(m,p,1) * gr_vf(c_one,vt,u(m,q,-1),p+q))), 0, "f_vgr + gr_vf = 0", passed)
!!! call expect (abs(u (m,q,1) * f_vgr (c_one, vt, ueps(m,p,-1), p+q) + &
    ueps(m,p,-1) * gr_vf(c_one,vt,u(m,q,1),p+q))), 0, "f_vgr + gr_vf = 0", passed)
!!! call expect (abs(u (m,q,-1) * f_vgr (c_one, vt, ueps(m,p,-1), p+q) + &
    ueps(m,p,-1) * gr_vf(c_one,vt,u(m,q,-1),p+q))), 0, "f_vgr + gr_vf = 0", passed)
!!! call expect (abs(v (m,q,1) * f_vgr (c_one, vt, ueps(m,p,-2), p+q) + &
    ueps(m,p,-2) * gr_vf(c_one,vt,u(m,q,1),p+q))), 0, "f_vgr + gr_vf = 0", passed)
!!! call expect (abs(u (m,q,-1) * f_vgr (c_one, vt, ueps(m,p,-2), p+q) + &
    ueps(m,p,-2) * gr_vf(c_one,vt,u(m,q,-1),p+q))), 0, "f_vgr + gr_vf = 0", passed)
call expect (abs(s_grf (c_one, ueps(m,p,2), u(m,q,1),t) + &
    s_fgr(c_one,u(m,q,1),ueps(m,p,2),t))), 0, "s_grf + s_fgr = 0", passed)
call expect (abs(sl_grf (c_one, ueps(m,p,2), u(m,q,1),t) + &
    sl_fgr(c_one,u(m,q,1),ueps(m,p,2),t))), 0, "sl_grf + sl_fgr = 0", passed)
call expect (abs(sr_grf (c_one, ueps(m,p,2), u(m,q,1),t) + &
    sr_fgr(c_one,u(m,q,1),ueps(m,p,2),t))), 0, "sr_grf + sr_fgr = 0", passed)
call expect (abs(slr_grf (c_one, c_two, ueps(m,p,2), u(m,q,1),t) + &
    slr_fgr(c_one,c_two,u(m,q,1),ueps(m,p,2),t))), 0, "slr_grf + slr_fgr = 0", passed)
call expect (abs(p_grf (c_one, ueps(m,p,2), u(m,q,1),t) + &

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    p_fgr(c_one,u(m,q,1),ueps(m,p,2),t)), 0, "p_grf + p_fgr = 0", passed)
call expect (abs(v_grf (c_one, ueps(m,p,2), u(m,q,1),t) + &
    v_fgr(c_one,u(m,q,1),ueps(m,p,2),t)), 0, "v_grf + v_fgr = 0", passed)
call expect (abs(vlr_grf (c_one, c_two, ueps(m,p,2), u(m,q,1),t) + &
    vlr_fgr(c_one,c_two,u(m,q,1),ueps(m,p,2),t)), 0, "vlr_grf + vlr_fgr = 0", passed)
call expect (abs(u(m,p,1) * f_potgr (c_one,c_one,testv) - testv * gr_potf &
    (c_one,c_one,u (m,p,1))), 0, "f_potgr - gr_potf = 0", passed)
call expect (abs (pot_fgr (c_one,u(m,p,1),testv) - pot_grf(c_one, &
    testv,u(m,p,1))), 0, "pot_fgr - pot_grf = 0", passed)
call expect (abs(u(m,p,1) * f_s2gr (c_one,c_one,c_one,testv) - testv * gr_s2f &
    (c_one,c_one,c_one,u (m,p,1))), 0, "f_s2gr - gr_s2f = 0", passed)
call expect (abs (s2_fgr (c_one,u(m,p,1),c_one,testv) - s2_grf(c_one, &
    testv,c_one,u(m,p,1))), 0, "s2_fgr - s2_grf = 0", passed)
call expect (abs(u (m,q,1) * f_svgr (c_one, c_one, vt, ueps(m,p,2)) + &
    ueps(m,p,2) * gr_svgr(c_one,c_one,vt,u(m,q,1))), 0, "f_svgr + gr_svgr = 0", passed)
call expect (abs(u (m,q,1) * f_slvgr (c_one, c_one, vt, ueps(m,p,2)) + &
    ueps(m,p,2) * gr_slvgr(c_one,c_one,vt,u(m,q,1))), 0, "f_slvgr + gr_slvgr = 0", passed)
call expect (abs(u (m,q,1) * f_srvgr (c_one, c_one, vt, ueps(m,p,2)) + &
    ueps(m,p,2) * gr_srvgr(c_one,c_one,vt,u(m,q,1))), 0, "f_srvgr + gr_srvgr = 0", passed)
call expect (abs(u (m,q,1) * f_slrvgr (c_one, c_two, c_one, vt, ueps(m,p,2)) + &
    ueps(m,p,2) * gr_slrvgr(c_one,c_two,c_one,vt,u(m,q,1))), 0, "f_slrvgr + gr_slrvgr = 0", passed)
call expect (abs (sv1_fgr (c_one,u(m,p,1),vt,ueps(m,q,2)) + sv1_grf(c_one, &
    ueps(m,q,2),vt,u(m,p,1))), 0, "sv1_fgr + sv1_grf = 0", passed)
call expect (abs (sv2_fgr (c_one,u(m,p,1),c_one,ueps(m,q,2)) + sv2_grf(c_one, &
    ueps(m,q,2),c_one,u(m,p,1))), 0, "sv2_fgr + sv2_grf = 0", passed)
call expect (abs (slv1_fgr (c_one,u(m,p,1),vt,ueps(m,q,2)) + slv1_grf(c_one, &
    ueps(m,q,2),vt,u(m,p,1))), 0, "slv1_fgr + slv1_grf = 0", passed)
call expect (abs (srv2_fgr (c_one,u(m,p,1),c_one,ueps(m,q,2)) + srv2_grf(c_one, &
    ueps(m,q,2),c_one,u(m,p,1))), 0, "srv2_fgr + srv2_grf = 0", passed)
call expect (abs (slrv1_fgr (c_one,c_two,u(m,p,1),vt,ueps(m,q,2)) + slrv1_grf(c_one,c_two, &
    ueps(m,q,2),vt,u(m,p,1))), 0, "slrv1_fgr + slrv1_grf = 0", passed)
call expect (abs (slrv2_fgr (c_one,c_two,u(m,p,1),c_one,ueps(m,q,2)) + slrv2_grf(c_one, &
    c_two,ueps(m,q,2),c_one,u(m,p,1))), 0, "slrv2_fgr + slrv2_grf = 0", passed)
call expect (abs(u (m,q,1) * f_pvgr (c_one, c_one, vt, ueps(m,p,2)) + &
    ueps(m,p,2) * gr_pvgr(c_one,c_one,vt,u(m,q,1))), 0, "f_pvgr + gr_pvgr = 0", passed)
call expect (abs (pv1_fgr (c_one,u(m,p,1),vt,ueps(m,q,2)) + pv1_grf(c_one, &
    ueps(m,q,2),vt,u(m,p,1))), 0, "pv1_fgr + pv1_grf = 0", passed)
call expect (abs (pv2_fgr (c_one,u(m,p,1),c_one,ueps(m,q,2)) + pv2_grf(c_one, &
    ueps(m,q,2),c_one,u(m,p,1))), 0, "pv2_fgr + pv2_grf = 0", passed)
call expect (abs(u (m,q,1) * f_v2gr (c_one, vt, vz, ueps(m,p,2)) + &
    ueps(m,p,2) * gr_v2gr(c_one,vt,vz,u(m,q,1))), 0, "f_v2gr + gr_v2gr = 0", passed)
call expect (abs(u (m,q,1) * f_v2lrgr (c_one, c_two, vt, vz, ueps(m,p,2)) + &
    ueps(m,p,2) * gr_v2lrgr(c_one,c_two,vt,vz,u(m,q,1))), 0, "f_v2lrgr + gr_v2lrgr = 0", passed)
call expect (abs (v2_fgr (c_one,u(m,p,1),vt,ueps(m,q,2)) + v2_grf(c_one, &
    ueps(m,q,2),vt,u(m,p,1))), 0, "v2_fgr + v2_grf = 0", passed)
call expect (abs (v2lr_fgr (c_one,c_two,u(m,p,1),vt,ueps(m,q,2)) + v2lr_grf(c_one, c_two, &
    ueps(m,q,2),vt,u(m,p,1))), 0, "v2lr_fgr + v2lr_grf = 0", passed)

<Test omega95_bispinors)+≡
print *, "*** Testing the gravitino propagator: ***"
print *, "Transversality:"
call expect (abs(p * (cmplx (p*p - m**2, m*w, kind=default) * &
    pr_grav(p,m,w,testv))), 0, "p.pr.test", passed)
call expect (abs(p * (cmplx (p*p - m**2, m*w, kind=default) * &
    pr_grav(p,m,w,ueps(m,p,2)))), 0, "p.pr.ueps ( 2)", passed)

```

---

```

call expect (abs(p * (cmplx (p*p - m**2, m*w, kind=default) * &
    pr_grav(p,m,w,ueps(m,p,1)))), 0, "p.pr.ueps ( 1)", passed)
call expect (abs(p * (cmplx (p*p - m**2, m*w, kind=default) * &
    pr_grav(p,m,w,ueps(m,p,-1)))), 0, "p.pr.ueps (-1)", passed)
call expect (abs(p * (cmplx (p*p - m**2, m*w, kind=default) * &
    pr_grav(p,m,w,ueps(m,p,-2)))), 0, "p.pr.ueps (-2)", passed)
call expect (abs(p * (cmplx (p*p - m**2, m*w, kind=default) * &
    pr_grav(p,m,w,veps(m,p,2)))), 0, "p.pr.veps ( 2)", passed)
call expect (abs(p * (cmplx (p*p - m**2, m*w, kind=default) * &
    pr_grav(p,m,w,veps(m,p,1)))), 0, "p.pr.veps ( 1)", passed)
call expect (abs(p * (cmplx (p*p - m**2, m*w, kind=default) * &
    pr_grav(p,m,w,veps(m,p,-1)))), 0, "p.pr.veps (-1)", passed)
call expect (abs(p * (cmplx (p*p - m**2, m*w, kind=default) * &
    pr_grav(p,m,w,veps(m,p,-2)))), 0, "p.pr.veps (-2)", passed)
print *, "Irreducibility:"
call expect (abs(f_potgr (c_one, c_one, (cmplx (p*p - m**2, m*w, &
    kind=default) * pr_grav(p,m,w,testv)))), 0, "g.pr.test", passed)
call expect (abs(f_potgr (c_one, c_one, (cmplx (p*p - m**2, m*w, &
    kind=default) * pr_grav(p,m,w,ueps(m,p,2))))), 0, &
    "g.pr.ueps ( 2)", passed)
call expect (abs(f_potgr (c_one, c_one, (cmplx (p*p - m**2, m*w, &
    kind=default) * pr_grav(p,m,w,ueps(m,p,1))))), 0, &
    "g.pr.ueps ( 1)", passed)
call expect (abs(f_potgr (c_one, c_one, (cmplx (p*p - m**2, m*w, &
    kind=default) * pr_grav(p,m,w,ueps(m,p,-1))))), 0, &
    "g.pr.ueps (-1)", passed)
call expect (abs(f_potgr (c_one, c_one, (cmplx (p*p - m**2, m*w, &
    kind=default) * pr_grav(p,m,w,ueps(m,p,-2))))), 0, &
    "g.pr.ueps (-2)", passed)
call expect (abs(f_potgr (c_one, c_one, (cmplx (p*p - m**2, m*w, &
    kind=default) * pr_grav(p,m,w,veps(m,p,2))))), 0, &
    "g.pr.veps ( 2)", passed)
call expect (abs(f_potgr (c_one, c_one, (cmplx (p*p - m**2, m*w, &
    kind=default) * pr_grav(p,m,w,veps(m,p,1))))), 0, &
    "g.pr.veps ( 1)", passed)
call expect (abs(f_potgr (c_one, c_one, (cmplx (p*p - m**2, m*w, &
    kind=default) * pr_grav(p,m,w,veps(m,p,-1))))), 0, &
    "g.pr.veps (-1)", passed)
call expect (abs(f_potgr (c_one, c_one, (cmplx (p*p - m**2, m*w, &
    kind=default) * pr_grav(p,m,w,veps(m,p,-2))))), 0, &
    "g.pr.veps (-2)", passed)

<omega_bundle.f90>≡
<omega_vectors.f90>
<omega_spinors.f90>
<omega_bispinors.f90>
<omega_vectorspinors.f90>
<omega_polarizations.f90>
<omega_tensors.f90>
<omega_tensor_polarizations.f90>
<omega_couplings.f90>
<omega_spinor_couplings.f90>
<omega_bispinor_couplings.f90>
<omega_vspinor_polarizations.f90>
<omega_utils.f90>

```



```

<omega95.f90>
<omega95_bispinors.f90>
<omega_parameters.f90>
<omega_parameters_madgraph.f90>
<omega_bundle_whizard.f90>≡
<omega_bundle.f90>
<omega_parameters_whizard.f90>

```

## X.21 O'Mega Virtual Machine

This module defines the O'Mega Virtual Machine (OVM) completely, whereby all environmental dependencies like masses, widths and couplings have to be given to the constructor `vm%init` at runtime.

Support for Majorana particles and vectorspinors is only partially, especially all fusions are missing. Maybe it would be easier to make an additional `omegavm95_bispinors` to avoid namespace issues. Non-type specific chunks could be reused

```

<omegavm95.f90>≡
<Copyleft>
module omevavm95
  use kinds, only: default
  use constants
  use iso_varying_string, string_t => varying_string
  use, intrinsic :: iso_fortran_env, only : input_unit, output_unit, error_unit
  use omega95
  use omega95_bispinors, only: bispinor, vectorspinor, veps, pr_grav
  use omega95_bispinors, only: bi_u => u
  use omega95_bispinors, only: bi_v => v
  use omega95_bispinors, only: bi_pr_psi => pr_psi
  use omega95_bispinors, only: operator (*), operator (+)
  use omega_color, only: ovm_color_sum, OCF => omega_color_factor
  implicit none
  private
  <Utilities Declarations>
  <OVM Data Declarations>
  <OVM Instructions>
contains
  <OVM Procedure Implementations>
  <Utilities Procedure Implementations>
end module omevavm95

```

This might not be the proper place but I don't know where to put it

```

<Utilities Declarations>≡
  integer, parameter, public :: stdin = input_unit
  integer, parameter, public :: stdout = output_unit
  integer, parameter, public :: stderr = error_unit
  integer, parameter :: MIN_UNIT = 11, MAX_UNIT = 99

<OVM Procedure Implementations>≡
  subroutine find_free_unit (u, iostat)
    integer, intent(out) :: u
    integer, intent(out), optional :: iostat
    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
      u = i
      if (present (iostat)) then
        iostat = 0
      end if
      return
    end if
  end if
end do
if (present (iostat)) then
  iostat = -1
end if
u = -1
end subroutine find_free_unit

```

These abstract data types would ideally be the interface to communicate quantum numbers between O'Mega and Whizard. This gives full flexibility to change the representation at any time

*(Utilities Declarations)*+≡

```

public :: color_t
type color_t
contains
  procedure :: write => color_write
end type color_t

public :: col_discrete
type, extends(color_t) :: col_discrete
  integer :: i
end type col_discrete

public :: flavor_t
type flavor_t
contains
  procedure :: write => flavor_write
end type flavor_t

public :: flv_discrete
type, extends(flavor_t) :: flv_discrete
  integer :: i
end type flv_discrete

public :: helicity_t
type :: helicity_t
contains
  procedure :: write => helicity_write
end type helicity_t

public :: hel_discrete
type, extends(helicity_t) :: hel_discrete

```

```

        integer :: i
    end type hel_discrete

    public :: hel_trigonometric
    type, extends(helicity_t) :: hel_trigonometric
        real :: theta
    end type hel_trigonometric

    public :: hel_exponential
    type, extends(helicity_t) :: hel_exponential
        real :: phi
    end type hel_exponential

    public :: hel_spherical
    type, extends(helicity_t) :: hel_spherical
        real :: theta, phi
    end type hel_spherical

    {Utilities Procedure Implementations}≡
    subroutine color_write (color, fh)
        class(color_t), intent(in) :: color
        integer, intent(in) :: fh
        select type(color)
        type is (col_discrete)
            write(fh, *) 'color_discrete%i' = ', color%i
        end select
    end subroutine color_write

    subroutine helicity_write (helicity, fh)
        class(helicity_t), intent(in) :: helicity
        integer, intent(in) :: fh
        select type(helicity)
        type is (hel_discrete)
            write(fh, *) 'helicity_discrete%i' = ', helicity%i
        type is (hel_trigonometric)
            write(fh, *) 'helicity_trigonometric%theta' = ', helicity%theta
        type is (hel_exponential)
            write(fh, *) 'helicity_exponential%phi' = ', helicity%phi
        type is (hel_spherical)
            write(fh, *) 'helicity_spherical%phi' = ', helicity%phi
            write(fh, *) 'helicity_spherical%theta' = ', helicity%theta
        end select
    end subroutine helicity_write

    subroutine flavor_write (flavor, fh)
        class(flavor_t), intent(in) :: flavor
        integer, intent(in) :: fh
        select type(flavor)
        type is (flv_discrete)
            write(fh, *) 'flavor_discrete%i' = ', flavor%i
        end select
    end subroutine flavor_write

```

### X.21.1 Memory Layout

Some internal parameters

```

(OVM Data Declarations)≡
  integer, parameter :: len_instructions = 8
  integer, parameter :: N_version_lines = 2
  ! Comment lines including the first header description line
  integer, parameter :: N_comments = 6
  ! Actual data lines plus intermediate description lines
  ! 'description \n 1 2 3 \n description \n 3 2 1' would count as 3
  integer, parameter :: N_header_lines = 5
  real(default), parameter, public :: N_ = three

```

This is the basic type of a VM

```

(OVM Data Declarations)+≡
  type :: basic_vm_t
    private
    logical :: verbose
    type(string_t) :: bytecode_file
    integer :: bytecode_fh, out_fh
    integer :: N_instructions, N_levels
    integer :: N_table_lines
    integer, dimension(:, :), allocatable :: instructions
    integer, dimension(:, :), allocatable :: levels
  end type

```

To allow for a lazy evaluation of amplitudes, we have to keep track whether a wave function has already been computed, to avoid multiple-computing that would arise when the bytecode has redundant fusions, which is necessary for flavor and color MC (and helicity MC when we use Weyl-van-der-Waerden-spinors)

```

(OVM Data Declarations)+≡
  type :: vm_scalar
    logical :: c
    complex(kind=default) :: v
  end type

  type :: vm_spinor
    logical :: c
    type(spinor) :: v
  end type

  type :: vm_conjspinor
    logical :: c
    type(conjspinor) :: v
  end type

  type :: vm_bispinor
    logical :: c
    type(bispinor) :: v
  end type

  type :: vm_vector

```

```

    logical :: c
    type(vector) :: v
end type

type :: vm_tensor_2
    logical :: c
    type(tensor) :: v
end type

type :: vm_tensor_1
    logical :: c
    type(tensor2odd) :: v
end type

type :: vm_vectorspinor
    logical :: c
    type(vectorspinor) :: v
end type

```

We need a memory pool for all the intermediate results

*(OVM Data Declarations)* +=

```

type, public, extends (basic_vm_t) :: vm_t
private
    type(string_t) :: version
    type(string_t) :: model
    integer :: N_momenta, N_particles, N_prt_in, N_prt_out, N_amplitudes
    ! helicities = helicity combinations
    integer :: N_helicities, N_col_flows, N_col_indices, N_flavors, N_col_factors

    integer :: N_scalars, N_spinors, N_conjspinors, N_bispinors
    integer :: N_vectors, N_tensors_2, N_tensors_1, N_vectorspinors

    integer :: N_coupl_real, N_coupl_real2, N_coupl_cmplx, N_coupl_cmplx2

    integer, dimension(:, :), allocatable :: table_flavor
    integer, dimension(:, :, :), allocatable :: table_color_flows
    integer, dimension(:, :), allocatable :: table_spin
    logical, dimension(:, :), allocatable :: table_ghost_flags
    type(OCF), dimension(:), allocatable :: table_color_factors
    logical, dimension(:, :), allocatable :: table_flv_col_is_allowed

    real(default), dimension(:), allocatable :: coupl_real
    real(default), dimension(:, :), allocatable :: coupl_real2
    complex(default), dimension(:), allocatable :: coupl_cmplx
    complex(default), dimension(:, :), allocatable :: coupl_cmplx2
    real(default), dimension(:), allocatable :: mass
    real(default), dimension(:), allocatable :: width

    type(momentum), dimension(:), allocatable :: momenta
    complex(default), dimension(:), allocatable :: amplitudes
    complex(default), dimension(:, :, :), allocatable :: table_amplitudes
    class(flavor_t), dimension(:), allocatable :: flavor
    class(color_t), dimension(:), allocatable :: color
! gfortran 4.7

```

```

!class(helicity_t), dimension(:), pointer :: helicity => null()
integer, dimension(:), allocatable :: helicity

type(vm_scalar), dimension(:), allocatable :: scalars
type(vm_spinor), dimension(:), allocatable :: spinors
type(vm_conjspinor), dimension(:), allocatable :: conjspinors
type(vm_bispinor), dimension(:), allocatable :: bispinors
type(vm_vector), dimension(:), allocatable :: vectors
type(vm_tensor_2), dimension(:), allocatable :: tensors_2
type(vm_tensor_1), dimension(:), allocatable :: tensors_1
type(vm_vectorspinor), dimension(:), allocatable :: vectorspinors

logical, dimension(:), allocatable :: hel_is_allowed
real(default), dimension(:), allocatable :: hel_max_abs
real(default) :: hel_sum_abs = 0, hel_threshold = 1E10
integer :: hel_count = 0, hel_cutoff = 100
integer, dimension(:), allocatable :: hel_map
integer :: hel_finite

logical :: openmp

contains
  <VM: TBP>
end type

<OVM Procedure Implementations>+≡
subroutine alloc_arrays (vm)
  type(vm_t), intent(inout) :: vm
  integer :: i
  allocate (vm%table_flavor(vm%N_particles, vm%N_flavors))
  allocate (vm%table_color_flows(vm%N_col_indices, vm%N_particles, &
                                vm%N_col_flows))
  allocate (vm%table_spin(vm%N_particles, vm%N_helicities))
  allocate (vm%table_ghost_flags(vm%N_particles, vm%N_col_flows))
  allocate (vm%table_color_factors(vm%N_col_factors))
  allocate (vm%table_flv_col_is_allowed(vm%N_flavors, vm%N_col_flows))
  allocate (vm%momenta(vm%N_momenta))
  allocate (vm%amplitudes(vm%N_amplitudes))
  allocate (vm%table_amplitudes(vm%N_flavors, vm%N_col_flows, &
                                vm%N_helicities))

  vm%table_amplitudes = zero
  allocate (vm%scalars(vm%N_scalars))
  allocate (vm%spinors(vm%N_spinors))
  allocate (vm%conjspinors(vm%N_conjspinors))
  allocate (vm%bispinors(vm%N_bispinors))
  allocate (vm%vectors(vm%N_vectors))
  allocate (vm%tensors_2(vm%N_tensors_2))
  allocate (vm%tensors_1(vm%N_tensors_1))
  allocate (vm%vectorspinors(vm%N_vectorspinors))
  allocate (vm%hel_is_allowed(vm%N_helicities))
  vm%hel_is_allowed = .True.
  allocate (vm%hel_max_abs(vm%N_helicities))
  vm%hel_max_abs = 0
  allocate (vm%hel_map(vm%N_helicities))

```

```

    vm%hel_map = /(i, i = 1, vm%N_helicities)/)
    vm%hel_finite = vm%N_helicities
end subroutine alloc_arrays

```

### *X.21.2 Controlling the VM*

These type-bound procedures steer the VM

*<VM: TBP>*≡

```

    procedure :: init => vm_init
    procedure :: write => vm_write
    procedure :: reset => vm_reset
    procedure :: run => vm_run
    procedure :: final => vm_final

```

The `init` completely sets the environment for the OVM. Parameters can be changed with `reset` without reloading the bytecode.

*<OVM Procedure Implementations>*+≡

```

subroutine vm_init (vm, bytecode_file, version, model, &
    coupl_real, coupl_real2, coupl_cmplx, coupl_cmplx2, &
    mass, width, verbose, out_fh, openmp)
class(vm_t), intent(out) :: vm
type(string_t), intent(in) :: bytecode_file
type(string_t), intent(in) :: version
type(string_t), intent(in) :: model
real(default), dimension(:), optional, intent(in) :: coupl_real
real(default), dimension(:, :), optional, intent(in) :: coupl_real2
complex(default), dimension(:), optional, intent(in) :: coupl_cmplx
complex(default), dimension(:, :), optional, intent(in) :: coupl_cmplx2
real(default), dimension(:), optional, intent(in) :: mass
real(default), dimension(:), optional, intent(in) :: width
logical, optional, intent(in) :: verbose
integer, optional, intent(in) :: out_fh
logical, optional, intent(in) :: openmp
vm%bytecode_file = bytecode_file
vm%version = version
vm%model = model
if (present (coupl_real)) then
    allocate (vm%coupl_real (size (coupl_real)), source=coupl_real)
end if
if (present (coupl_real2)) then
    allocate (vm%coupl_real2 (2, size (coupl_real2, 2)), source=coupl_real2)
end if
if (present (coupl_cmplx)) then
    allocate (vm%coupl_cmplx (size (coupl_cmplx)), source=coupl_cmplx)
end if
if (present (coupl_cmplx2)) then
    allocate (vm%coupl_cmplx2 (2, size (coupl_cmplx2, 2)), &
        source=coupl_cmplx2)
end if
if (present (mass)) then
    allocate (vm%mass(size(mass)), source=mass)
end if
if (present (width)) then

```

```

        allocate (vm%width(size (width)), source=width)
    end if
    if (present (openmp)) then
        vm%openmp = openmp
    else
        vm%openmp = .false.
    end if

    call basic_init (vm, verbose, out_fh)
end subroutine vm_init

```

*(OVM Procedure Implementations)*+≡

```

subroutine vm_reset (vm, &
    coupl_real, coupl_real2, coupl_cmplx, coupl_cmplx2, &
    mass, width, verbose, out_fh)
class(vm_t), intent(inout) :: vm
real(default), dimension(:), optional, intent(in) :: coupl_real
real(default), dimension(:, :), optional, intent(in) :: coupl_real2
complex(default), dimension(:), optional, intent(in) :: coupl_cmplx
complex(default), dimension(:, :), optional, intent(in) :: coupl_cmplx2
real(default), dimension(:), optional, intent(in) :: mass
real(default), dimension(:), optional, intent(in) :: width
logical, optional, intent(in) :: verbose
integer, optional, intent(in) :: out_fh
if (present (coupl_real)) then
    vm%coupl_real = coupl_real
end if
if (present (coupl_real2)) then
    vm%coupl_real2 = coupl_real2
end if
if (present (coupl_cmplx)) then
    vm%coupl_cmplx = coupl_cmplx
end if
if (present (coupl_cmplx2)) then
    vm%coupl_cmplx2 = coupl_cmplx2
end if
if (present (mass)) then
    vm%mass = mass
end if
if (present (width)) then
    vm%width = width
end if
if (present (verbose)) then
    vm%verbose = verbose
end if
if (present (out_fh)) then
    vm%out_fh = out_fh
end if
end subroutine vm_reset

```

Mainly for debugging

*(OVM Procedure Implementations)*+≡

```

subroutine vm_write (vm)

```



```

class(vm_t), intent(in) :: vm
integer :: i, j, k
call basic_write (vm)
write(vm%out_fh, *) 'table_flavor           = ', vm%table_flavor
write(vm%out_fh, *) 'table_color_flows      = ', vm%table_color_flows
write(vm%out_fh, *) 'table_spin            = ', vm%table_spin
write(vm%out_fh, *) 'table_ghost_flags     = ', vm%table_ghost_flags
write(vm%out_fh, *) 'table_color_factors   = ', vm%table_color_factors
write(vm%out_fh, *) 'table_flv_col_is_allowed = ', &
    vm%table_flv_col_is_allowed
do i = 1, vm%N_flavors
  do j = 1, vm%N_col_flows
    do k = 1, vm%N_helicities
      write(vm%out_fh, *) 'table_amplitudes(f,c,h), f, c, h = ', vm%table_amplitudes(i,j,k),
    end do
  end do
end do
if (allocated(vm%coupl_real)) then
  write(vm%out_fh, *) 'coupl_real          = ', vm%coupl_real
end if
if (allocated(vm%coupl_real2)) then
  write(vm%out_fh, *) 'coupl_real2         = ', vm%coupl_real2
end if
if (allocated(vm%coupl_cmplx)) then
  write(vm%out_fh, *) 'coupl_cmplx         = ', vm%coupl_cmplx
end if
if (allocated(vm%coupl_cmplx2)) then
  write(vm%out_fh, *) 'coupl_cmplx2        = ', vm%coupl_cmplx2
end if
write(vm%out_fh, *) 'mass                 = ', vm%mass
write(vm%out_fh, *) 'width                 = ', vm%width
write(vm%out_fh, *) 'momenta                = ', vm%momenta
! gfortran 4.7
!do i = 1, size(vm%flavor)
!  call vm%flavor(i)%write (vm%out_fh)
!end do
!do i = 1, size(vm%color)
!  call vm%color(i)%write (vm%out_fh)
!end do
!do i = 1, size(vm%helicity)
!  call vm%helicity(i)%write (vm%out_fh)
!end do
write(vm%out_fh, *) 'helicity              = ', vm%helicity
write(vm%out_fh, *) 'amplitudes             = ', vm%amplitudes
write(vm%out_fh, *) 'scalars              = ', vm%scalars
write(vm%out_fh, *) 'spinors              = ', vm%spinors
write(vm%out_fh, *) 'conjspinors         = ', vm%conjspinors
write(vm%out_fh, *) 'bispinors            = ', vm%bispinors
write(vm%out_fh, *) 'vectors              = ', vm%vectors
write(vm%out_fh, *) 'tensors_2           = ', vm%tensors_2
write(vm%out_fh, *) 'tensors_1           = ', vm%tensors_1
write(vm%out_fh, *) 'vectorspinors       = ', vm%vectorspinors
write(vm%out_fh, *) 'N_momenta            = ', vm%N_momenta
write(vm%out_fh, *) 'N_particles         = ', vm%N_particles

```

```

write(vm%out_fh, *) 'N_prt_in      = ', vm%N_prt_in
write(vm%out_fh, *) 'N_prt_out    = ', vm%N_prt_out
write(vm%out_fh, *) 'N_amplitudes = ', vm%N_amplitudes
write(vm%out_fh, *) 'N_helicities = ', vm%N_helicities
write(vm%out_fh, *) 'N_col_flows  = ', vm%N_col_flows
write(vm%out_fh, *) 'N_col_indices = ', vm%N_col_indices
write(vm%out_fh, *) 'N_flavors    = ', vm%N_flavors
write(vm%out_fh, *) 'N_col_factors = ', vm%N_col_factors
write(vm%out_fh, *) 'N_scalars    = ', vm%N_scalars
write(vm%out_fh, *) 'N_spinors    = ', vm%N_spinors
write(vm%out_fh, *) 'N_conjspinors = ', vm%N_conjspinors
write(vm%out_fh, *) 'N_bispinors  = ', vm%N_bispinors
write(vm%out_fh, *) 'N_vectors    = ', vm%N_vectors
write(vm%out_fh, *) 'N_tensors_2  = ', vm%N_tensors_2
write(vm%out_fh, *) 'N_tensors_1  = ', vm%N_tensors_1
write(vm%out_fh, *) 'N_vectorspinors = ', vm%N_vectorspinors
write(vm%out_fh, *) 'Overall size of VM: '
! GNU extension
! write(vm%out_fh, *) 'sizeof(wavefunctions) = ', &
!   sizeof(vm%scalars) + sizeof(vm%spinors) + sizeof(vm%conjspinors) + &
!   sizeof(vm%bispinors) + sizeof(vm%vectors) + sizeof(vm%tensors_2) + &
!   sizeof(vm%tensors_1) + sizeof(vm%vectorspinors)
! write(vm%out_fh, *) 'sizeof(mometa) = ', sizeof(vm%momenta)
! write(vm%out_fh, *) 'sizeof(amplitudes) = ', sizeof(vm%amplitudes)
! write(vm%out_fh, *) 'sizeof(tables) = ', &
!   sizeof(vm%table_amplitudes) + sizeof(vm%table_spin) + &
!   sizeof(vm%table_flavor) + sizeof(vm%table_flg_col_is_allowed) + &
!   sizeof(vm%table_color_flows) + sizeof(vm%table_color_factors) + &
!   sizeof(vm%table_ghost_flags)
end subroutine vm_write

```

Most of this is redundant (Fortran will deallocate when we leave the scope) but when we change from allocatables to pointers, it is necessary to avoid leaks

(*OVM Procedure Implementations*)+≡

```

subroutine vm_final (vm)
  class(vm_t), intent(inout) :: vm
  deallocate (vm%table_flavor)
  deallocate (vm%table_color_flows)
  deallocate (vm%table_spin)
  deallocate (vm%table_ghost_flags)
  deallocate (vm%table_color_factors)
  deallocate (vm%table_flg_col_is_allowed)
  if (allocated (vm%coupl_real)) then
    deallocate (vm%coupl_real)
  end if
  if (allocated (vm%coupl_real2)) then
    deallocate (vm%coupl_real2)
  end if
  if (allocated (vm%coupl_cmplx)) then
    deallocate (vm%coupl_cmplx)
  end if
  if (allocated (vm%coupl_cmplx2)) then
    deallocate (vm%coupl_cmplx2)
  end if
end subroutine vm_final

```

```

end if
if (allocated (vm%mass)) then
  deallocate (vm%mass)
end if
if (allocated (vm%width)) then
  deallocate (vm%width)
end if
deallocate (vm%momenta)
deallocate (vm%flavor)
deallocate (vm%color)
deallocate (vm%helicity)
deallocate (vm%amplitudes)
deallocate (vm%table_amplitudes)
deallocate (vm%scalars)
deallocate (vm%spinors)
deallocate (vm%conjspinors)
deallocate (vm%bispinors)
deallocate (vm%vectors)
deallocate (vm%tensors_2)
deallocate (vm%tensors_1)
deallocate (vm%vectorspinors)
end subroutine vm_final

```

Handing over the polymorph object `helicity` didn't work out as planned. A work-around is the use of `pointers`. `flavor` and `color` are not yet used but would have to be changed to `pointers` as well. At least this potentially avoids copying. Actually, neither the allocatable nor the pointer version works in `gfortran 4.7` due to the broken `select type`. Back to Stone Age, i.e. integers.

(*OVM Procedure Implementations*) $\equiv$

```

subroutine vm_run (vm, mom, flavor, color, helicity)
  class(vm_t), intent(inout) :: vm
  real(default), dimension(0:3, *), intent(in) :: mom
  class(flavor_t), dimension(:), optional, intent(in) :: flavor
  class(color_t), dimension(:), optional, intent(in) :: color
  ! gfortran 4.7
  !class(helicity_t), dimension(:), optional, target, intent(in) :: helicity
  integer, dimension(:), optional, intent(in) :: helicity
  integer :: i, h, hi
  do i = 1, vm%N_momenta
    if (i <= vm%N_prt_in) then
      vm%momenta(i) = - mom(:, i)      ! incoming, crossing symmetry
    else
      vm%momenta(i) = mom(:, i)      ! outgoing
    end if
  end do
  if (present (flavor)) then
    allocate(vm%flavor(size(flavor)), source=flavor)
  else
    if (.not. (allocated (vm%flavor))) then
      allocate(flv_discrete::vm%flavor(vm%N_particles))
    end if
  end if
  if (present (color)) then

```

```

        allocate(vm%color(size(color)), source=color)
    else
        if (.not. (allocated (vm%color))) then
            allocate(col_discrete::vm%color(vm%N_col_flows))
        end if
    end if
    ! gfortran 4.7
    if (present (helicity)) then
        !vm%helicity => helicity
        vm%helicity = helicity
        call vm_run_one_helicity (vm, 1)
    else
        !if (.not. (associated (vm%helicity))) then
            !allocate(hel_discrete::vm%helicity(vm%N_particles))
        !end if
        if (.not. (allocated (vm%helicity))) then
            allocate(vm%helicity(vm%N_particles))
        end if
        if (vm%hel_finite == 0) return
        do hi = 1, vm%hel_finite
            h = vm%hel_map(hi)
            !<Work around [[gfortran 4.7 Bug 56731]] Implementation>>
            vm%helicity = vm%table_spin(:,h)
            call vm_run_one_helicity (vm, h)
        end do
    end if
end subroutine vm_run

```

This only removes the ICE but still leads to a segmentation fault in `gfortran` 4.7. I am running out of ideas how to make this compiler work with arrays of polymorph datatypes.

```

<Work around gfortran 4.7 Bug 56731 Declarations>≡
integer :: hj

<Work around gfortran 4.7 Bug 56731 Implementation>≡
do hj = 1, size(vm%helicity)
    select type (hel => vm%helicity(hj))
        type is (hel_discrete)
            hel%i = vm%table_spin(hj,h)
        end select
    end do

<Original version>≡
select type (hel => vm%helicity)
    type is (hel_discrete)
        hel(:)%i = vm%table_spin(:,h)
    end select

<OVM Procedure Implementations>+≡
subroutine vm_run_one_helicity (vm, h)
    class(vm_t), intent(inout) :: vm
    integer, intent(in) :: h
    integer :: f, c, i
    vm%amplitudes = zero
    if (vm%N_levels > 0) then

```

```

        call null_all_wfs (vm)
        call iterate_instructions (vm)
    end if
    i = 1
    do c = 1, vm%N_col_flows
        do f = 1, vm%N_flavors
            if (vm%table_flg_col_is_allowed(f,c)) then
                vm%table_amplitudes(f,c,h) = vm%amplitudes(i)
                i = i + 1
            end if
        end do
    end do
end subroutine

```

*(OVM Procedure Implementations)+≡*

```

subroutine null_all_wfs (vm)
    type(vm_t), intent(inout) :: vm
    integer :: i, j
    vm%scalars%c = .False.
    vm%scalars%v = zero
    vm%spinors%c = .False.
    vm%conjspinors%c = .False.
    vm%bispinors%c = .False.
    vm%vectorspinors%c = .False.
    do i = 1, 4
        vm%spinors%v%a(i) = zero
        vm%conjspinors%v%a(i) = zero
        vm%bispinors%v%a(i) = zero
        do j = 1, 4
            vm%vectorspinors%v%psi(i)%a(j) = zero
        end do
    end do
    vm%vectors%c = .False.
    vm%vectors%v%t = zero
    vm%tensors_1%c = .False.
    vm%tensors_2%c = .False.
    do i = 1, 3
        vm%vectors%v%x(i) = zero
        vm%tensors_1%v%e(i) = zero
        vm%tensors_1%v%b(i) = zero
        do j = 1, 3
            vm%tensors_2%v%t(i,j) = zero
        end do
    end do
end subroutine

```

### X.21.3 Reading the bytecode

*(OVM Procedure Implementations)+≡*

```

subroutine load_header (vm, IO)
    type(vm_t), intent(inout) :: vm
    integer, intent(inout) :: IO

```

```

integer, dimension(len_instructions) :: line
read(vm%bytecode_fh, fmt = *, iostat = IO) line
vm%N_momenta = line(1)
vm%N_particles = line(2)
vm%N_prt_in = line(3)
vm%N_prt_out = line(4)
vm%N_amplitudes = line(5)
vm%N_helicities = line(6)
vm%N_col_flows = line(7)
if (vm%N_momenta == 0) then
    vm%N_col_indices = 2
else
    vm%N_col_indices = line(8)
end if
read(vm%bytecode_fh, fmt = *, iostat = IO)
read(vm%bytecode_fh, fmt = *, iostat = IO) line
vm%N_flavors = line(1)
vm%N_col_factors = line(2)
vm%N_scalars = line(3)
vm%N_spinors = line(4)
vm%N_conjspinors = line(5)
vm%N_bispinors = line(6)
vm%N_vectors = line(7)
vm%N_tensors_2 = line(8)
read(vm%bytecode_fh, fmt = *, iostat = IO)
read(vm%bytecode_fh, fmt = *, iostat = IO) line
vm%N_tensors_1 = line(1)
vm%N_vectorspinors = line(2)
! Add 1 for seperating label lines like 'Another table'
vm%N_table_lines = vm%N_helicities + 1 + vm%N_flavors + 1 + vm%N_col_flows &
    + 1 + vm%N_col_flows + 1 + vm%N_col_factors + 1 + vm%N_col_flows
end subroutine load_header

```

*(OVM Procedure Implementations)+≡*

```

subroutine read_tables (vm, IO)
    type(vm_t), intent(inout) :: vm
    integer, intent(inout) :: IO
    integer :: i
    integer, dimension(2) :: tmpcf
    integer, dimension(3) :: tmpfactor
    integer, dimension(vm%N_flavors) :: tmpF
    integer, dimension(vm%N_particles) :: tmpP
    real(default) :: factor
    do i = 1, vm%N_helicities
        read(vm%bytecode_fh, fmt = *, iostat = IO) vm%table_spin(:, i)
    end do

    read(vm%bytecode_fh, fmt = *, iostat = IO)
    do i = 1, vm%N_flavors
        read(vm%bytecode_fh, fmt = *, iostat = IO) vm%table_flavor(:, i)
    end do

    read(vm%bytecode_fh, fmt = *, iostat = IO)
    do i = 1, vm%N_col_flows

```

```

        read(vm%bytecode_fh, fmt = *, iostat = IO) vm%table_color_flows(:, :, i)
    end do

    read(vm%bytecode_fh, fmt = *, iostat = IO)
    do i = 1, vm%N_col_flows
        read(vm%bytecode_fh, fmt = *, iostat = IO) tmpP
        vm%table_ghost_flags(:, i) = int_to_log(tmpP)
    end do

    read(vm%bytecode_fh, fmt = *, iostat = IO)
    do i = 1, vm%N_col_factors
        read(vm%bytecode_fh, fmt = '(2I9)', iostat = IO, advance='no') tmpcf
        factor = zero
        do
            read(vm%bytecode_fh, fmt = '(3I9)', iostat = IO, advance='no', EOR=10) tmpfactor
            factor = factor + color_factor(tmpfactor(1), tmpfactor(2), tmpfactor(3))
        end do
        10 vm%table_color_factors(i) = OCF(tmpcf(1), tmpcf(2), factor)
    end do

    read(vm%bytecode_fh, fmt = *, iostat = IO)
    do i = 1, vm%N_col_flows
        read(vm%bytecode_fh, fmt = *, iostat = IO) tmpF
        vm%table_flv_col_is_allowed(:, i) = int_to_log(tmpF)
    end do
end subroutine read_tables

```

This checking has proven useful more than once

*(OVM Procedure Implementations)*+≡

```

subroutine extended_version_check (vm, IO)
    type(vm_t), intent(in) :: vm
    integer, intent(inout) :: IO
    character(256) :: buffer
    read(vm%bytecode_fh, fmt = *, iostat = IO) buffer
    if (vm%model /= buffer) then
        print *, "Bytecode has been generated for another/older model."
        stop 1
    else
        if (vm%verbose) then
            write (vm%out_fh, fmt = *) "Using the model: "
            write (vm%out_fh, fmt = *) char(vm%model)
        end if
    end if
end subroutine extended_version_check

```

This chunk is copied verbatim from the `basic_vm`

*(OVM Procedure Implementations)*+≡

```

subroutine basic_init (vm, verbose, out_fh)
    type(vm_t), intent(inout) :: vm
    logical, optional, intent(in) :: verbose
    integer, optional, intent(in) :: out_fh
    if (present (verbose)) then
        vm%verbose = verbose
    end if
end subroutine basic_init

```

```

else
    vm%verbose = .true.
end if
if (present (out_fh)) then
    vm%out_fh = out_fh
else
    vm%out_fh = stdout
end if
call set_stream (vm)
call alloc_and_count (vm)
if (vm%N_levels > 0) then
    call read_bytecode (vm)
    call sanity_check (vm)
end if
close (vm%bytecode_fh)
end subroutine basic_init

subroutine basic_write (vm)
    type(vm_t), intent(in) :: vm
    integer :: i
    write (vm%out_fh, *) '====> VM ', char(vm%version), ' <===='
    write (vm%out_fh, *) 'verbose          = ', vm%verbose
    write (vm%out_fh, *) 'bytecode_file   = ', char (vm%bytecode_file)
    write (vm%out_fh, *) 'N_instructions = ', vm%N_instructions
    write (vm%out_fh, *) 'N_levels      = ', vm%N_levels
    write (vm%out_fh, *) 'instructions   = '
    do i = 1, vm%N_instructions
        write (vm%out_fh, *) vm%instructions(:, i)
    end do
    write (vm%out_fh, *) 'levels          = ', vm%levels
end subroutine basic_write

subroutine alloc_and_count (vm)
    type(vm_t), intent(inout) :: vm
    integer, dimension(len_instructions) :: line
    character(256) :: buffer
    integer :: i, IO
    read(vm%bytecode_fh, fmt = *, iostat = IO) buffer
    if (vm%version /= buffer) then
        print *, "Bytecode has been generated with another Omega.Targets."
        stop 1
    else
        if (vm%verbose) then
            write (vm%out_fh, fmt = *) "Bytecode version fits."
        end if
    end if
    call extended_version_check (vm, IO)
    if (vm%verbose) then
        write (vm%out_fh, fmt = *) "Trying to allocate."
    end if
    do i = 1, N_comments
        read(vm%bytecode_fh, fmt = *, iostat = IO)
    end do
    call load_header (vm, IO)

```



```

call alloc_arrays (vm)
if (vm%N_momenta /= 0) then
  do i = 1, vm%N_table_lines + 1
    read(vm%bytecode_fh, fmt = *, iostat = IO)
  end do
  vm%N_instructions = 0
  vm%N_levels = 0
  do
    read(vm%bytecode_fh, fmt = *, end = 42) line
    if (line(1) /= 0) then
      vm%N_instructions = vm%N_instructions + 1
    else
      vm%N_levels = vm%N_levels + 1
    end if
  end do
  42 rewind(vm%bytecode_fh, iostat = IO)
  allocate (vm%instructions(len_instructions, vm%N_instructions))
  allocate (vm%levels(vm%N_levels))
  if (IO /= 0) then
    print *, "Error: vm.alloc : Couldn't load bytecode!"
    stop 1
  end if
end if
end subroutine alloc_and_count

subroutine read_bytecode (vm)
  type(vm_t), intent(inout) :: vm
  integer, dimension(len_instructions) :: line
  integer :: i, j, IO
  ! Jump over version number, comments, header and first table description
  do i = 1, N_version_lines + N_comments + N_header_lines + 1
    read (vm%bytecode_fh, fmt = *, iostat = IO)
  end do
  call read_tables (vm, IO)
  read (vm%bytecode_fh, fmt = *, iostat = IO)
  i = 0; j = 0
  do
    read (vm%bytecode_fh, fmt = *, iostat = IO) line
    if (IO /= 0) exit
    if (line(1) == 0) then
      if (j <= vm%N_levels) then
        j = j + 1
        vm%levels(j) = i          ! last index of a level is saved
      else
        print *, 'Error: vm.read_bytecode: File has more levels than anticipated!'
        stop 1
      end if
    else
      if (i <= vm%N_instructions) then
        i = i + 1                ! A valid instruction line
        vm%instructions(:, i) = line
      else
        print *, 'Error: vm.read_bytecode: File is larger than anticipated!'
        stop 1
      end if
    end if
  end do
end subroutine read_bytecode

```

```

        end if
    end if
end do
end subroutine read_bytecode

subroutine iterate_instructions (vm)
    type(vm_t), intent(inout) :: vm
    integer :: i, j
    if (vm%openmp) then
        !$omp parallel
        do j = 1, vm%N_levels - 1
            !$omp do schedule (static)
            do i = vm%levels (j) + 1, vm%levels (j + 1)
                call decode (vm, i)
            end do
            !$omp end do
        end do
        !$omp end parallel
    else
        do j = 1, vm%N_levels - 1
            do i = vm%levels (j) + 1, vm%levels (j + 1)
                call decode (vm, i)
            end do
        end do
    end if
end subroutine iterate_instructions

subroutine set_stream (vm)
    type(vm_t), intent(inout) :: vm
    integer :: IO
    call find_free_unit (vm%bytecode_fh, IO)
    open (vm%bytecode_fh, file = char (vm%bytecode_file), form = 'formatted', &
        access = 'sequential', status = 'old', position = 'rewind', iostat = IO, &
        action = 'read')
    if (IO /= 0) then
        print *, "Error: vm.set_stream: Bytecode file '", char(vm%bytecode_file), &
            "' not found!"

        stop 1
    end if
end subroutine set_stream

subroutine sanity_check (vm)
    type(vm_t), intent(in) :: vm
    if (vm%levels(1) /= 0) then
        print *, "Error: vm.vm_init: levels(1) != 0"
        stop 1
    end if
    if (vm%levels(vm%N_levels) /= vm%N_instructions) then
        print *, "Error: vm.vm_init: levels(N_levels) != N_instructions"
        stop 1
    end if
    if (vm%verbose) then
        write(vm%out_fh, *) "vm passed sanity check. Starting calculation."
    end if
end if

```

```
end subroutine sanity_check
```

### *X.21.4 Main Decode Function*

This is the heart of the OVM

```
<OVM Procedure Implementations>+≡
! pure & ! if no warnings
subroutine decode (vm, instruction_index)
  type(vm_t), intent(inout) :: vm
  integer, intent(in) :: instruction_index
  integer, dimension(len_instructions) :: i, curr
  complex(default) :: bracket
  integer :: tmp
  real(default) :: w
  i = vm%instructions (:, instruction_index)
  select case (i(1))
  case ( : -1)      ! Jump over subinstructions

  <cases of decode>
  case (0)
    print *, 'Error: Levelbreak put in decode! Line:', &
      instruction_index
    stop 1
  case default
    print *, "Error: Decode has case not caught! Line: ", &
      instruction_index
    stop 1
  end select
end subroutine decode
```

### *Momenta*

The most trivial instruction

```
<OVM Instructions>≡
integer, parameter :: ovm_ADD_MOMENTA = 1

<cases of decode>≡
case (ovm_ADD_MOMENTA)
  vm%momenta(i(4)) = vm%momenta(i(5)) + vm%momenta(i(6))
  if (i(7) > 0) then
    vm%momenta(i(4)) = vm%momenta(i(4)) + vm%momenta(i(7))
  end if
```

### *Loading External states*

```
<OVM Instructions>+≡
integer, parameter :: ovm_LOAD_SCALAR = 10
integer, parameter :: ovm_LOAD_SPINOR_INC = 11
integer, parameter :: ovm_LOAD_SPINOR_OUT = 12
```

```

integer, parameter :: ovm_LOAD_CONJSPINOR_INC = 13
integer, parameter :: ovm_LOAD_CONJSPINOR_OUT = 14
integer, parameter :: ovm_LOAD_MAJORANA_INC = 15
integer, parameter :: ovm_LOAD_MAJORANA_OUT = 16
integer, parameter :: ovm_LOAD_VECTOR_INC = 17
integer, parameter :: ovm_LOAD_VECTOR_OUT = 18
integer, parameter :: ovm_LOAD_VECTORSPINOR_INC = 19
integer, parameter :: ovm_LOAD_VECTORSPINOR_OUT = 20
integer, parameter :: ovm_LOAD_TENSOR2_INC = 21
integer, parameter :: ovm_LOAD_TENSOR2_OUT = 22
integer, parameter :: ovm_LOAD_BRS_SCALAR = 30
integer, parameter :: ovm_LOAD_BRS_SPINOR_INC = 31
integer, parameter :: ovm_LOAD_BRS_SPINOR_OUT = 32
integer, parameter :: ovm_LOAD_BRS_CONJSPINOR_INC = 33
integer, parameter :: ovm_LOAD_BRS_CONJSPINOR_OUT = 34
integer, parameter :: ovm_LOAD_BRS_VECTOR_INC = 37
integer, parameter :: ovm_LOAD_BRS_VECTOR_OUT = 38
integer, parameter :: ovm_LOAD_MAJORANA_GHOST_INC = 23
integer, parameter :: ovm_LOAD_MAJORANA_GHOST_OUT = 24
integer, parameter :: ovm_LOAD_BRS_MAJORANA_INC = 35
integer, parameter :: ovm_LOAD_BRS_MAJORANA_OUT = 36

```

```

⟨cases of decode⟩+≡
case (ovm_LOAD_SCALAR)
  vm%scalars(i(4))%v = one
  vm%scalars(i(4))%c = .True.

case (ovm_LOAD_SPINOR_INC)
  call load_spinor(vm%spinors(i(4)), - ⟨p⟩, ⟨m⟩, &
    vm%helicity(i(5)), ovm_LOAD_SPINOR_INC)

case (ovm_LOAD_SPINOR_OUT)
  call load_spinor(vm%spinors(i(4)), ⟨p⟩, ⟨m⟩, &
    vm%helicity(i(5)), ovm_LOAD_SPINOR_OUT)

case (ovm_LOAD_CONJSPINOR_INC)
  call load_conjspinor(vm%conjspinors(i(4)), - ⟨p⟩, &
    ⟨m⟩, vm%helicity(i(5)), ovm_LOAD_CONJSPINOR_INC)

case (ovm_LOAD_CONJSPINOR_OUT)
  call load_conjspinor(vm%conjspinors(i(4)), ⟨p⟩, &
    ⟨m⟩, vm%helicity(i(5)), ovm_LOAD_CONJSPINOR_OUT)

case (ovm_LOAD_MAJORANA_INC)
  call load_bispinor(vm%bispinors(i(4)), - ⟨p⟩, &
    ⟨m⟩, vm%helicity(i(5)), ovm_LOAD_MAJORANA_INC)

case (ovm_LOAD_MAJORANA_OUT)
  call load_bispinor(vm%bispinors(i(4)), ⟨p⟩, ⟨m⟩, &
    vm%helicity(i(5)), ovm_LOAD_MAJORANA_OUT)

case (ovm_LOAD_VECTOR_INC)
  call load_vector(vm%vectors(i(4)), - ⟨p⟩, ⟨m⟩, &
    vm%helicity(i(5)), ovm_LOAD_VECTOR_INC)

```

```

case (ovm_LOAD_VECTOR_OUT)
  call load_vector(vm%vectors(i(4)),  $\langle p \rangle$ ,  $\langle m \rangle$ , &
    vm%helicity(i(5)), ovm_LOAD_VECTOR_OUT)

case (ovm_LOAD_VECTORSPINOR_INC)
  !select type (h => vm%helicity(i(5)))
  !type is (hel_discrete)
    !vm%vectorspinors(i(4))%v = veps( $\langle m \rangle$ , -  $\langle p \rangle$ , &
      !h%i)

  !end select
  vm%vectorspinors(i(4))%v = veps( $\langle m \rangle$ , -  $\langle p \rangle$ , &
    vm%helicity(i(5)))
  vm%vectorspinors(i(4))%c = .True.

case (ovm_LOAD_VECTORSPINOR_OUT)
  !select type (h => vm%helicity(i(5)))
  !type is (hel_discrete)
    !vm%vectorspinors(i(4))%v = veps( $\langle m \rangle$ ,  $\langle p \rangle$ , &
      !h%i)

  !end select
  vm%vectorspinors(i(4))%v = veps( $\langle m \rangle$ ,  $\langle p \rangle$ , &
    vm%helicity(i(5)))
  vm%vectorspinors(i(4))%c = .True.

case (ovm_LOAD_TENSOR2_INC)
  !select type (h => vm%helicity(i(5)))
  !type is (hel_discrete)
    !vm%tensors_2(i(4))%v = eps2( $\langle m \rangle$ , -  $\langle p \rangle$ , &
      !h%i)

  !end select
  vm%tensors_2(i(4))%c = .True.

case (ovm_LOAD_TENSOR2_OUT)
  !select type (h => vm%helicity(i(5)))
  !type is (hel_discrete)
    !vm%tensors_2(i(4))%v = eps2( $\langle m \rangle$ ,  $\langle p \rangle$ , h%i)
  !end select
  vm%tensors_2(i(4))%c = .True.

case (ovm_LOAD_BRS_SCALAR)
  vm%scalars(i(4))%v = (0, -1) * ( $\langle p \rangle$  *  $\langle p \rangle$  - &
     $\langle m \rangle$ **2)
  vm%scalars(i(4))%c = .True.

case (ovm_LOAD_BRS_SPINOR_INC)
  print *, 'not implemented'
  stop 1
case (ovm_LOAD_BRS_SPINOR_OUT)
  print *, 'not implemented'
  stop 1
case (ovm_LOAD_BRS_CONJSPINOR_INC)
  print *, 'not implemented'
  stop 1

```

```

case (ovm_LOAD_BRS_CONJSPINOR_OUT)
  print *, 'not implemented'
  stop 1
case (ovm_LOAD_BRS_VECTOR_INC)
  print *, 'not implemented'
  stop 1
case (ovm_LOAD_BRS_VECTOR_OUT)
  print *, 'not implemented'
  stop 1
case (ovm_LOAD_MAJORANA_GHOST_INC)
  print *, 'not implemented'
  stop 1
case (ovm_LOAD_MAJORANA_GHOST_OUT)
  print *, 'not implemented'
  stop 1
case (ovm_LOAD_BRS_MAJORANA_INC)
  print *, 'not implemented'
  stop 1
case (ovm_LOAD_BRS_MAJORANA_OUT)
  print *, 'not implemented'
  stop 1

```

### *Brackets and Fusions*

NB: during, execution, the type of the coupling constant is implicit in the instruction

```

<OVM Instructions>+≡
integer, parameter :: ovm_CALC_BRACKET = 2

integer, parameter :: ovm_FUSE_V_FF = -1
integer, parameter :: ovm_FUSE_F_VF = -2
integer, parameter :: ovm_FUSE_F_FV = -3
integer, parameter :: ovm_FUSE_VA_FF = -4
integer, parameter :: ovm_FUSE_F_VAF = -5
integer, parameter :: ovm_FUSE_F_FVA = -6
integer, parameter :: ovm_FUSE_VA2_FF = -7
integer, parameter :: ovm_FUSE_F_VA2F = -8
integer, parameter :: ovm_FUSE_F_FVA2 = -9
integer, parameter :: ovm_FUSE_A_FF = -10
integer, parameter :: ovm_FUSE_F_AF = -11
integer, parameter :: ovm_FUSE_F_FA = -12
integer, parameter :: ovm_FUSE_VL_FF = -13
integer, parameter :: ovm_FUSE_F_VLF = -14
integer, parameter :: ovm_FUSE_F_FVL = -15
integer, parameter :: ovm_FUSE_VR_FF = -16
integer, parameter :: ovm_FUSE_F_VRF = -17
integer, parameter :: ovm_FUSE_F_FVR = -18
integer, parameter :: ovm_FUSE_VLR_FF = -19
integer, parameter :: ovm_FUSE_F_VLRF = -20
integer, parameter :: ovm_FUSE_F_FVLR = -21
integer, parameter :: ovm_FUSE_SP_FF = -22
integer, parameter :: ovm_FUSE_F_SPF = -23
integer, parameter :: ovm_FUSE_F_FSP = -24

```

```

integer, parameter :: ovm_FUSE_S_FF = -25
integer, parameter :: ovm_FUSE_F_SF = -26
integer, parameter :: ovm_FUSE_F_FS = -27
integer, parameter :: ovm_FUSE_P_FF = -28
integer, parameter :: ovm_FUSE_F_PF = -29
integer, parameter :: ovm_FUSE_F_FP = -30
integer, parameter :: ovm_FUSE_SL_FF = -31
integer, parameter :: ovm_FUSE_F_SLF = -32
integer, parameter :: ovm_FUSE_F_FSL = -33
integer, parameter :: ovm_FUSE_SR_FF = -34
integer, parameter :: ovm_FUSE_F_SRF = -35
integer, parameter :: ovm_FUSE_F_FSR = -36
integer, parameter :: ovm_FUSE_SLR_FF = -37
integer, parameter :: ovm_FUSE_F_SLRF = -38
integer, parameter :: ovm_FUSE_F_FSLR = -39

```

```

integer, parameter :: ovm_FUSE_G_GG = -40
integer, parameter :: ovm_FUSE_V_SS = -41
integer, parameter :: ovm_FUSE_S_VV = -42
integer, parameter :: ovm_FUSE_S_VS = -43
integer, parameter :: ovm_FUSE_V_SV = -44
integer, parameter :: ovm_FUSE_S_SS = -45
integer, parameter :: ovm_FUSE_S_SVV = -46
integer, parameter :: ovm_FUSE_V_SSV = -47
integer, parameter :: ovm_FUSE_S_SSS = -48
integer, parameter :: ovm_FUSE_V_VVV = -49

```

```

integer, parameter :: ovm_FUSE_S_G2 = -50
integer, parameter :: ovm_FUSE_G_SG = -51
integer, parameter :: ovm_FUSE_G_GS = -52
integer, parameter :: ovm_FUSE_S_G2_SKEW = -53
integer, parameter :: ovm_FUSE_G_SG_SKEW = -54
integer, parameter :: ovm_FUSE_G_GS_SKEW = -55

```

Shorthands

```

⟨p⟩≡
  vm%momenta(i(5))

⟨m⟩≡
  vm%mass(i(2))

⟨p1⟩≡
  vm%momenta(curr(6))

⟨p2⟩≡
  vm%momenta(curr(8))

⟨v1⟩≡
  vm%vectors(curr(5))%v

⟨v2⟩≡
  vm%vectors(curr(7))%v

⟨s1⟩≡
  vm%scalars(curr(5))%v

⟨s2⟩≡
  vm%scalars(curr(7))%v

```

```

<c>≡
  sgn_coupl_cmplx(vm, curr(2))
<c1>≡
  sgn_coupl_cmplx2(vm, curr(2), 1)
<c2>≡
  sgn_coupl_cmplx2(vm, curr(2), 2)
<check for matching color and flavor amplitude of brakel (old)>≡
  if ((i(4) == o%cols(1)) .or. (i(4) == o%cols(2)) .or. &
      ((mode%col_MC .eq. FULL_SUM) .or. (mode%col_MC .eq. DIAG_COL))) then
Just a stub for now. Will be reimplemented with the polymorph type color
similar to the select type(helicity) when we need it.
<check for matching color and flavor amplitude>≡
<cases of decode>+≡
  case (ovm_CALC_BRAKET)
    <check for matching color and flavor amplitude>
    tmp = instruction_index + 1
    do
      if (tmp > vm%N_instructions) exit
      curr = vm%instructions(:, tmp)
      if (curr(1) >= 0) exit ! End of fusions
      select case (curr(1))
        case (ovm_FUSE_V_FF, ovm_FUSE_VL_FF, ovm_FUSE_VR_FF)
          brakel = vm%vectors(curr(4))%v * vec_ff(vm, curr)

        case (ovm_FUSE_F_VF, ovm_FUSE_F_VLF, ovm_FUSE_F_VRF)
          brakel = vm%conjspinors(curr(4))%v * ferm_vf(vm, curr)

        case (ovm_FUSE_F_FV, ovm_FUSE_F_FVL, ovm_FUSE_F_FVR)
          brakel = ferm_fv(vm, curr) * vm%spinors(curr(4))%v

        case (ovm_FUSE_VA_FF)
          brakel = vm%vectors(curr(4))%v * vec_ff2(vm, curr)

        case (ovm_FUSE_F_VAF)
          brakel = vm%conjspinors(curr(4))%v * ferm_vf2(vm, curr)

        case (ovm_FUSE_F_FVA)
          brakel = ferm_fv2(vm, curr) * vm%spinors(curr(4))%v

        case (ovm_FUSE_S_FF, ovm_FUSE_SP_FF)
          brakel = vm%scalars(curr(4))%v * scal_ff(vm, curr)

        case (ovm_FUSE_F_SF, ovm_FUSE_F_SPF)
          brakel = vm%conjspinors(curr(4))%v * ferm_sf(vm, curr)

        case (ovm_FUSE_F_FS, ovm_FUSE_F_FSP)
          brakel = ferm_fs(vm, curr) * vm%spinors(curr(4))%v

        case (ovm_FUSE_G_GG)
          brakel = vm%vectors(curr(4))%v * &
            g_gg(<c>, &
              <v1>, <p1>, &

```



```

     $\langle v2 \rangle, \langle p2 \rangle$ )

case (ovm_FUSE_S_VV)
    braket = vm%scalars(curr(4))%v *  $\langle c \rangle$  * &
            ( $\langle v1 \rangle$  * vm%vectors(curr(6))%v)

case (ovm_FUSE_V_SS)
    braket = vm%vectors(curr(4))%v * &
            v_ss( $\langle c \rangle, \langle s1 \rangle, \langle p1 \rangle, \langle s2 \rangle, \langle p2 \rangle$ )

case (ovm_FUSE_S_G2, ovm_FUSE_S_G2_SKEW)
    braket = vm%scalars(curr(4))%v * scal_g2(vm, curr)

case (ovm_FUSE_G_SG, ovm_FUSE_G_GS, ovm_FUSE_G_SG_SKEW, ovm_FUSE_G_GS_SKEW)
    braket = vm%vectors(curr(4))%v * gauge_sg(vm, curr)

case (ovm_FUSE_S_VS)
    braket = vm%scalars(curr(4))%v * &
            s_vs( $\langle c \rangle, \langle v1 \rangle, \langle p1 \rangle, \langle s2 \rangle, \langle p2 \rangle$ )

case (ovm_FUSE_V_SV)
    braket = (vm%vectors(curr(4))%v * vm%vectors(curr(6))%v) * &
            ( $\langle c \rangle$  *  $\langle s1 \rangle$ )

case (ovm_FUSE_S_SS)
    braket = vm%scalars(curr(4))%v * &
             $\langle c \rangle$  * &
            ( $\langle s1 \rangle$  * vm%scalars(curr(6))%v)

case (ovm_FUSE_S_SSS)
    braket = vm%scalars(curr(4))%v * &
             $\langle c \rangle$  * &
            ( $\langle s1 \rangle$  * vm%scalars(curr(6))%v * &
             $\langle s2 \rangle$ )

case (ovm_FUSE_S_SVV)
    braket = vm%scalars(curr(4))%v * &
             $\langle c \rangle$  * &
             $\langle s1 \rangle$  * (vm%vectors(curr(6))%v * &
             $\langle v2 \rangle$ )

case (ovm_FUSE_V_SSV)
    braket = vm%vectors(curr(4))%v * &
            ( $\langle c \rangle$  *  $\langle s1 \rangle$  * &
            vm%scalars(curr(6))%v) *  $\langle v2 \rangle$ 

case (ovm_FUSE_V_VVV)
    braket =  $\langle c \rangle$  * &
            ( $\langle v1 \rangle$  * vm%vectors(curr(6))%v) * &
            (vm%vectors(curr(4))%v *  $\langle v2 \rangle$ )

```

```

    case default
        print *, 'Braket', curr(1), 'not implemented'
        stop 1

    end select
    vm%amplitudes(i(4)) = vm%amplitudes(i(4)) + curr(3) * braket
    tmp = tmp + 1
end do

vm%amplitudes(i(4)) = vm%amplitudes(i(4)) * i(2)
if (i(5) > 1) then
    vm%amplitudes(i(4)) = vm%amplitudes(i(4)) * &          ! Symmetry factor
    (one / sqrt(real(i(5), kind=default)))
end if

```

### Propagators

```

<OVM Instructions>+≡
integer, parameter :: ovm_PROPAGATE_SCALAR = 51
integer, parameter :: ovm_PROPAGATE_COL_SCALAR = 52
integer, parameter :: ovm_PROPAGATE_GHOST = 53
integer, parameter :: ovm_PROPAGATE_SPINOR = 54
integer, parameter :: ovm_PROPAGATE_CONJSPINOR = 55
integer, parameter :: ovm_PROPAGATE_MAJORANA = 56
integer, parameter :: ovm_PROPAGATE_COL_MAJORANA = 57
integer, parameter :: ovm_PROPAGATE_UNITARITY = 58
integer, parameter :: ovm_PROPAGATE_COL_UNITARITY = 59
integer, parameter :: ovm_PROPAGATE_FEYNMAN = 60
integer, parameter :: ovm_PROPAGATE_COL_FEYNMAN = 61
integer, parameter :: ovm_PROPAGATE_VECTORSPINOR = 62
integer, parameter :: ovm_PROPAGATE_TENSOR2 = 63
integer, parameter :: ovm_PROPAGATE_NONE = 64

<check for matching color and flavor amplitude of propagator (old)>≡
if ((mode%col_MC .eq. FULL_SUM) .or. (mode%col_MC .eq. DIAG_COL)) then
    select case(i(1))
        case (ovm_PROPAGATE_PSI)
            go = .not. vm%spinors%c(i(4))
        case (ovm_PROPAGATE_PSIBAR)
            go = .not. vm%conjspinors%c(i(4))
        case (ovm_PROPAGATE_UNITARITY, ovm_PROPAGATE_FEYNMAN, &
            ovm_PROPAGATE_COL_FEYNMAN)
            go = .not. vm%vectors%c(i(4))
        end select
    else
        go = (i(8) == o%cols(1)) .or. (i(8) == o%cols(2))
    end if
    if (go) then
<cases of decode>+≡
    <check for matching color and flavor amplitude>
    case (ovm_PROPAGATE_SCALAR : ovm_PROPAGATE_NONE)
        tmp = instruction_index + 1
    do

```

---

```

curr = vm%instructions(:,tmp)
if (curr(1) >= 0) exit ! End of fusions
select case (curr(1))
case (ovm_FUSE_V_FF, ovm_FUSE_VL_FF, ovm_FUSE_VR_FF)
  vm%vectors(curr(4))%v = vm%vectors(curr(4))%v + curr(3) * &
    vec_ff(vm, curr)

case (ovm_FUSE_F_VF, ovm_FUSE_F_VLF, ovm_FUSE_F_VRF)
  vm%spinors(curr(4))%v = vm%spinors(curr(4))%v + curr(3) * &
    ferm_vf(vm, curr)

case (ovm_FUSE_F_FV, ovm_FUSE_F_FVL, ovm_FUSE_F_FVR)
  vm%conjspinors(curr(4))%v = vm%conjspinors(curr(4))%v + curr(3) * &
    ferm_fv(vm, curr)

case (ovm_FUSE_VA_FF)
  vm%vectors(curr(4))%v = vm%vectors(curr(4))%v + curr(3) * &
    vec_ff2(vm, curr)

case (ovm_FUSE_F_VAF)
  vm%spinors(curr(4))%v = vm%spinors(curr(4))%v + curr(3) * &
    ferm_vf2(vm, curr)

case (ovm_FUSE_F_FVA)
  vm%conjspinors(curr(4))%v = vm%conjspinors(curr(4))%v + curr(3) * &
    ferm_fv2(vm, curr)

case (ovm_FUSE_S_FF, ovm_FUSE_SP_FF)
  vm%scalars(curr(4))%v = vm%scalars(curr(4))%v + curr(3) * &
    scal_ff(vm, curr)

case (ovm_FUSE_F_SF, ovm_FUSE_F_SPF)
  vm%spinors(curr(4))%v = vm%spinors(curr(4))%v + curr(3) * &
    ferm_sf(vm, curr)

case (ovm_FUSE_F_FS, ovm_FUSE_F_FSP)
  vm%conjspinors(curr(4))%v = vm%conjspinors(curr(4))%v + curr(3) * &
    ferm_fs(vm, curr)

case (ovm_FUSE_G_GG)
  vm%vectors(curr(4))%v = vm%vectors(curr(4))%v + curr(3) * &
    g_gg(<c>, <v1>, &
      <p1>, <v2>, &
      <p2>)

case (ovm_FUSE_S_VV)
  vm%scalars(curr(4))%v = vm%scalars(curr(4))%v + curr(3) * &
    <c> * &
    (<v1> * vm%vectors(curr(6))%v)

case (ovm_FUSE_V_SS)
  vm%vectors(curr(4))%v = vm%vectors(curr(4))%v + curr(3) * &
    v_ss(<c>, <s1>, <p1>, &
      <s2>, <p2>)

```

---

```

case (ovm_FUSE_S_G2, ovm_FUSE_S_G2_SKEW)
  vm%scalars(curr(4))%v = vm%scalars(curr(4))%v + &
    scal_g2(vm, curr) * curr(3)

case (ovm_FUSE_G_SG, ovm_FUSE_G_GS, ovm_FUSE_G_SG_SKEW, ovm_FUSE_G_GS_SKEW)
  vm%vectors(curr(4))%v = vm%vectors(curr(4))%v + &
    gauge_sg(vm, curr) * curr(3)

case (ovm_FUSE_S_VS)
  vm%scalars(curr(4))%v = vm%scalars(curr(4))%v + &
    s_vs( $\langle c \rangle$ , &
       $\langle v1 \rangle$ ,  $\langle p1 \rangle$ , &
       $\langle s2 \rangle$ ,  $\langle p2 \rangle$ ) * curr(3)

case (ovm_FUSE_V_SV)
  vm%vectors(curr(4))%v = vm%vectors(curr(4))%v + &
    vm%vectors(curr(6))%v * &
    ( $\langle c \rangle$  *  $\langle s1 \rangle$  * curr(3))

case (ovm_FUSE_S_SS)
  vm%scalars(curr(4))%v = vm%scalars(curr(4))%v + &
     $\langle c \rangle$  * &
    ( $\langle s1 \rangle$  * vm%scalars(curr(6))%v) * curr(3)

case (ovm_FUSE_S_SSS)
  vm%scalars(curr(4))%v = vm%scalars(curr(4))%v + &
     $\langle c \rangle$  * &
    ( $\langle s1 \rangle$  * vm%scalars(curr(6))%v * &
     $\langle s2 \rangle$ ) * curr(3)

case (ovm_FUSE_S_SVV)
  vm%scalars(curr(4))%v = vm%scalars(curr(4))%v + &
     $\langle c \rangle$  * &
     $\langle s1 \rangle$  * (vm%vectors(curr(6))%v * &
     $\langle v2 \rangle$ ) * curr(3)

case (ovm_FUSE_V_SSV)
  vm%vectors(curr(4))%v = vm%vectors(curr(4))%v + &
    ( $\langle c \rangle$  *  $\langle s1 \rangle$  * &
    vm%scalars(curr(6))%v) *  $\langle v2 \rangle$  * curr(3)

case (ovm_FUSE_V_VVV)
  vm%vectors(curr(4))%v = vm%vectors(curr(4))%v + &
    ( $\langle c \rangle$  * ( $\langle v1 \rangle$  * &
    vm%vectors(curr(6))%v)) * curr(3) *  $\langle v2 \rangle$ 

case default
  print *, 'Fusion', curr(1), 'not implemented'
  stop 1

end select
tmp = tmp + 1

```

```

end do

select case (i(3))
case (0)
  w = zero

case (1)
  w = vm%width(i(2))

case (2)
  w = wd_tl( $\langle p \rangle$ , vm%width(i(2)))

case default
  print *, 'not implemented'
  stop 1

end select

select case (i(1))
 $\langle propagator \text{ cases in decode} \rangle$ 
end select

 $\langle propagator \text{ cases in decode} \rangle \equiv$ 
case (ovm_PROPAGATE_SCALAR)
  vm%scalars(i(4))%v = pr_phi( $\langle p \rangle$ ,  $\langle m \rangle$ , &
                               w, vm%scalars(i(4))%v)
  vm%scalars(i(4))%c = .True.

case (ovm_PROPAGATE_COL_SCALAR)
  vm%scalars(i(4))%v = - one / N_ * pr_phi( $\langle p \rangle$ , &
                                              $\langle m \rangle$ , w, vm%scalars(i(4))%v)
  vm%scalars(i(4))%c = .True.

case (ovm_PROPAGATE_GHOST)
  vm%scalars(i(4))%v = imago * pr_phi( $\langle p \rangle$ ,  $\langle m \rangle$ , &
                                       w, vm%scalars(i(4))%v)
  vm%scalars(i(4))%c = .True.

case (ovm_PROPAGATE_SPINOR)
  vm%spinors(i(4))%v = pr_psi( $\langle p \rangle$ ,  $\langle m \rangle$ , &
                              w, vm%spinors(i(4))%v)
  vm%spinors(i(4))%c = .True.

case (ovm_PROPAGATE_CONJSPINOR)
  vm%conjspinors(i(4))%v = pr_psibar( $\langle p \rangle$ ,  $\langle m \rangle$ , &
                                       w, vm%conjspinors(i(4))%v)
  vm%conjspinors(i(4))%c = .True.

case (ovm_PROPAGATE_MAJORANA)
  vm%bispinors(i(4))%v = bi_pr_psi( $\langle p \rangle$ ,  $\langle m \rangle$ , &
                                    w, vm%bispinors(i(4))%v)
  vm%bispinors(i(4))%c = .True.

case (ovm_PROPAGATE_COL_MAJORANA)

```

```

vm%bispinors(i(4))%v = (- one / N_) * &
                        bi_pr_psi(<p>, <m>, &
                                w, vm%bispinors(i(4))%v)
vm%bispinors(i(4))%c = .True.

case (ovm_PROPAGATE_UNITARITY)
vm%vectors(i(4))%v = pr_unitarity(<p>, <m>, &
                                w, vm%vectors(i(4))%v)
vm%vectors(i(4))%c = .True.

case (ovm_PROPAGATE_COL_UNITARITY)
vm%vectors(i(4))%v = - one / N_ * pr_unitarity(<p>, &
                                                <m>, w, vm%vectors(i(4))%v)
vm%vectors(i(4))%c = .True.

case (ovm_PROPAGATE_FEYNMAN)
vm%vectors(i(4))%v = pr_feynman(<p>, vm%vectors(i(4))%v)
vm%vectors(i(4))%c = .True.

case (ovm_PROPAGATE_COL_FEYNMAN)
vm%vectors(i(4))%v = - one / N_ * &
                        pr_feynman(<p>, vm%vectors(i(4))%v)
vm%vectors(i(4))%c = .True.

case (ovm_PROPAGATE_VECTORSPINOR)
vm%vectorspinors(i(4))%v = pr_grav(<p>, <m>, &
                                w, vm%vectorspinors(i(4))%v)
vm%vectorspinors(i(4))%c = .True.

case (ovm_PROPAGATE_TENSOR2)
vm%tensors_2(i(4))%v = pr_tensor(<p>, <m>, &
                                w, vm%tensors_2(i(4))%v)
vm%tensors_2(i(4))%c = .True.

case (ovm_PROPAGATE_NONE)
! This will not work with color MC. Appropriate type%c has to be set to
! .True.

```

### X.21.5 Helper functions

Factoring out these parts helps a lot to keep sane but might hurt the performance of the VM noticeably. In that case, we have to copy & paste to avoid the additional function calls. Note that with preprocessor macros, we could maintain this factorized form (and factor out even more since types don't have to match), in case we would decide to allow this

```

<load outer wave function>≡
!select type (h)
!type is (hel_trigonometric)
!wf%v = (cos (h%theta) * load_wf (m, p, + 1) + &
        !sin (h%theta) * load_wf (m, p, - 1)) * sqrt2
!type is (hel_exponential)
!wf%v = exp (+ imago * h%phi) * load_wf (m, p, + 1) + &

```

```

        !exp (- imago * h%phi) * load_wf (m, p, - 1)
!type is (hel_spherical)
    !wf%v = (exp (+ imago * h%phi) * cos (h%theta) * load_wf (m, p, + 1) + &
        !exp (- imago * h%phi) * sin (h%theta) * load_wf (m, p, - 1)) * &
        !sqrt2
!type is(hel_discrete)
    !wf%v = load_wf (m, p, h%i)
!end select
wf%v = load_wf (m, p, h)
wf%c = .True.

```

Caveat: Helicity MC not tested with Majorana particles but should be fine

```

<check for matching color and flavor amplitude of wf (old)>≡
if ((mode%col_MC .eq. FULL_SUM) .or. (mode%col_MC .eq. DIAG_COL)) then
    go = .not. vm%spinors%c(i(4))
else
    go = (i(8) == o%cols(1)) .or. (i(8) == o%cols(2))
end if
if (go) ..

```

<OVM Procedure Implementations>+≡

```

subroutine load_bispinor(wf, p, m, h, opcode)
    type(vm_bispinor), intent(out) :: wf
    type(momentum), intent(in) :: p
    real(default), intent(in) :: m
    !class(helicity_t), intent(in) :: h
    integer, intent(in) :: h
    integer, intent(in) :: opcode
    procedure(bi_u), pointer :: load_wf
    <check for matching color and flavor amplitude>
    select case (opcode)
    case (ovm_LOAD_MAJORANA_INC)
        load_wf => bi_u
    case (ovm_LOAD_MAJORANA_OUT)
        load_wf => bi_v
    case default
        load_wf => null()
    end select
    <load outer wave function>
end subroutine load_bispinor

```

```

subroutine load_spinor(wf, p, m, h, opcode)
    type(vm_spinor), intent(out) :: wf
    type(momentum), intent(in) :: p
    real(default), intent(in) :: m
    !class(helicity_t), intent(in) :: h
    integer, intent(in) :: h
    integer, intent(in) :: opcode
    procedure(u), pointer :: load_wf
    <check for matching color and flavor amplitude>
    select case (opcode)
    case (ovm_LOAD_SPINOR_INC)
        load_wf => u
    case (ovm_LOAD_SPINOR_OUT)
        load_wf => v
    end select
end subroutine load_spinor

```

```

    case default
        load_wf => null()
    end select
    <load outer wave function>
end subroutine load_spinor

subroutine load_conjspinor(wf, p, m, h, opcode)
    type(vm_conjspinor), intent(out) :: wf
    type(momentum), intent(in) :: p
    real(default), intent(in) :: m
    !class(helicity_t), intent(in) :: h
    integer, intent(in) :: h
    integer, intent(in) :: opcode
    procedure(ubar), pointer :: load_wf
    <check for matching color and flavor amplitude>
    select case (opcode)
    case (ovm_LOAD_CONJSPINOR_INC)
        load_wf => vbar
    case (ovm_LOAD_CONJSPINOR_OUT)
        load_wf => ubar
    case default
        load_wf => null()
    end select
    <load outer wave function>
end subroutine load_conjspinor

subroutine load_vector(wf, p, m, h, opcode)
    type(vm_vector), intent(out) :: wf
    type(momentum), intent(in) :: p
    real(default), intent(in) :: m
    !class(helicity_t), intent(in) :: h
    integer, intent(in) :: h
    integer, intent(in) :: opcode
    procedure(eps), pointer :: load_wf
    <check for matching color and flavor amplitude>
    load_wf => eps
    <load outer wave function>
    if (opcode == ovm_LOAD_VECTOR_OUT) then
        wf%v = conjg(wf%v)
    end if
end subroutine load_vector

<OVM Procedure Implementations>+≡
function ferm_vf(vm, curr) result (x)
    type(spinor) :: x
    class(vm_t), intent(in) :: vm
    integer, dimension(:), intent(in) :: curr
    procedure(f_vf), pointer :: load_wf
    select case (curr(1))
    case (ovm_FUSE_F_VF)
        load_wf => f_vf
    case (ovm_FUSE_F_VLF)
        load_wf => f_vlf
    case (ovm_FUSE_F_VRF)

```



```

        load_wf => f_vrf
    case default
        load_wf => null()
    end select
    x = load_wf(<c>, <v1>, vm%spinors(curr(6))%v)
end function ferm_vf

function ferm_vf2(vm, curr) result (x)
    type(spinor) :: x
    class(vm_t), intent(in) :: vm
    integer, dimension(:), intent(in) :: curr
    procedure(f_vaf), pointer :: load_wf
    select case (curr(1))
    case (ovm_FUSE_F_VAF)
        load_wf => f_vaf
    case default
        load_wf => null()
    end select
    x = f_vaf(<c1>, <c2>, <v1>, vm%spinors(curr(6))%v)
end function ferm_vf2

function ferm_sf(vm, curr) result (x)
    type(spinor) :: x
    class(vm_t), intent(in) :: vm
    integer, dimension(:), intent(in) :: curr
    select case (curr(1))
    case (ovm_FUSE_F_SF)
        x = f_sf(<c>, <s1>, vm%spinors(curr(6))%v)
    case (ovm_FUSE_F_SPF)
        x = f_spf(<c1>, <c2>, <s1>, vm%spinors(curr(6))%v)
    case default
    end select
end function ferm_sf

function ferm_fv(vm, curr) result (x)
    type(conjspinor) :: x
    class(vm_t), intent(in) :: vm
    integer, dimension(:), intent(in) :: curr
    procedure(f_fv), pointer :: load_wf
    select case (curr(1))
    case (ovm_FUSE_F_FV)
        load_wf => f_fv
    case (ovm_FUSE_F_FVL)
        load_wf => f_fvl
    case (ovm_FUSE_F_FVR)
        load_wf => f_fvr
    case default
        load_wf => null()
    end select
    x = load_wf(<c>, vm%conjspinors(curr(5))%v, vm%vectors(curr(6))%v)
end function ferm_fv

function ferm_fv2(vm, curr) result (x)
    type(conjspinor) :: x

```

```

class(vm_t), intent(in) :: vm
integer, dimension(:), intent(in) :: curr
procedure(f_fva), pointer :: load_wf
select case (curr(1))
case (ovm_FUSE_F_FVA)
    load_wf => f_fva
case default
    load_wf => null()
end select
x = f_fva(<c1>, <c2>, &
          vm%conjspinors(curr(5))%v, vm%vectors(curr(6))%v)
end function ferm_fv2

function ferm_fs(vm, curr) result (x)
type(conjspinor) :: x
class(vm_t), intent(in) :: vm
integer, dimension(:), intent(in) :: curr
procedure(f_fs), pointer :: load_wf
select case (curr(1))
case (ovm_FUSE_F_FS)
    x = f_fs(<c>, vm%conjspinors(curr(5))%v, vm%scalars(curr(6))%v)
case (ovm_FUSE_F_FSP)
    x = f_fsp(<c1>, <c2>, &
              vm%conjspinors(curr(5))%v, vm%scalars(curr(6))%v)
case default
    x%a = zero
end select
end function ferm_fs

function vec_ff(vm, curr) result (x)
type(vector) :: x
class(vm_t), intent(in) :: vm
integer, dimension(:), intent(in) :: curr
procedure(v_ff), pointer :: load_wf
select case (curr(1))
case (ovm_FUSE_V_FF)
    load_wf => v_ff
case (ovm_FUSE_VL_FF)
    load_wf => vl_ff
case (ovm_FUSE_VR_FF)
    load_wf => vr_ff
case default
    load_wf => null()
end select
x = load_wf(<c>, vm%conjspinors(curr(5))%v, vm%spinors(curr(6))%v)
end function vec_ff

function vec_ff2(vm, curr) result (x)
type(vector) :: x
class(vm_t), intent(in) :: vm
integer, dimension(:), intent(in) :: curr
procedure(va_ff), pointer :: load_wf
select case (curr(1))
case (ovm_FUSE_VA_FF)

```

```

        load_wf => va_ff
    case default
        load_wf => null()
    end select
    x = load_wf( $\langle c1 \rangle$ ,  $\langle c2 \rangle$ , &
        vm%conjspinors(curr(5))%v, vm%spinors(curr(6))%v)
end function vec_ff2

function scal_ff(vm, curr) result (x)
    complex(default) :: x
    class(vm_t), intent(in) :: vm
    integer, dimension(:), intent(in) :: curr
    select case (curr(1))
    case (ovm_FUSE_S_FF)
        x = s_ff( $\langle c \rangle$ , &
            vm%conjspinors(curr(5))%v, vm%spinors(curr(6))%v)
    case (ovm_FUSE_SP_FF)
        x = sp_ff( $\langle c1 \rangle$ ,  $\langle c2 \rangle$ , &
            vm%conjspinors(curr(5))%v, vm%spinors(curr(6))%v)
    case default
        x = zero
    end select
end function scal_ff

function scal_g2(vm, curr) result (x)
    complex(default) :: x
    class(vm_t), intent(in) :: vm
    integer, dimension(:), intent(in) :: curr
    select case (curr(1))
    case (ovm_FUSE_S_G2)
        x =  $\langle c \rangle * ((\langle p1 \rangle * \langle v2 \rangle) * \&$ 
             $(\langle p2 \rangle * \langle v1 \rangle) - \&$ 
             $(\langle p1 \rangle * \langle p2 \rangle) * \&$ 
             $(\langle v2 \rangle * \langle v1 \rangle))$ 
    case (ovm_FUSE_S_G2_SKEW)
        x = - phi_vv( $\langle c \rangle$ ,  $\langle p1 \rangle$ ,  $\langle p2 \rangle$ , &
             $\langle v1 \rangle$ ,  $\langle v2 \rangle$ )
    case default
        x = zero
    end select
end function scal_g2

pure function gauge_sg(vm, curr) result (x)
    type(vector) :: x
    class(vm_t), intent(in) :: vm
    integer, dimension(:), intent(in) :: curr
    select case (curr(1))
    case (ovm_FUSE_G_SG)
        x =  $\langle c \rangle * \langle s1 \rangle * ( \&$ 
             $-(\langle p1 \rangle + \langle p2 \rangle) * \&$ 
             $\langle v2 \rangle) * \langle p2 \rangle - \&$ 
             $(-(\langle p1 \rangle + \langle p2 \rangle) * \&$ 
             $\langle p2 \rangle) * \langle v2 \rangle)$ 
    case (ovm_FUSE_G_GS)

```

```

      x = <c> * <s1> * ( &
        -((<p1> + <p2>) * &
          <v2>) * <p2> - &
        -((<p1> + <p2>) * &
          <p2>) * <v2>)
    case (ovm_FUSE_G_SG_SKEW)
      x = - v_phiv(<c>, <s1>, <p1>, &
        <p2>, <v2>)
    case (ovm_FUSE_G_GS_SKEW)
      x = - v_phiv(<c>, <s2>, <p1>, &
        <p2>, <v1>)
    case default
      x = [zero, zero, zero, zero]
    end select
  end function gauge_sg

```

Some really tiny ones that hopefully get inlined by the compiler

*(OVM Procedure Implementations)+≡*

```

elemental function sgn_coupl_cmplx(vm, j) result (s)
  class(vm_t), intent(in) :: vm
  integer, intent(in) :: j
  complex(default) :: s
  s = isign(1, j) * vm%coupl_cmplx(abs(j))
end function sgn_coupl_cmplx

elemental function sgn_coupl_cmplx2(vm, j, i) result (s)
  class(vm_t), intent(in) :: vm
  integer, intent(in) :: j, i
  complex(default) :: s
  if (i == 1) then
    s = isign(1, j) * vm%coupl_cmplx2(i, abs(j))
  else
    s = isign(1, j) * vm%coupl_cmplx2(i, abs(j))
  end if
end function sgn_coupl_cmplx2

elemental function int_to_log(i) result(yorn)
  integer, intent(in) :: i
  logical :: yorn
  if (i /= 0) then
    yorn = .true.
  else
    yorn = .false.
  end if
end function

elemental function color_factor(num, den, pwr) result (cf)
  integer, intent(in) :: num, den, pwr
  real(kind=default) :: cf
  if (pwr == 0) then
    cf = (one * num) / den
  else
    cf = (one * num) / den * (N**pwr)
  end if

```

```
end function color_factor
```

### *X.21.6 O'Mega Interface*

We want to keep the interface close to the native Fortran code but of course one has to hand over the vm additionally

*<VM: TBP>+≡*

```
procedure :: number_particles_in => vm_number_particles_in
procedure :: number_particles_out => vm_number_particles_out
procedure :: number_color_indices => vm_number_color_indices
procedure :: reset_helicity_selection => vm_reset_helicity_selection
procedure :: new_event => vm_new_event
procedure :: color_sum => vm_color_sum
procedure :: spin_states => vm_spin_states
procedure :: number_spin_states => vm_number_spin_states
procedure :: number_color_flows => vm_number_color_flows
procedure :: flavor_states => vm_flavor_states
procedure :: number_flavor_states => vm_number_flavor_states
procedure :: color_flows => vm_color_flows
procedure :: color_factors => vm_color_factors
procedure :: number_color_factors => vm_number_color_factors
procedure :: is_allowed => vm_is_allowed
procedure :: get_amplitude => vm_get_amplitude
```

*<OVM Procedure Implementations>+≡*

```
elemental function vm_number_particles_in (vm) result (n)
  class(vm_t), intent(in) :: vm
  integer :: n
  n = vm%N_prt_in
end function vm_number_particles_in

elemental function vm_number_particles_out (vm) result (n)
  class(vm_t), intent(in) :: vm
  integer :: n
  n = vm%N_prt_out
end function vm_number_particles_out

elemental function vm_number_spin_states (vm) result (n)
  class(vm_t), intent(in) :: vm
  integer :: n
  n = vm%N_helicities
end function vm_number_spin_states

pure subroutine vm_spin_states (vm, a)
  class(vm_t), intent(in) :: vm
  integer, dimension(:,:), intent(out) :: a
  a = vm%table_spin
end subroutine vm_spin_states

elemental function vm_number_flavor_states (vm) result (n)
  class(vm_t), intent(in) :: vm
  integer :: n
  n = vm%N_flavors
```

```

end function vm_number_flavor_states

pure subroutine vm_flavor_states (vm, a)
  class(vm_t), intent(in) :: vm
  integer, dimension(:,:), intent(out) :: a
  a = vm%table_flavor
end subroutine vm_flavor_states

elemental function vm_number_color_indices (vm) result (n)
  class(vm_t), intent(in) :: vm
  integer :: n
  n = vm%N_col_indices
end function vm_number_color_indices

elemental function vm_number_color_flows (vm) result (n)
  class(vm_t), intent(in) :: vm
  integer :: n
  n = vm%N_col_flows
end function vm_number_color_flows

pure subroutine vm_color_flows (vm, a, g)
  class(vm_t), intent(in) :: vm
  integer, dimension(:,:), intent(out) :: a
  logical, dimension(:,:), intent(out) :: g
  a = vm%table_color_flows
  g = vm%table_ghost_flags
end subroutine vm_color_flows

elemental function vm_number_color_factors (vm) result (n)
  class(vm_t), intent(in) :: vm
  integer :: n
  n = vm%N_col_factors
end function vm_number_color_factors

pure subroutine vm_color_factors (vm, cf)
  class(vm_t), intent(in) :: vm
  type(OCF), dimension(:), intent(out) :: cf
  cf = vm%table_color_factors
end subroutine vm_color_factors

! pure & ! pure unless OpenMp
function vm_color_sum (vm, flv, hel) result (amp2)
  class(vm_t), intent(in) :: vm
  integer, intent(in) :: flv, hel
  real(default) :: amp2
  amp2 = ovm_color_sum (flv, hel, vm%table_amplitudes, vm%table_color_factors)
end function vm_color_sum

subroutine vm_new_event (vm, p)
  class(vm_t), intent(inout) :: vm
  real(default), dimension(0:3,*), intent(in) :: p
  logical :: mask_dirty
  integer :: hel
  call vm%run (p)

```

```

if ((vm%hel_threshold .gt. 0) .and. (vm%hel_count .le. vm%hel_cutoff)) then
  call omega_update_helicity_selection (vm%hel_count, vm%table_amplitudes, &
    vm%hel_max_abs, vm%hel_sum_abs, vm%hel_is_allowed, vm%hel_threshold, &
    vm%hel_cutoff, mask_dirty)
  if (mask_dirty) then
    vm%hel_finite = 0
    do hel = 1, vm%N_helicities
      if (vm%hel_is_allowed(hel)) then
        vm%hel_finite = vm%hel_finite + 1
        vm%hel_map(vm%hel_finite) = hel
      end if
    end do
  end if
end if
end subroutine vm_new_event

pure subroutine vm_reset_helicity_selection (vm, threshold, cutoff)
  class(vm_t), intent(inout) :: vm
  real(kind=default), intent(in) :: threshold
  integer, intent(in) :: cutoff
  integer :: i
  vm%hel_is_allowed = .True.
  vm%hel_max_abs = 0
  vm%hel_sum_abs = 0
  vm%hel_count = 0
  vm%hel_threshold = threshold
  vm%hel_cutoff = cutoff
  vm%hel_map = (/ (i, i = 1, vm%N_helicities) /)
  vm%hel_finite = vm%N_helicities
end subroutine vm_reset_helicity_selection

pure function vm_is_allowed (vm, flv, hel, col) result (yorn)
  class(vm_t), intent(in) :: vm
  logical :: yorn
  integer, intent(in) :: flv, hel, col
  yorn = vm%table_flv_col_is_allowed(flv,col) .and. vm%hel_is_allowed(hel)
end function vm_is_allowed

pure function vm_get_amplitude (vm, flv, hel, col) result (amp_result)
  class(vm_t), intent(in) :: vm
  complex(kind=default) :: amp_result
  integer, intent(in) :: flv, hel, col
  amp_result = vm%table_amplitudes(flv, col, hel)
end function vm_get_amplitude

```

(C)yleft≡

```

! $Id: omegalib.nw 6301 2014-11-25 09:34:00Z bchokoufe $
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```



---

# —Y—

## INDEX

This index has been generated automatically and might not be 100%ly accurate. In particular, hyperlinks have been observed to be off by one page.

\*, **27, 27, 19**, used: 826, 826,  
 828, 789, 790, 790, 792,  
 795, 795, 812, 27, 29, 30,  
 30, 31, 32, 32, 32, 32, 47,  
 56, 62, 86, 86, 565, 188,  
 189, 96, 108, 112, 122,  
 263, 267, 484, 487, ??, ??,  
 519, 522, 555, 559, 294,  
 315, 330, 331, 342, 361,  
 373, 383, 394, 399, 401,  
 424, 441, ??, ??  
 +, **27, 27, 19**, used: ??, ??, ??,  
 ??, 756, 756, 743, 743,  
 746, 753, 826, 828, 790,  
 790, 790, 793, 793, 794,  
 27, 29, 29, 30, 30, 30, 31,  
 32, 32, 32, 33, 47, 56, 57,  
 60, 62, 63, 65, 181, 181,  
 84, 86, 700, 565, 568, 572,  
 574, 211, 97, 98, 116, 120,  
 122, 122, 124, 709, 715,  
 263, 484, 487, ??, ??, 519,  
 522, 555, 559, 294, 315,  
 330, 331, 342, 361, 373,  
 383, 394, 399, 405, 424,  
 441, ??, ??  
 −, **27, 27, 19**, used: ??, 756,  
 749, 751, 752, 752, 797,  
 797, 798, 727, 727, 834,  
 835, 826, 790, 791, 802,  
 803, 818, 21, 27, 29, 29,  
 29, 30, 31, 31, 31, 33, 33,  
 56, 57, 57, 60, 61, 62, 62,  
 63, 65, 66, 66, 86, 568,  
 569, 569, 570, 575, ??,  
 186, 211, 211, 214, 111,  
 124, 131, 708, 709, 237,  
 263, 268, ??, ??, ??, 496,  
 497, 527, 527, 428, 70  
 /, **27, 27, 19**, used: 826, 826,  
 790, 790, 790, 791, 21, 24,  
 24, 24, 27, 31, 32, 74, 237,  
 ??, ??, 428  
 //, **240, 453, ??, ??, 500, 531,**  
**277, 300, 321, 335, 348,**  
**366, 377, 387, 400, 413,**  
**428, ??, ??**, used: 240,  
 240, 240, 240, 241, 454,  
 454, 454, 454, 454, ??, ??,  
 500, 500, 501, 501, 501,  
 531, 532, 532, 277, 278,  
 278, 300, 300, 300, 321,  
 321, 321, 335, 336, 336,  
 336, 336, 348, 348, 348,  
 349, 349, 366, 366, 366,  
 367, 367, 377, 377, 377,  
 378, 378, 387, 387, 387,  
 388, 388, 401, 401, 401,  
 401, 413, 413, 414, 414,  
 414, 428, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??  
 <, **27, 27, 19**, used: 756, 757,  
 757, 757, 758, 758, 758,  
 759, 761, 762, 762, 762,  
 763, 763, 764, 764, 742,  
 745, 746, 746, 752, 826,  
 789, 789, 790, 791, 791,  
 792, 794, 794, 795, 813,  
 818, 818, 24, 27, 29, 29,  
 31, 31, 33, 45, 55, 56, 56,  
 57, 57, 60, 86, 568, 569,  
 70, 184, 192, 193, 193,  
 197, 198, 198, 199, 199,  
 200, 204, 205, 214, 215,  
 95, 98, 125, 708, 260, 261,  
 262, ??, ??, ??, ??, ??,  
 ??, 497, 527, 438, 439,  
 440, 719, 719, 719, 720,  
 721, 722, 722, 723  
 <<, **707**, used: 710, 710  
 <=, **27, 27, 19**, used: ??, 742,  
 742, 742, 742, 743, 743,  
 791, 792, 802, 803, 812,  
 816, 27, 28, 47, 48, 55, 56,  
 61, 63, 693, 575, 74, 107,  
 124, 131, 709, 448, 448,  
 498, 499, 530, 530, 402,  
 409  
 <>, **27, 27, 19**, used: ??, 761,  
 744, 745, 746, 751, 752,  
 752, 797, 797, 798, 798,  
 772, 774, 835, 836, 826,  
 829, 793, 793, 794, 812,  
 816, 817, 11, 12, 13, 16,  
 27, 42, 56, 62, 64, 64, 65,  
 218, 219, 699, 701, 568,  
 568, 569, 193, 200, 200,  
 204, 213, 213, 213, 216,  
 102, 102, 130, 130  
 =, **27, 27, 19**, used: ??, ??, ??,

??, ??, ??, ??, 757, 757,  
 757, 758, 758, 758, 759,  
 759, 760, 761, 762, 762,  
 762, 763, 763, 763, 764,  
 764, 744, 744, 745, 745,  
 745, 746, 753, 738, 770,  
 770, 773, 826, 826, 828,  
 829, 829, 790, 791, 791,  
 792, 794, 794, 795, 795,  
 809, 810, 810, 811, 811,  
 817, 818, 11, 12, 27, 29,  
 29, 30, 31, 31, 31, 32, 55,  
 56, 56, 56, 57, 57, 57, 57,  
 57, 58, 58, 58, 58, 58, 58,  
 59, 59, 59, 59, 60, 62, 62,  
 62, 62, 63, 63, 63, 64, 64,  
 64, 64, 64, 64, 64, 64, 64,  
 65, 66, 694, 181, 181, 84,  
 85, 86, 86, 218, 219, 219,  
 565, 565, 565, 565, 565,  
 569, 569, 570, 570, 573,  
 575, 76, 77, 78, 192, 192,  
 192, 193, 194, 195, 195,  
 196, 196, 197, 197, 197,  
 198, 198, 198, 200, 201,  
 202, 205, 214, 95, 104,  
 104, 119, 119, 125, 131,  
 271, 271, 324, 325, 408,  
 721  
 >, **27**, **27**, **19**, used: ??, 756,  
 756, 743, 743, 749, 751,  
 752, 753, 732, 733, 835,  
 790, 790, 791, 792, 792,  
 794, 802, 803, 803, 17, 21,  
 27, 30, 55, 56, 56, 59, 59,  
 60, 62, 64, 64, 64, 64, 65,  
 66, 568, 570, 186, 192,  
 192, 193, 197, 197, 198,  
 199, 199, 199, 204, 205,  
 211, 211, 212, 237, 238,  
 239, 240, 240, 241, 260,  
 261, 262, 263, 446, 448,  
 450, 454, 454, 454, 481,  
 484, 487, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??,  
 496, 497, 499, 500, 501,  
 501, 501, 518, 519, 522,  
 527, 527, 530, 531, 531,  
 532, 532, 554, 555, 559,  
 275, 277, 277, 278, 278,  
 293, 294, 298, 299, 300,  
 300, 300, 315, 315, 320,  
 320, 321, 321, 321, 328,  
 329, 330, 330, 331, 334,  
 335, 336, 336, 336, 342,  
 342, 345, 347, 348, 349,  
 349, 360, 361, 364, 365,  
 366, 367, 367, 372, 373,  
 375, 377, 377, 378, 378,  
 383, 383, 385, 387, 387,  
 388, 388, 393, 394, 412,  
 413, 414, 414, 414, 424,  
 424, 428, 438, 439, 440,  
 441, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, 719, 719, 719, 720,  
 722, 722, 723  
 >:, ??, ??, used:  
 >::, ??, ??, used: 765, 799, 799,  
 799, 799, 799, 800, 800,  
 800  
 >:::, ??, ??, used: 766, 766, 799,  
 800, 800, 800, 800  
 >=, **27**, **27**, **19**, used: 756, 756,  
 759, 760, 746, 751, 752,  
 836, 790, 803, 27, 29, 57,  
 57, 62, 63, 568, 569, 569,  
 575, 98, 110, 124, 709,  
 237, 238, 448, 448, ??, ??,  
 498, 499, 530, 530, 275,  
 276, 298, 298, 319, 320,  
 333, 334, 345, 346, 364,  
 364, 375, 376, 385, 386,  
 402, 411, 412, 428, ??, ??,  
 ??, ??  
 >>, **707**, used:  
 ?arg\_specs (label), ??, ??, used:  
 ?cmp (label), ??, **744**, **747**, ??,  
**740**, **742**, used:  
 ?env (label), ??, ??, used:  
 ?epsilon (label), ??, ??, used:  
 ?exit\_code (label), ??, ??, used:  
 ?f (label), **28**, **31**, **20**, used:  
 ?foutput (label), ??, ??, used:  
 ?mode (label), ??, ??, used: ??  
 ?msg (label), ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, used: ??,  
 ??, ??, ??  
 ?pp\_diff (label), ??, ??, used:  
 ?prefix (label), ??, ??, used:

- 
- ?printer* (label), ??, ??, used:  
*?set\_verbose* (label), ??, ??,  
     used:  
*?sinput* (label), ??, ??, used:  
*?skip* (label), ??, ??, used:  
*?stride* (label), **743, 743, 740**,  
     **740**, used:  
*?suffix* (label), ??, ??, used:  
*?use\_stderr* (label), ??, ??, used:  
  
*?verbose* (label), ??, ??, ??, ??,  
     used:  
 @?, ??, ??, used:  
 A, **447, 397, 137**, used: **447**,  
     **449, 457, 457, 458, 459**,  
     **462, 463, 464, 467, 467**,  
     **467, 468, 469, 471, 471**,  
     **472, 472, 473, 473, 476**,  
     **479, 398, 403, 403, 404**,  
     **405, 405, 407**  
 A (module), **730, 104**, used: **730**,  
     **730, 730, 730, 104, 104**,  
     **104, 105, 108, 108, 109**,  
     **110, 110, 111, 111, 111**,  
     **111, 111, 111, 112, 112**,  
     **112, 112, 116, 116, 117**,  
     **117, 117, 117, 117, 117**,  
     **118, 118, 118, 119, 120**,  
     **120, 121, 121, 121**  
*abs*, **54, 56, 62, 51**, used: **826**,  
     **697, 186, 229, 229, 233**,  
     **233, 262, 263, 264, 446**,  
     **481, 487, 487, ??, ??, ??**,  
     **??, ??, ??, 497, 498, 518**,  
     **522, 522, 527, 529, 554**,  
     **560, 560, 293, 294, 294**,  
     **315, 316, 316, 328, 329**,  
     **330, 331, 331, 342, 343**,  
     **343, 360, 362, 362, 372**,  
     **373, 373, 383, 383, 384**,  
     **393, 394, 394, 424, 425**,  
     **425, 440, 441, 441, ??, ??**,  
     **??, ??, ??, ??**  
*actions* (field), **730**, used: **730**,  
     **730, 730, ??, ??**  
*AD*, **450**, used:  
*add*, **755, 759, 762, 780, 781**,  
     **781, 782, 769, 769, 770**,  
     **772, 773, 826, 826, 827**,  
     **828, 830, 831, 30, 43**,  
     **44, 48, 54, 56, 62, 181**,  
     **181, 181, 181, 181, 182**,  
     **565, 754, 779, 780, 767**,  
     **768, 768, 823, 824, 825**,  
     **51, 180, 564**, used: ??,  
     ??, 765, 761, 746, 749,  
     781, 781, 782, 785, 785,  
     785, 786, 770, 770, 773,  
     773, 828, 830, 830, 830,  
     830, 830, 831, 831, 831,  
     831, 831, 730, 816, 816,  
     29, 29, 30, 30, 44, 44, 44,  
     45, 45, 46, 46, 48, 181,  
     181, 181, 182, 220, 220,  
     220, 220, 221, 699, 700,  
     700, 700, 702, 565, ??,  
     575, 74, 186, 214, 215,  
     216, 103, 104, 107, 108,  
     111, 116, 117, 119, 120,  
     120, 120, 123, 124, 124,  
     131, 132, 133, 567  
*add'*, **56**, used: 56, 56  
*add1*, **565**, used: 565, 565, 565  
*addn*, **565**, used: 565, 565  
*addto\_ketset*, **120**, used: 120  
*addto\_ketset\_map*, **120**, used:  
     120  
*add\_complex\_array\_tag*, **416**,  
     used: 416  
*add\_degree*, **29**, used: 29  
*add\_derivatives*, **830**, used: 830,  
     830  
*add\_flavors*, **700**, used: 700  
*add\_fusion2*, **220**, used: 220  
*add\_fusion3*, **220**, used: 221  
*add\_fusionn*, **220**, used:  
*add\_node*, **41, 45, 37**, used: 45,  
     47, 111, 118  
*add\_non\_empty*, **770, 773**, used:  
     770, 773  
*add\_offspring*, **41, 45, 110, 37**,  
     used: 110, 110, 118  
*add\_offspring\_unsafe*, **41, 45**,  
     **37**, used: 45, 47  
*add\_permute3*, **220**, used: 220  
*add\_permute4*, **221**, used: 221  
*add\_to\_list*, **124**, used: 124  
*add\_tree*, **699**, used: 699  
*add\_unique*, **816**, used: 817  
*add\_vertex3*, **220**, used: 221

- add\_vertex4*, **221**, used: **221**  
*add\_vertices*, **104**, used: **104**  
*AdjSUN*, **81, 80**, used: **81, 574, 230, 238, 448, ??, ??, 499, 530, 275, 298, 320, 334, 345, 364, 375, 385, 399, 412, 428, ??, ??, 719**  
*AH*, **274, 297**, used: **275, 277, 281, 281, 282, 283, 284, 285, 285, 286, 287, 291, 298, 299, 303, 303, 304, 305, 305, 306, 307, 307, 308, 312**  
*Al*, **450**, used:  
*AL*, **450**, used:  
*Algebra* (module), **826, 823**, used: **181, 240, 453, ??, ??, 500, 531, 277, 300, 321, 335, 348, 366, 377, 387, 400, 413, 428, ??, ??, 181, 181**  
*All*, **178**, used: **713**  
*allowed*, **211, 94, 121, 90**, used: **212, 213, 121**  
*allows\_fusion*, **696**, used: **696**  
*allows\_momentum\_fusion*, **696**, used: **696**  
*all\_bosons*, **398**, used: **406**  
*all\_compatible*, **74**, used: **76, 76**  
*all\_feynman*, **396**, used: **396, 400**  
*all\_leptons*, **398**, used: **406**  
*all\_quarks*, **398**, used: **406**  
*alpha* (camllex regexpr), **566**, used: **566, 566**  
*alphanum* (camllex regexpr), **566**, used: **566**  
*Alpha\_QED*, **241, 450, ??, ??, 278, 300, 321, 337, 349, 367, 378, 388, 414, 428, ??, ??, used: 243, 244, ??, ??, 428**  
*Alpha\_WWW0*, **241, ??, ??, 428**, used: **249, ??, ??, 428**  
*Alpha\_WWW2*, **241, ??, ??, 428**, used: **249, ??, ??, 428**  
*Alpha\_ZZWW0*, **241, ??, ??, 428**, used: **249, ??, ??, 428**  
*Alpha\_ZZWW1*, **241, ??, ??, 428**, used: **249, ??, ??, 428**  
*Alpha\_ZZZZ*, **241, ??, ??, 428**, used: **249, ??, ??, 428**  
*AltH* (module), **??, ??**, used: **??**  
*alt\_fuse2*, **271**, used:  
*alt\_fuse3*, **271**, used:  
*amplitude*, **207, 208, 116, 178, 178**, used: **208, 121, 121**  
*amplitude* (type), **698, 699, 94, 100, 103, 122, 127, 128, 698, 89, 91**, used: **698, 699, 94, 101, 122, 127, 128, 128, 129, 129, 698, 698, 89, 89, 90, 90, 90, 90, 90, 91, 91, 92, 92, 92, 92, 93**  
*Amplitude* (module), **101**, used: **104, 117**  
*Amplitude* (sig), **100**, used: **101**  
*amplitudes*, **94, 121, 127, 132, 89, 92**, used: **133, 715, 717**  
*amplitudes* (type), **127, 129, 178, 91**, used: **127, 178, 179, 92, 92, 92, 92, 92, 92, 92, 92, 92, 92, 92**  
*amplitudes'* (type), **129**, used:  
*amplitudes\_by\_flavor*, **708**, used: **712, 712, 712**  
*amplitudes\_to\_channel*, **178**, used: **715, 716**  
*amplitudes\_to\_feynmf*, **712**, used: **717**  
*amplitudes\_to\_feynmf\_color\_only*, **712**, used: **717**  
*amplitudes\_to\_feynmf\_sans\_color*, **712**, used: **717**  
*amplitude\_to\_dot*, **94, 125, 91**, used: **716**  
*analyze\_tree*, **702**, used:  
*And*, **69, 74, 68**, used: **69, 75**  
*AND*, **??, ??**, used: **??, 70**  
*AND* (camlyacc token), **71**, used: **71, 71**  
*angle* (type), **450**, used: **450**  
*anomalous\_bbA*, **254, ??, ??, 433**, used: **258, ??, ??, 436**

- anomalous\_bbWW*, **256**, ??, ??,  
**435**, used: **258**, ??, ??,  
**436**
- anomalous\_bbZ*, **254**, ??, ??,  
**433**, used: **258**, ??, ??,  
**436**
- anomalous\_gauge\_higgs*, **252**,  
**339**, **352**, **369**, **430**,  
used: **253**, **430**
- anomalous\_gauge\_higgs4*, **253**,  
**339**, **352**, **369**, **430**,  
used: **253**, **430**
- anomalous\_higgs*, **253**, **339**, **352**,  
**369**, **430**, used: **253**, **431**
- anomalous\_higgs4*, **253**, **339**,  
**352**, **369**, **430**, used: **253**,  
**431**
- anomalous\_quartic\_gauge*, **249**,  
??, ??, **428**, used: **251**,  
??, ??, **428**
- anomalous\_tbW*, **255**, ??, ??,  
**433**, used: **258**, ??, ??,  
**436**
- anomalous\_tbWA*, **255**, ??, ??,  
**434**, used: **258**, ??, ??,  
**436**
- anomalous\_tbWZ*, **256**, ??, ??,  
**434**, used: **258**, ??, ??,  
**436**
- anomalous\_top\_DuDd*, **257**, ??,  
??, **436**, used: **258**, ??,  
??, **436**
- anomalous\_top\_qBuB*, **257**, ??,  
??, **435**, used: **258**, ??,  
??, **436**
- anomalous\_top\_qBuB\_ff*, **257**,  
??, ??, **435**, used: **257**,  
??, ??, **435**
- anomalous\_top\_qBuB\_tt*, **257**,  
??, ??, **435**, used: **257**,  
??, ??, **435**
- anomalous\_top\_qGuG*, **256**, ??,  
??, **435**, used: **258**, ??,  
??, **436**
- anomalous\_top\_qGuG\_ff*, **256**,  
??, ??, **435**, used: **256**,  
??, ??, **435**
- anomalous\_top\_qGuG\_tt*, **256**,  
??, ??, **435**, used: **256**,  
??, ??, **435**
- anomalous\_top\_quqd1*, **258**, ??,  
used: **258**, ??
- anomalous\_top\_quqd1\_ff*, **258**,  
??, used: **258**, ??
- anomalous\_top\_quqd1\_tq*, **257**,  
??, used: **258**, ??
- anomalous\_top\_quqd8*, **258**, ??,  
used: **258**, ??
- anomalous\_top\_quqd8\_ff*, **258**,  
??, used: **258**, ??
- anomalous\_top\_quqd8\_tq*, **258**,  
??, used: **258**, ??
- anomalous\_top\_qW*, **257**, ??, ??,  
**436**, used: **258**, ??, ??,  
**436**
- anomalous\_top\_qW\_ff*, **257**, ??,  
??, **436**, used: **257**, ??,  
??, **436**
- anomalous\_top\_qW\_tq*, **257**, ??,  
??, **435**, used: **257**, ??,  
??, **436**
- anomalous\_triple\_gauge*, **247**,  
??, ??, **428**, used: **248**,  
??, ??, **428**
- anomalous\_ttA*, **253**, ??, ??,  
**432**, used: **258**, ??, ??,  
**436**
- anomalous\_ttG*, **254**, ??, ??,  
**433**, used: **258**, ??, ??,  
**436**
- anomalous\_ttGG*, **255**, ??, ??,  
**434**, used: **258**, ??, ??,  
**436**
- anomalous\_ttH*, **255**, **434**, used:  
**258**, **436**
- anomalous\_ttWW*, **256**, ??, ??,  
**435**, used: **258**, ??, ??,  
**436**
- anomalous\_ttZ*, **254**, ??, ??,  
**433**, used: **258**, ??, ??,  
**436**
- anomaly\_higgs*, **290**, **311**, **326**,  
**339**, **352**, **369**, **380**, **391**,  
used: **291**, **312**, **327**, **340**,  
**353**, **370**, **380**, **391**
- Anomtop* (module), ??, used: ??
- anom\_ferm\_ass*, **273**, **273**, **273**,  
**274**, **272**, used: **321**, **323**,  
**324**, **325**, **325**, **327**, **328**,  
**329**, **330**

1060

- 435, 435, 435, 435, 435,  
 435, 435, 436, 436, 437  
*aux\_top\_flavors*, **237**, ??, ??,  
**428**, used: **237**, **237**, ??,  
 ??, **428**  
*Aux\_Vector*, **137**, used: **238**, ??,  
 ??, **428**  
*Aux\_Vector\_DScalar*, **138**, used:  
 188  
*Aux\_Vector\_Vector*, **138**, used:  
 188  
*A\_0*, **450**, used:  
*A\_P*, **450**, used:  
*B*, **230**, used: **230**, **230**, **231**, **232**  
*B1*, **344**, used: **344**, **347**, **353**  
*B2*, **344**, used: **344**, **347**, **353**  
*bag* (type), **211**, used: **211**  
*bal*, **756**, used: **756**, **757**, **758**,  
 758, 759  
*baryon*, **241**, **454**, ??, ??, **501**,  
**532**, **278**, **300**, **321**, **336**,  
**349**, **367**, **378**, **388**, **414**,  
**428**, ??, ??, used: **241**,  
 454, ??, ??, **501**, **532**, **278**,  
**300**, **321**, **336**, **349**, **367**,  
**378**, **388**, **414**, **428**, ??, ??  
*baryonic\_vertex*, **184**, used: **193**,  
 193, 196  
*base*, **780**, **781**, **781**, **782**, **780**,  
**780**, used: **782**, **215**  
*base* (type), **780**, **780**, **781**, **781**,  
**782**, **213**, **216**, **118**, **779**,  
**779**, **780**, used: **780**, **780**,  
**781**, **781**, **781**, **781**, **782**,  
**779**, **779**, **780**, **780**, **780**,  
**780**, **780**, **780**, **780**  
*basis*, **784**, **786**, **784**, used: **786**,  
 78, 215  
*Bbar*, **230**, used: **230**, **230**, **231**,  
 232  
*BBB*, **138**, used: **188**, **461**, **461**,  
 507, 507, 538, 539, 540,  
 540  
*BBWW*, **236**, ??, ??, **428**, used:  
**237**, **256**, **259**, ??, ??, ??,  
 ??, ??, ??, **428**, **435**, **437**  
*bcdi\_of\_flavor*, **398**, used: **409**,  
 409  
*Be*, **450**, used:  
*begin\_step*, **734**, **732**, used: **133**  
*Binary* (module), **10**, **21**, **125**, **8**,  
**19**, **91**, used: **15**, **22**, **23**,  
**33**, **34**, **125**, **127**, **718**, ??,  
 19, 20  
*Binary* (sig), **10**, **8**, used: **8**  
*Binary\_Majorana* (module), **127**,  
**91**, used:  
*binomial*, **790**, **787**, used: **86**  
*binomial'*, **790**, used: **790**, **790**  
*bits*, **61**, used: **62**, **62**, **62**, **62**, **63**,  
**63**, **63**, **64**, **64**, **65**  
*Bits* (module), **61**, **53**, used: **66**,  
**66**, **67**, **53**  
*bits0*, **61**, used: **61**  
*BitsW* (module), **66**, **53**, used:  
**66**, **67**  
*boson* (type), **397**, **137**, used:  
 397, 138  
*Boson*, **95**, **125**, **397**, used: **95**,  
 96, 125, 126, 397, 400,  
 403, 403, 403, 403, 404,  
 404, 404, 404, 404, 405,  
 405, 405, 405, 405, 405,  
 406, 407, 408  
*boson2* (type), **137**, used: **139**  
*Bound* (sig), **17**, **8**, used: **24**, **33**,  
 127, 127, 8, 19, 20, 91, 91  
*bounded\_power*, **16**, used: **17**  
*bounded\_power\_fold*, **16**, used:  
 16, 17  
*bra*, **94**, **100**, **103**, **122**, **89**, used:  
 122  
*bracket*, ??, ??, used: ??  
*bracket\_tmpfile*, ??, ??, used: ??  
*braket* (type), **94**, **100**, **103**, **122**,  
**89**, used: **94**, **100**, **100**,  
 100, 101, 103, 122, 89, 90  
*brakets*, **94**, **101**, **103**, **122**, **90**,  
 used: **122**  
*brakets* (field), **100**, **103**, used:  
 103, 116, 120, 121, 122,  
 122, 123, 123, 125, 125  
*Branch*, **693**, used: **693**, **693**, **693**,  
 694  
*Broken\_Gauge* (sig), **177**, used:  
*broken\_\_is\_unit*, **829**, used:  
*BRS*, **135**, used: **570**  
*BSM\_anom* (module), **274**, **272**,  
 used: ??



- BSM\_bsm* (module), **273, 272**,  
used: ??, ??, ??, ??, ??,  
??, ??, ??, ??
- BSM\_flags* (sig), **273, 272**, used:  
**273, 273, 274, 274, 297,**  
**319, 332, 343, 363, 374,**  
**384, 272**
- BSM\_ungauged* (module), **273,**  
**272**, used: ??
- buff\_printf*, ??, used: ??, ??
- build\_forest*, **47**, used: **47, 48**
- bundle* (field), **118**, used: **118,**  
**118, 118, 119, 119, 119**
- Bundle* (module), **780, 779**,  
used: **213, 216, 118**
- bundle\_to\_strings*, **214**, used:
- by\_color*, **213**, used: **213, 215,**  
**216, 216, 216**
- c* (type), **218, 218, 218, 222,**  
**571, 575, 225, 226, 228,**  
**231, 245, 266, 269, 455,**  
??, ??, **503, 534, 280,**  
**302, 323, 337, 350, 368,**  
**379, 389, 406, 416, 428,**  
??, ??, **720, 217, 217,**  
**217**, used: **218, 218, 218,**  
**219, 222, 217, 217, 217**
- C*, **230**, used: **230, 230, 231, 232**
- C* (module), **827, 828, 829, 831,**  
**84, 183, 112, 128, 708,**  
**824, 825, 578**, used: **827,**  
**828, 86, 112, 116, 117,**  
**133, 134, 715, 717, 824,**  
**825, 825, 825, 825**
- C1*, **446, 497, 528**, used: **446,**  
**447, 458, 458, 462, 463,**  
**476, 477, 478, 479, 497,**  
**498, 506, 513, 514, 528,**  
**529, 537, 548, 549**
- C1c*, **446, 497, 528**, used: **446,**  
**447, 462, 479, 497, 498,**  
**514, 528, 529, 549**
- C2*, **446, 497, 528**, used: **446,**  
**447, 458, 458, 462, 463,**  
**476, 477, 478, 479, 497,**  
**498, 506, 513, 514, 528,**  
**529, 537, 548, 549**
- C2* (module), **85**, used: **86**
- C2c*, **446, 497, 528**, used: **446,**  
**447, 462, 479, 497, 498,**  
**514, 528, 529, 549**
- C3*, **528**, used: **528, 529, 549**
- C3c*, **528**, used: **528, 529, 549**
- C4*, **528**, used: **528, 529, 549**
- C4c*, **528**, used: **528, 529, 549**
- CA* (module), **117**, used: **117,**  
**117, 118, 118, 118, 118,**  
**118, 119, 119, 119, 119,**  
**120, 120, 120, 120, 121,**  
**121, 121, 121, 121, 121,**  
**121, 122, 122, 122, 122,**  
**122, 123, 123, 123, 123,**  
**123, 123, 124, 124, 124,**  
**124, 124, 125, 125, 125**
- Cache* (module), **737, 736**, used:  
**105**
- Cache\_Default*, **713**, used: **713**
- Cache\_Ignore*, **98**, used: **98**
- Cache\_Initialize*, **713**, used: **713**
- cache\_mode* (type), **98, 713**,  
used:
- cache\_name*, **105**, used: **105, 105,**  
**105**
- cache\_option*, **98, 713**, used: **98,**  
**105, 713, 715**
- Cache\_Overwrite*, **98**, used: **98**
- cache\_prefix*, **729, 729**, used: **105**
- cache\_suffix*, **729, 729**, used: **105**
- Cache\_Use*, **98**, used: **98**
- call\_function*, **703**, used: **703**
- call\_subroutine*, **703**, used: **703**
- canonicalize*, **755, 761, 764, 809,**  
**754, 806**, used: **809, 709**
- cascade* (camlyacc non-terminal),  
**71**, used: **71**
- Cascade* (module), **73, 72**, used:  
**95, 112, 128, 708, 91**
- cascades* (camlyacc non-terminal),  
**71**, used: **71, 71**
- Cascade\_lexer* (module), ??, ??,  
**70**, used: **75**
- Cascade\_parser* (module), ??, ??,  
**71**, used: ??, **75**, ??, **70**
- Cascade\_syntax* (module), **68**,  
**68**, used: ??, ??, **74**, ??,  
**71, 71**
- Cbar*, **230**, used: **230, 230, 231,**  
**232**

- CF* (module), **708**, used: **708**,  
**713**, **715**, **715**, **716**, **716**,  
**716**, **716**, **716**
- CF\_aux*, **184**, used: **185**, **186**,  
**186**, **193**, **193**, **200**, **200**,  
**200**, **205**
- cf\_aux\_propagator*, **184**, used:  
**185**
- cf\_in* (type), **184**, used: **184**
- CF\_in*, **184**, used: **185**, **186**, **186**,  
**192**, **192**, **197**, **197**, **198**,  
**199**, **199**, **205**
- CF\_io*, **184**, used: **185**, **186**, **186**,  
**193**, **193**, **194**, **200**, **200**,  
**200**, **201**, **202**, **202**, **205**
- cf\_out* (type), **184**, used: **184**
- CF\_out*, **184**, used: **185**, **186**,  
**186**, **192**, **193**, **197**, **198**,  
**198**, **199**, **199**, **205**
- Ch* (module), **222**, **571**, **184**,  
**207**, **225**, **226**, **228**, **231**,  
**240**, **266**, **269**, **453**, **??**,  
**??**, **500**, **531**, **277**, **300**,  
**321**, **335**, **348**, **366**, **377**,  
**387**, **400**, **413**, **428**, **??**,  
**??**, **720**, **172**, used: **571**,  
**184**, **207**, **211**, **122**, **267**,  
**269**, **172**, **224**
- channel*, **733**, **732**, used: **133**
- channel* (field), **732**, used: **733**,  
**733**
- channel* (type), **732**, used: **732**
- Channel*, **732**, **128**, used: **733**,  
**128**
- Chaotic* (module), **43**, **39**, used:
- char* (type), **446**, **497**, **528**, used:
- char* (camllex regexp), **70**, used:
- charge*, **240**, **454**, **??**, **??**, **501**,  
**531**, **277**, **300**, **321**, **336**,  
**348**, **366**, **377**, **387**, **414**,  
**428**, **??**, **??**, used: **241**,  
**454**, **??**, **??**, **501**, **532**, **278**,  
**300**, **321**, **336**, **349**, **367**,  
**378**, **388**, **414**, **428**, **??**, **??**
- charged\_chargino\_currents*, **456**,  
**504**, **535**, used: **477**, **513**,  
**548**
- charged\_currents*, **456**, **504**, **535**,  
**282**, **303**, **325**, **338**, **350**,  
**368**, **379**, **389**, **417**, **??**,  
**??**, used: **477**, **513**, **548**,  
**291**, **312**, **327**, **340**, **353**,  
**370**, **380**, **391**, **422**, **??**, **??**
- charged\_currents'*, **246**, **??**, **??**,  
**428**, **??**, used: **246**, **246**,  
**??**, **??**, **428**, **??**
- charged\_currents''*, **246**, **??**, **??**,  
**428**, used: **246**, **??**, **??**,  
**428**
- charged\_currents\_ckm*, **246**, **??**,  
**??**, **428**, used: **258**, **??**,  
**??**, **436**
- charged\_currents\_triv*, **246**, **??**,  
**??**, **428**, used: **258**, **??**,  
**??**, **436**
- charged\_heavy\_currents*, **282**,  
used: **291**
- charged\_quark\_currents*, **456**,  
**504**, **535**, used: **477**, **513**,  
**548**
- charged\_slepton\_currents*, **456**,  
**504**, **535**, used: **477**, **513**,  
**548**
- charged\_squark\_currents*, **456**,  
**504**, **536**, used: **477**, **513**,  
**548**
- charged\_squark\_currents'*, **456**,  
**504**, **536**, used: **456**, **504**,  
**536**
- charged\_up\_currents*, **??**, used:  
**??**
- charged\_Z*, **457**, **505**, **536**, used:  
**477**, **513**, **548**
- charges*, **222**, **571**, **184**, **207**,  
**225**, **226**, **228**, **231**, **241**,  
**266**, **269**, **454**, **??**, **??**,  
**501**, **532**, **278**, **300**, **321**,  
**336**, **349**, **367**, **378**, **388**,  
**401**, **414**, **428**, **??**, **??**,  
**720**, **172**, used: **571**, **184**,  
**207**, **211**, **122**, **266**, **269**
- Charges* (module), **181**, **180**,  
used: **222**, **225**, **226**, **228**,  
**231**, **240**, **266**, **453**, **??**, **??**,  
**500**, **531**, **277**, **300**, **321**,  
**335**, **348**, **366**, **377**, **387**,  
**400**, **413**, **428**, **??**, **??**, **720**,

- 172, 224, 224, 224, 224,  
444, ??, 495, 525, 272,  
272, 273, ??
- Chargino*, 447, 498, 529, used:  
447, 449, 455, 456, 457,  
458, 458, 458, 458, 461,  
461, 462, 462, 476, 479,  
498, 500, 503, 504, 505,  
506, 506, 506, 507, 507,  
514, 529, 531, 535, 535,  
536, 537, 537, 537, 538,  
539, 549
- charlist*, 529, used: 529
- check*, 55, used: 55, 55
- check\_charges*, 94, 122, 90, used:  
715
- chg*, 508, 539, used: 539, 539,  
540, 540
- Chi*, 137, used: 456, 457, 457,  
458, 458, 459, 459, 459,  
462, 462, 476, 476, 504,  
505, 505, 506, 506, 506,  
507, 535, 536, 536, 537,  
537, 538, 538, 541, 369
- Chibar*, 137, used: 456, 457, 457,  
458, 458, 459, 459, 459,  
462, 504, 505, 505, 506,  
506, 506, 507, 535, 536,  
536, 537, 537, 538, 538,  
541, 541
- chiggs* (type), 528, used: 529
- CHiggs*, 529, used: 529, 531, 537,  
537, 537, 543, 543, 543,  
543, 544, 544, 544, 544,  
544, 546, 547, 547, 549
- children*, 94, 100, 103, 121, 89,  
used: 121
- children* (type), 20, 22, 24, 26,  
26, 33, 33, 41, 41, 42,  
42, 43, 45, 94, 97, 97,  
97, 98, 100, 103, 109,  
121, 18, 36, 37, 40, 89,  
93, used: 20, 41, 41, 42,  
42, 42, 43, 45, 97, 97, 98,  
100, 100, 101, 103, 109,  
121, 18, 19, 20, 20, 36, 36,  
37, 37, 37, 38, 38, 39, 40,  
40, 40, 93, 93
- choose*, 755, 758, 762, 794, 754,  
789, used: 10, 10, 17, 17,  
74, 496, 527
- choose'*, 794, used: 794, 794
- choose2*, 10, 496, 527, used: 11,  
12, 496, 527
- choose3*, 10, used: 12
- choose\_opt*, 755, 758, 762, 754,  
used:
- chopn*, 743, 740, used:
- chopn'*, 742, used: 742, 743
- chopn''*, 742, used: 742, 742
- CKetSet* (module), 119, used:  
119, 120, 120
- CKM\_12*, 450, used:
- CKM\_13*, 450, used:
- CKM\_23*, 450, used:
- ckm\_present*, 234, 234, 234,  
234, 235, 235, 235, 235,  
236, 444, 444, 444, 445,  
445, 445, 445, ??, ??,  
495, 495, 496, 496, 526,  
526, 526, 410, 410, 410,  
427, 428, 224, 443, ??,  
495, 525, 272, 273,  
used: 240, 258, 454, 461,  
466, 466, 470, 477, 478,  
??, ??, ??, ??, 500, 507,  
511, 511, 513, 513, 539,  
545, 545, 547, 548, 413,  
418, 428, 436
- classify*, 745, 31, 741, used: 790,  
793, 793, 17, 17, 32
- classify\_nodes*, 124, used: 124
- class\_size*, 30, used: 30, 30, 31
- class\_size\_3*, 30, used: 30
- class\_size\_n*, 30, used: 30
- clist*, 529, 402, used: 529, 407
- clone*, 745, 269, 741, used: 745,  
777, 16, 269, 269
- clone3*, 269, used: 270
- clone4*, 269, used: 270
- clonen*, 270, used: 270
- cloop*, 496, 527, used: 496, 496,  
527, 527
- cloop\_kk*, 398, used: 398, 402,  
403, 403, 403, 403, 404,  
404, 404, 404
- cloop\_kk2*, 398, used: 402
- close\_channel*, 733, used: 734
- CM* (module), 207, 117, 128,  
708, used: 207, 208, 208,

- 117, 117, 118, 119, 119,  
119, 120, 121, 121, 123,  
124, 125, 129, 129, 709,  
710, 710, 712
- CMap* (module), 129, used: 133,  
133
- cmdline*, 731, 730, used: 713
- cmp\_float*, ??, ??, used:
- coarsest\_partition*, 78, 215, used:  
79, 215
- coarsest\_partition'*, 78, used: 78,  
78
- collect23*, 26, used: 26
- collect3*, 26, used: 26
- collect34*, 26, used: 26
- collect4*, 26, used: 26
- collect\_derivatives*, 830, used:  
830
- collect\_vertices*, 104, used: 104
- COLON*, ??, ??, used: ??, 70
- COLON* (camlyacc token), 71,  
used: 71, 72
- color*, 222, 571, 184, 207, 225,  
226, 228, 230, 238, 266,  
267, 448, ??, ??, 499,  
530, 275, 298, 320, 334,  
345, 364, 375, 385, 399,  
412, 428, ??, ??, 719,  
172, used: 571, 184, 186,  
186, 191, 195, 203, 204,  
205, 205, 205, 207, 213,  
129, 710, 710, 266, 267
- color* (label), 223, 175, used: 575
- color* (type), 83, 83, 86, 80,  
used: 83, 83, 87, 80, 80
- Color* (module), 81, 80, used:  
571, 572, 572, 573, 574,  
183, 207, 213, 127, 129,  
129, 129, 134, 134, 134,  
225, 226, 228, 230, 238,  
448, ??, ??, 499, 530, 275,  
298, 320, 334, 345, 364,  
375, 385, 399, 412, 428,  
??, ??, 719, 172, 175, 178,  
178, 92, 92
- colored\_only*, 712, used: 712
- colored\_vertex*, 184, used: 192,  
192, 192, 192, 193, 193,  
193, 193, 195, 197, 197,  
197, 197, 198, 198, 198,
- 199, 199, 199, 199, 199,  
200, 200, 203, 203
- Colorize* (module), 183, 183,  
used: 95, 97, 117, 128,  
708, 91, 93
- Colorized* (sig), 178, used: 183
- Colorized\_Gauge* (sig), 178,  
used: 183
- colorize\_amplitude*, 120, used:  
121
- colorize\_amplitudes*, 121, used:  
121
- colorize\_braket*, 120, used: 120
- colorize\_braket1*, 119, used: 120
- colorize\_coupling*, 119, used:  
119, 119
- colorize\_crossed\_amplitude*, 206,  
used: 207
- colorize\_crossed\_amplitude1*,  
205, 206, used: 205, 206,  
206
- colorize\_dag*, 118, used: 120
- colorize\_external*, 119, used: 120
- colorize\_fusion*, 119, used: 120
- colorize\_fusion2*, 191, used: 204
- colorize\_fusion3*, 195, used: 204
- colorize\_fusionn*, 203, used: 204
- colorize\_nodes*, 118, used: 118
- colorize\_sterile\_nodes*, 118, used:  
118
- colorize\_wf*, 117, used: 119
- colors*, 129, used:
- colors* (type), 129, used:
- color\_current*, 231, used: 232
- color\_currents*, 245, ??, ??, 281,  
303, 323, 338, 351, 379,  
389, 417, 428, ??, ??,  
used: 258, ??, ??, 291,  
312, 327, 340, 353, 380,  
391, 422, 436, ??, ??
- color\_factors*, 127, 129, 92,  
used:
- color\_factors* (field), 129, used:  
129, 134, 134
- color\_flow*, 129, used: 133, 133
- color\_flows*, 127, 129, 92, used:
- color\_flows* (field), 129, used:  
129, 134
- color\_flow\_ambiguous*, 184,  
used: 199, 200

- color\_flow\_of\_string*, **184**, used: 186
- columns*, **569**, used: 570
- column\_tabs*, **569**, used: 570
- col\_currents*, **462, 508, 539**, used: 477, 513, 548
- col\_lqino\_currents*, **542**, used: 548
- col\_lq\_currents*, **542**, used: 548
- col\_sfermion\_currents*, **462, 508, 542**, used: 477, 513, 548
- Combinatorics* (module), **789, 787**, used: 10, 10, 17, 17, 24, 24, 27, 33, 34, 86, 74, 204, 96, 117, 127, 496, 527
- combine\_decays*, **696**, used: 696, 697
- compare*, **??, ??, ??, ??, 765, 755, 761, 763, 744, 746, 781, 784, 769, 769, 772, 730, 9, 11, 12, 13, 16, 27, 27, 28, 40, 41, 42, 42, 43, 43, 43, 54, 56, 62, 81, 218, 218, 219, 219, 699, 700, 702, 575, 78, 186, 214, 215, 215, 215, 103, 103, 104, 109, 111, 116, 119, 119, 123, 124, 129, 129, 131, 225, 226, 228, 231, 245, 266, 269, 455, ??, ??, 503, 534, 280, 302, 323, 337, 350, 368, 379, 389, 406, 416, 428, ??, ??, 720, ??, ??, 754, 740, 783, 767, 768, 6, 19, 35, 36, 40, 51, 80, 217**, used: **??, ??, ??, ??, ??, 765, 763, 744, 746, 747, 747, 749, 753, 797, 797, 797, 820, 820, 828, 829, 830, 830, 831, 832, 730, 793, 793, 809, 816, 816, 817, 16, 27, 28, 42, 43, 45, 47, 48, 55, 56, 62, 694, 696, 81, 218, 219, 219, 699, 700, 700, 701, 702, 575, 78, 186, 213, 213, 214, 215, 215, 215, 216, 216, 96, 102, 102, 103, 104, 109, 110, 116, 118, 119, 124, 127, 129, 129, 130, 130, 131, 133, 709, 714, 225, 226, 228, 231, 245, 266, 269, 455, ??, ??, 503, 534, 280, 302, 323, 337, 350, 368, 379, 389, 406, 416, 428, ??, ??, 720**
- compare'*, **761**, used: 761, 761
- compare\_base*, **780, 213, 216, 118, 779**, used: 781
- compare\_elt*, **780, 213, 216, 118, 779**, used: 781, 213
- Comphep* (module), **568, 568**, used:
- Comphep\_lexer* (module), **??, ??, 566**, used: 573
- Comphep\_parser* (module), **??, ??, 567**, used: **??, 573, ??, 566**
- Comphep\_syntax* (module), **564, 564**, used: **??, ??, 571, 572, 575, ??, 567, 567**
- complement\_index\_sets*, **746**, used: 746
- complete\_fusion\_tower*, **111**, used: 116
- Complex*, **171**, used: **244, ??, ??, 428**
- Complex\_Array*, **171**, used: 416
- compose*, **755, 759, 764, 796, 797, 798, 754, 796**, used: 759, 764, 800, 800
- compose\_inverse\_ok*, **800**, used: 800
- compose\_ok*, **800**, used: 800
- compress*, **749, 748**, used: 749
- compress2*, **749, 748**, used:
- compressed* (type), **748, 748**, used: 748, 748
- compressed2* (type), **748, 748**, used: 748, 748
- concat*, **757**, used: **??, ??, ??, 757, 759, 784, 784, 735, 737, 738, 738, 738, 820, 829, 831, 832, 810, 812, 17, 17, 55, 62, 697, 697, 83, 701, 701, 701, 703, 576, 69, 70, 75, 75, 75, 78, 78, 186, 203, 213, 214,**

- 215, 124, 129, 709, 710,  
710, 712, 713, 714, 715,  
723
- Config* (module), **729, 729**, used:  
737, 105
- conj*, **81, 84, 85**, used: 82, 82, 82
- Conj*, **166**, used:
- ConjSpinor*, **135**, used: 570, 228,  
230, 237, 448, ??, ??, 498,  
530, 275, 275, 298, 298,  
319, 333, 345, 364, 375,  
385, 399, 411, 428, ??, ??,  
719
- conjugate*, **81, 84, 218, 222**,  
**571, 575, 186, 207, 94**,  
**100, 101, 121, 225, 225**,  
**226, 226, 228, 228, 230**,  
**231, 239, 245, 266, 266**,  
**268, 269, 449, 455, ??**,  
**??, 500, 503, 531, 534**,  
**277, 280, 299, 302, 320**,  
**323, 335, 337, 347, 350**,  
**365, 368, 376, 379, 386**,  
**389, 400, 406, 412, 416**,  
**428, ??, ??, ??, ??, 720**,  
**720, 174, 80, 217, 88**,  
used: 84, 84, 220, 221,  
571, 573, 575, 76, 77, 78,  
186, 186, 206, 206, 207,  
211, 216, 216, 101, 104,  
112, 116, 119, 120, 121,  
123, 710, 710, 710, 710,  
225, 226, 228, 231, 245,  
266, 266, 268, 269, 455,  
??, ??, 503, 505, 534, 536,  
280, 302, 323, 337, 350,  
368, 379, 389, 406, 416,  
428, ??, ??, 720
- conjugate* (label), **223, 175**, used:  
575
- Conjugates*, **571**, used: 573
- conjugate\_lorentz*, **570**, used:  
570, 573
- conjugate\_sans\_color*, **186, 207**,  
**178, 178**, used: 207
- conj\_char*, **446, 497, 528**, used:  
449, 455, 456, 457, 458,  
458, 458, 458, 461, 461,  
462, 476, 500, 503, 504,  
505, 506, 506, 506, 507,  
507, 531, 535, 535, 536,  
537, 537, 537, 538, 539
- conj\_chiggs*, **528**, used: 531
- conj\_iso*, **402**, used: 403, 403,  
404
- conj\_symbol*, **487, 522, 560**,  
used: 487, 522, 560, 561
- cons*, **755, 758, 761, 820, 808**,  
**754, 820, 805**, used: 758,  
759, 761, 46, 47
- Const*, **166**, used: 575, 239, 244,  
245, 245, 245, 245, 449,  
??, ??, 276, 280, 280, 280,  
280, 299, 302, 302, 302,  
302, 320, 322, 322, 322,  
322, 335, 337, 337, 337,  
337, 346, 350, 350, 350,  
350, 365, 367, 367, 368,  
368, 376, 378, 378, 379,  
379, 386, 389, 389, 389,  
389, 412, 416, 416, 416,  
416, 416, 428, ??, ??, ??,  
??, ??, ??
- constant* (type), **222, 571, 184**,  
**207, 94, 99, 225, 226**,  
**228, 230, 241, 266, 268**,  
**450, ??, ??, 501, 532**,  
**278, 300, 321, 337, 349**,  
**367, 378, 388, 401, 414**,  
**428, ??, ??, 719, 174**,  
**88**, used: 571, 575, 184,  
207, 94, 95, 97, 99, 99, 99,  
100, 104, 105, 225, 226,  
228, 231, 245, 266, 266,  
268, 269, 455, ??, ??, 503,  
534, 280, 302, 323, 337,  
350, 368, 379, 389, 406,  
416, 428, ??, ??, 720, 174,  
175, 175, 175, 175, 217,  
183, 183, 89, 91, 93
- Constant*, **137**, used: 575, 236,  
445, ??, ??, 496, 526, 274,  
297, 319, 333, 344, 363,  
374, 384, 396, 410, 428,  
??, ??
- constant\_symbol*, **222, 571, 188**,  
**207, 226, 227, 230, 233**,  
**264, 267, 268, 487, ??**,  
**??, 522, 560, 294, 316**,  
**331, 343, 362, 374, 384**,

- 394, 409, 425, 441, ??,**  
**??, 723, 175,** used: 571,  
188, 207, 267, 268
- constant\_symbol* (label), **223,**  
**175,** used: 575
- constraints*, **94, 101, 103, 122,**  
**127, 129, 90, 92,** used:  
122
- constraints* (field), **100, 103,**  
**129,** used: 103, 116, 117,  
121, 129, 134, 134
- consume*, **82,** used: 82
- contract*, **81, 82,** used: 83, 86
- contract4* (type), **139,** used: 139,  
140
- copy\_matrix*, **833, 833,** used:  
836, 837, 837
- Cos*, **450, 166,** used:
- Cos2al*, **450,** used:
- Cos2am2b*, **450,** used:
- Cos2be*, **450,** used:
- Cos4be*, **450,** used:
- Cosamb*, **450,** used:
- Cosapb*, **450,** used:
- Cospsi*, **278, 300, 321,** used:
- Costhw*, **241, ??, ??, 278, 300,**  
**321, 337, 349, 367, 378,**  
**388, 414, 428, ??, ??,**  
used: 244, 245, ??, ??,  
280, 302, 322, 337, 350,  
367, 378, 389, 416, 428, ??
- Cot*, **166,** used:
- count*, **82, 83,** used: 86
- Count* (module), **28, 20,** used:
- Count* (sig), **28, 19,** used: 20
- count\_color\_strings*, **204,** used:  
204
- count\_diagrams*, **94, 122, 90,**  
used: 716
- count\_flavors*, **572,** used: 574
- count\_fusions*, **94, 122, 90,** used:  
716
- count\_ghosts*, **84,** used: 86
- count\_ghosts1*, **84,** used: 84
- count\_maps*, **699,** used: 699
- count\_non\_zero*, **66,** used: 66
- count\_non\_zero'*, **66,** used: 66,  
66
- count\_processes*, **129,** used: 133
- count\_propagators*, **94, 122, 90,**  
used: 716
- count\_trees*, **41, 47, 39,** used:  
122
- coupling*, **94, 99, 99, 100, 103,**  
**121, 89,** used: 103, 121
- coupling* (field), **99, 99,** used: 99,  
108, 112
- coupling* (type), **94, 97, 97, 97,**  
**98, 100, 103, 121, 89,**  
**93,** used: 94, 97, 99, 99,  
100, 100, 100, 101, 103,  
103, 103, 109, 121, 131,  
89, 91, 93
- Coupling* (module), **135,** used:  
218, 219, 220, 570, 571,  
572, 572, 572, 574, 575,  
575, 183, 94, 99, 99, 99,  
100, 104, 105, 225, 226,  
227, 230, 236, 239, 266,  
445, 449, 457, 457, 457,  
459, 461, 461, 462, ??, ??,  
??, ??, 496, 505, 526, 537,  
274, 276, 297, 299, 319,  
320, 333, 335, 344, 346,  
363, 365, 374, 376, 384,  
386, 390, 396, 410, 412,  
428, 428, ??, ??, ??, ??,  
718, 172, 174, 174, 174,  
175, 175, 175, 217, 89
- coupling\_tag*, **94, 99, 99, 100,**  
**103, 121, 89,** used: 103,  
121
- coupling\_tag* (field), **99, 99,** used:  
99, 108, 112
- coupling\_tag\_raw*, **99,** used: 99
- coupling\_to\_string*, **97, 97, 97,**  
**98, 93,** used: 99
- Cpp* (module), **578,** used:
- create*, **756, 733, 730, 730,** used:  
??, ??, 756, 733, 733, 733,  
221, 575, 576, 98, 236,  
445, ??, ??, 496, 526, 274,  
297, 319, 333, 344, 363,  
374, 384, 396, 410, 428,  
??, ??
- created* (field), **732,** used: 733,  
734
- create\_class*, **29,** used: 31

- CRing* (sig), **826, 823**, used: **826, 823**  
*cross*, **123**, used: **123**  
*crossing*, **210, 216, 210**, used:  
*Crossing-Bundle* (module), **216**,  
 used:  
*Crossing-Projection* (module),  
**216**, used: **216**  
*cross\_in*, **84**, used:  
*cross\_out*, **84**, used: **85, 85**  
*cross\_uncolored*, **206**, used: **207**  
*CS* (module), **74**, used: **75**  
*csign* (type), **397**, used: **397, 397**  
*Custom*, **137**, used: **236, 445, ??,**  
**??, 496, 526, 274, 297,**  
**319, 333, 344, 363, 374,**  
**384, 396, 410, 428, ??, ??**  
*CWFBundle* (module), **118**,  
 used: **118, 119, 119, 119,**  
**120**  
*CWFMap* (module), **119**, used:  
**119, 120, 120, 120, 121**  
*Cycle* (exn), **41, 45, 37**, used:  
*Cycles* (module), **82**, used: **84, 85**  
*Cycles* (sig), **81**, used: **82**  
*C\_12\_34*, **139**, used: **190, 232,**  
**248, 249, 250, 463, ??, ??,**  
**508, 542, 284, 305, 326,**  
**338, 351, 369, 380, 390,**  
**405, 420, 428, ??, ??, 721**  
*C\_13\_42*, **139**, used: **190, 232,**  
**248, 249, 250, 463, ??, ??,**  
**508, 542, 284, 305, 326,**  
**338, 351, 369, 380, 390,**  
**405, 420, 428, ??, ??, 721**  
*C\_14\_23*, **139**, used: **190, 232,**  
**248, 249, 250, 463, ??, ??,**  
**508, 542, 284, 305, 326,**  
**338, 351, 369, 380, 390,**  
**405, 420, 428, ??, ??, 721**  
*C\_quqd1L\_bt*, **241**, ??, used:  
**257, ??**  
*C\_quqd1L\_tb*, **241**, ??, used:  
**257, ??**  
*C\_quqd1R\_bt*, **241**, ??, used:  
**257, ??**  
*C\_quqd1R\_tb*, **241**, ??, used:  
**257, ??**  
*C\_quqd8L\_bt*, **241**, ??, used:  
**258, ??**  
*C\_quqd8L\_tb*, **241**, ??, used:  
**258, ??**  
*C\_quqd8R\_bt*, **241**, ??, used:  
**258, ??**  
*C\_quqd8R\_tb*, **241**, ??, used:  
**258, ??**  
*d* (field), **55**, used: **55, 55, 55, 56,**  
**56, 56, 56, 57, 57, 57, 58,**  
**58, 59, 59, 60, 60, 66**  
*D*, **230, 236, 447, ??, ??, 498,**  
**529, 274, 297, 319, 333,**  
**344, 363, 374, 384, 411,**  
**428, ??, ??, used: 230,**  
**230, 231, 232, 237, 239,**  
**243, 245, 245, 246, 246,**  
**246, 246, 254, 254, 255,**  
**255, 256, 256, 256, 257,**  
**257, 257, 257, 257, 258,**  
**258, 258, 259, 447, 449,**  
**453, 455, 455, 456, 457,**  
**457, 457, 458, 459, 461,**  
**462, 462, 476, 479, ??, ??,**  
**??, ??, ??, ??, ??, ??, ??,**  
**??, ??, ??, ??, ??, ??, ??,**  
**??, ??, ??, ??, ??, ??, ??,**  
**??, ??, ??, ??, ??, ??, ??,**  
**??, ??, ??, ??, ??, ??, ??,**  
**498, 500, 503, 503, 504,**  
**505, 505, 506, 507, 507,**  
**508, 514, 529, 531, 534,**  
**535, 535, 537, 537, 538,**  
**538, 539, 539, 540, 540,**  
**540, 540, 549, 275, 277,**  
**281, 281, 281, 281, 281,**  
**282, 282, 282, 282, 283,**  
**291, 297, 299, 302, 303,**  
**303, 303, 303, 303, 304,**  
**304, 304, 304, 312, 319,**  
**320, 323, 323, 323, 323,**  
**324, 325, 325, 325, 327,**  
**333, 335, 338, 338, 338,**  
**338, 338, 338, 340, 344,**  
**347, 350, 350, 350, 351,**  
**351, 351, 353, 363, 365,**  
**368, 368, 368, 368, 370,**  
**375, 376, 379, 379, 379,**  
**379, 379, 381, 385, 386,**  
**389, 389, 389, 389, 390,**  
**391, 411, 412, 417, 417,**  
**417, 417, 418, 418, 418,**  
**418, 422, 428, 433, 433,**



- 433, 434, 434, 435, 435,  
 435, 435, 436, 436, 437,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??
- D* (module), **782, 100, 103**,  
 used: 782, 782, 100, 101,  
 103, 110, 110, 111, 111,  
 111, 111, 111, 112, 112,  
 116, 117, 117, 117, 118,  
 118, 118, 118, 120, 120,  
 120, 122, 123, 123, 124,  
 124, 125
- D'* (module), **110**, used: 110
- dag* (field), **118**, used: 118, 120
- DAG* (module), **40, 35**, used:  
 100, 103, 109, 110
- dag\_to\_dot*, **124**, used: 125, 125
- data* (field), **809, 810**, used: 809,  
 809, 811, 811
- date*, **727, 726**, used: 728
- date* (field), **727, 726**, used: 728,  
 802, 9, 20, 40, 54, 218,  
 698, 568, 183, 93, 224,  
 444, ??, 495, 526, 273, ??,  
 678, ??, 718
- Dbar*, **230**, used: 230, 230, 231,  
 232
- debug*, **712**, used: 713
- decay* (type), **692, 693, 210**,  
**211, 691, 209**, used: 692,  
 693, 695, 695, 210, 211,  
 691, 691, 691, 691, 209,  
 209
- Decay*, **210, 211, 209**, used: 211,  
 212, 212
- Decay* (module), **54, 59, 64, 53**,  
 used: 116
- decays* (field), **695**, used: 696,  
 696, 696, 697
- decay\_of\_momenta*, **692, 694**,  
**691**, used:
- declare*, **222**, used: 222
- declare\_argument*, **703**, used:  
 703, 703
- decode*, **717**, used: 717
- Default* (module), **798, 67, 796**,  
**53**, used: 707, 707, 717,  
 53, 707
- DefaultW* (module), **67, 53**,  
 used: 707
- default\_function*, **703**, used: 703
- default\_subroutine*, **703**, used:  
 703
- default\_width*, **236, 445**, ??, ??,  
**496, 526, 274, 297, 319**,  
**333, 344, 363, 374, 384**,  
**396, 410, 428**, ??, ??,  
 used: 236, 239, 445, 449,  
 ??, ??, ??, ??, 496, 499,  
 526, 531, 274, 276, 297,  
 299, 319, 320, 333, 334,  
 344, 346, 363, 365, 374,  
 376, 384, 386, 396, 400,  
 410, 412, 428, 428, ??, ??,  
 ??, ??
- Delta*, **450**, used:
- den* (field), **83, 84, 80**, used: 86
- dependencies*, **41, 46, 94, 101**,  
**103, 122, 38, 89**, used:  
 116, 117, 120, 122, 131,  
 132
- dependencies* (field), **100, 103**,  
 used: 103, 116, 117, 121
- derive*, **827, 829, 824**, used: 830,  
 830, 830
- derived* (field), **171**, used: 575,  
 225, 227, 229, 232, 245,  
 455, ??, ??, 503, 534, 280,  
 302, 323, 337, 350, 368,  
 379, 389, 407, 416, 428,  
 ??, ??, 721
- derived\_arrays* (field), **171**, used:  
 575, 225, 227, 229, 232,  
 245, 455, ??, ??, 503, 534,  
 280, 302, 323, 337, 350,  
 368, 379, 389, 407, 416,  
 428, ??, ??, 721
- derived\_parameters*, **244**, ??, ??,  
**280, 302, 322, 337, 350**,  
**367, 378, 389, 428**, ??,  
 ??, used: 245, ??, ??,  
 280, 302, 323, 337, 350,  
 368, 379, 389, 428, ??, ??
- derived\_parameter\_arrays*, **245**,  
 ??, ??, **280, 302, 322**,  
**337, 350, 368, 379, 389**,  
**416, 428**, ??, ??, used:  
 245, ??, ??, 280, 302, 323,

- 337, 350, 368, 379, 389,  
 416, 428, ??, ??  
*derive\_inner*, 827, 830, 824,  
 used:  
*derive\_inner'*, 827, 830, 824,  
 used:  
*derive\_outer*, 827, 830, 825,  
 used: 831  
*descend*, 771, 771, 771, 772,  
 774, 774, 774, 774,  
 used: 771, 771, 771, 772,  
 774, 774, 774, 774  
*description*, 727, 28, 73, 76,  
 726, 73, used: 728, 55,  
 61, 117, 134, 267  
*description* (field), 727, 76, used:  
 727, 76, 76, 79  
*DH*, 447, used:  
*diag*, 496, 527, used: 496, 496,  
 527, 527  
*diagnostic* (type), 178, used: 178  
*diagram*, 710, used: 711  
*diagrams*, 28, 31, 707, 717, 717,  
 20, 707, used: 32  
*diagrams* (field), 813, 807, used:  
 814, 815, 711, 711, 711  
*diagrams\_per\_keystone*, 28, 32,  
 20, used: 32  
*diagrams\_via\_keystones*, 28, 32,  
 20, used:  
*diagram\_class* (type), 28, used:  
*diagram\_sans\_color*, 710, used:  
 711  
*dictionary*, 127, 129, 92, used:  
*dictionary* (field), 129, used: 129,  
 134  
*diet*, 395, 395, 395, 395, 395,  
 396, 396, 272, used: 396,  
 406  
*diff*, 210, 216, 210, used: ??,  
 746, 785, 216, 133  
*Diff*, 166, used: 244, 245, ??, ??,  
 280, 302, 322, 337, 350,  
 367, 378, 389, 416, 428, ??  
*DIFF\_ELEMENT* (sig), ??, ??,  
 used: ??, ??, ??, ??  
*digit* (camllex regexpr), 70, 566,  
 used: 70, 566, 566  
*digits*, 732, used: 733, 734  
*digits* (field), 732, used: 733, 734,  
 734  
*dim*, 54, 55, 61, 51, used: 62, 62,  
 62, 64, 65, 66, 697, 697, 74  
*dim0*, 61, used: 61, 62, 62, 62,  
 63, 63, 63  
*Dim4\_Vector\_Vector\_Vector\_L*,  
 138, used: 188, 247, ??,  
 ??, 428  
*Dim4\_Vector\_Vector\_Vector\_L5*,  
 138, used: 188, 247, ??,  
 ??, 428  
*Dim4\_Vector\_Vector\_Vector\_T*,  
 138, used: 188, 247, ??,  
 ??, 428  
*Dim4\_Vector\_Vector\_Vector\_T5*,  
 138, used: 188, 247, ??,  
 ??, 428  
*Dim5\_Scalar\_Gauge2*, 138,  
 used: 188, 252, 253, 463,  
 508, 339, 352, 369, 391,  
 430, 430, 720  
*Dim5\_Scalar\_Gauge2\_Skew*,  
 138, used: 188, 463, 508,  
 290, 311, 326  
*Dim5\_Scalar\_Vector\_Vector\_T*,  
 138, used: 188  
*Dim5\_Scalar\_Vector\_Vector\_TU*,  
 138, used: 188, 252  
*Dim5\_Scalar\_Vector\_Vector\_U*,  
 138, used: 188, 252, 430  
*Dim5\_Tensor\_2\_Vector\_Vector\_1*,  
 138, used: 188  
*Dim5\_Tensor\_2\_Vector\_Vector\_2*,  
 138, used: 188  
*Dim6\_Gauge\_Gauge\_Gauge*,  
 138, used: 188, 247, ??,  
 ??, 428  
*Dim6\_Gauge\_Gauge\_Gauge\_5*,  
 138, used: 188, 247, ??,  
 ??, 428  
*Dim6\_Vector\_Vector\_Vector\_T*,  
 138, used: 188  
*Dim7\_Tensor\_2\_Vector\_Vector\_T*,  
 138, used: 188  
*disambiguate\_fusions*, 131, used:  
 134  
*Discrete* (module), 43, 39, used:  
*disjoint*, 785, used: 786  
*distribute\_degrees*, 31, used: 31

- distribute\_degrees'*, **31**, used: **31**,  
**31**
- distribute\_degrees''*, **31**, used: **31**,  
**31**
- DIV*, **??**, **??**, used: **??**, **566**
- DIV* (camlyacc token), **567**,  
used: **567**, **567**
- divide*, **565**, **564**, used: **??**, **567**
- division*, **818**, used: **818**
- DL*, **236**, **??**, **??**, **428**, used: **237**,  
**257**, **259**, **??**, **??**, **??**, **??**,  
**??**, **??**, **428**, **436**, **437**
- Dodd*, **297**, used: **297**
- domain* (type), **765**, **765**, **764**,  
used: **765**, **765**, **764**, **765**
- dot*, **564**, **564**, used: **??**, **567**
- DOT*, **??**, **??**, used: **??**, **566**
- DOT* (camlyacc token), **567**,  
used: **567**, **567**
- Dotproduct*, **564**, **564**, used: **564**
- DR*, **236**, **??**, **??**, **428**, used: **237**,  
**257**, **259**, **??**, **??**, **??**, **??**,  
**??**, **??**, **428**, **436**, **437**
- drb*, **61**, used: **61**, **62**, **62**, **62**, **65**,  
**66**
- drb0*, **61**, used: **62**, **62**, **63**, **63**
- DScalar2\_Vector2*, **139**, used:  
**189**
- DScalar4*, **139**, used: **189**
- dummy*, **733**, **732**, used: **133**
- Dummy* (module), **578**, used:  
*dummy\_flavor*, **572**, used: **574**
- dump*, **819**, **808**, used:
- Duplicate* (exn), **54**, **55**, **61**, **692**,  
**693**, **50**, **691**, used:
- Dyn* (module), **781**, **780**, used:  
**782**, **213**
- Dyn* (sig), **780**, **780**, used: **780**
- D\_Alpha\_WWWW0\_S*, **241**, **??**,  
**??**, **428**, used: **250**, **??**,  
**??**, **428**
- D\_Alpha\_WWWW0\_T*, **241**, **??**,  
**??**, **428**, used: **250**, **??**,  
**??**, **428**
- D\_Alpha\_WWWW0\_U*, **241**, **??**,  
**??**, **428**, used: **250**, **??**,  
**??**, **428**
- D\_Alpha\_WWWW2\_S*, **241**, **??**,  
**??**, **428**, used: **250**, **??**,  
**??**, **428**
- D\_Alpha\_WWWW2\_T*, **241**, **??**,  
**??**, **428**, used: **250**, **??**,  
**??**, **428**
- D\_Alpha\_ZZWW0\_S*, **241**, **??**,  
**??**, **428**, used: **250**, **??**,  
**??**, **428**
- D\_Alpha\_ZZWW0\_T*, **241**, **??**,  
**??**, **428**, used: **250**, **??**,  
**??**, **428**
- D\_Alpha\_ZZWW1\_S*, **241**, **??**,  
**??**, **428**, used: **250**, **??**,  
**??**, **428**
- D\_Alpha\_ZZWW1\_T*, **241**, **??**,  
**??**, **428**, used: **250**, **??**,  
**??**, **428**
- D\_Alpha\_ZZWW1\_U*, **241**, **??**,  
**??**, **428**, used: **250**, **??**,  
**??**, **428**
- D\_Alpha\_ZZZZ\_S*, **241**, **??**, **??**,  
**428**, used: **250**, **??**, **??**,  
**428**
- D\_Alpha\_ZZZZ\_T*, **241**, **??**, **??**,  
**428**, used: **250**, **??**, **??**,  
**428**
- D\_K1\_L*, **344**, used: **344**, **347**,  
**353**
- D\_K1\_R*, **344**, used: **344**, **347**,  
**353**
- D\_K2\_L*, **344**, used: **344**, **347**,  
**353**
- D\_K2\_R*, **344**, used: **344**, **347**,  
**353**
- e* (type), **??**, **??**, **??**, **??**, used:  
**??**, **??**, **??**, **??**, **??**, **??**, **??**
- e* (camlyacc non-terminal), **567**,  
used: **567**, **567**
- E*, **241**, **450**, **??**, **??**, **501**, **532**,  
**278**, **300**, **321**, **337**, **349**,  
**367**, **378**, **388**, **414**, **428**,  
**??**, **??**, used: **244**, **??**, **??**,  
**428**
- edge* (type), **41**, **41**, **42**, **42**, **43**,  
**45**, **109**, **36**, **37**, **40**,  
used: **41**, **41**, **42**, **42**, **42**,  
**43**, **45**, **100**, **109**, **36**, **36**,  
**37**, **37**, **37**, **38**, **38**, **38**, **39**,  
**39**, **39**, **40**, **40**, **40**
- Edges* (module), **109**, used: **109**
- edges\_feynmf*, **812**, used: **812**

- edges\_feynmf'*, **812**, used: **812**,  
**812**
- EEnd*, **??**, **??**, used: **??**
- Eidelta*, **450**, used:
- electromagnetic\_currents*, **245**,  
**??**, **??**, **281**, **302**, **323**,  
**338**, **350**, **368**, **379**, **389**,  
**417**, **428**, **??**, **??**, used:  
**258**, **??**, **??**, **291**, **312**, **327**,  
**340**, **353**, **370**, **380**, **391**,  
**422**, **436**, **??**, **??**
- electromagnetic\_currents'*, **??**,  
used: **??**
- electromagnetic\_currents\_2*, **455**,  
**503**, **535**, used: **477**, **513**,  
**548**
- electromagnetic\_currents\_3*, **455**,  
**503**, **534**, used: **477**, **513**,  
**548**
- electromagnetic\_sfermion\_currents*,  
**455**, **503**, **534**, used: **477**,  
**513**, **548**
- Electron*, **227**, used: **228**, **228**,  
**229**, **229**
- elements*, **755**, **761**, **763**, **754**,  
used: **746**, **781**, **781**, **784**,  
**784**, **785**, **829**, **829**, **830**,  
**832**, **44**, **47**, **700**, **186**, **215**,  
**215**, **216**, **103**, **120**, **123**,  
**124**
- elements'*, **761**, used: **761**, **761**
- eliminate\_common\_fusions*, **132**,  
used: **134**
- eliminate\_common\_fusions1*,  
**132**, used: **132**
- elt* (type), **780**, **780**, **781**, **781**,  
**782**, **784**, **784**, **213**, **216**,  
**118**, **779**, **779**, **780**, **783**,  
used: **780**, **780**, **781**, **781**,  
**781**, **781**, **781**, **782**, **784**,  
**213**, **779**, **779**, **779**, **779**,  
**780**, **780**, **780**, **780**, **780**,  
**783**, **784**
- Elt\_Base* (sig), **780**, **779**, used:  
**781**, **781**, **779**, **780**
- embedding*, **748**, **748**, used:
- embedding* (field), **748**, used: **748**,  
**749**, **749**, **750**
- embedding1*, **749**, **748**, used:
- embedding1* (field), **748**, used:  
**749**, **749**, **750**
- embedding2*, **749**, **748**, used:
- embedding2* (field), **748**, used:  
**749**, **749**, **750**
- embed\_in\_decay*, **694**, used: **694**,  
**694**, **695**
- embed\_in\_decays*, **695**, used:  
**695**, **696**
- empty*, **755**, **756**, **761**, **784**, **784**,  
**769**, **769**, **770**, **772**, **773**,  
**730**, **41**, **43**, **44**, **45**, **48**,  
**696**, **127**, **134**, **754**, **783**,  
**767**, **768**, **768**, **730**, **37**,  
**92**, used: **??**, **??**, **765**,  
**761**, **746**, **746**, **749**, **781**,  
**781**, **784**, **785**, **785**, **785**,  
**786**, **786**, **770**, **770**, **770**,  
**770**, **772**, **773**, **773**, **773**,  
**774**, **828**, **829**, **829**, **831**,  
**831**, **730**, **730**, **816**, **817**,  
**29**, **44**, **44**, **44**, **45**, **45**, **45**,  
**46**, **46**, **47**, **48**, **48**, **48**, **696**,  
**220**, **221**, **222**, **700**, **700**,  
**700**, **702**, **78**, **186**, **215**,  
**216**, **103**, **104**, **111**, **111**,  
**116**, **117**, **118**, **119**, **120**,  
**120**, **123**, **124**, **124**, **131**,  
**132**, **133**, **715**, **715**, **225**,  
**226**, **227**, **230**, **718**
- Empty*, **755**, used: **756**, **756**, **757**,  
**758**, **758**, **759**, **760**, **760**,  
**761**
- em\_lqino\_currents*, **542**, used:  
**548**
- em\_lq\_currents*, **542**, used: **548**
- em\_up\_type\_currents*, **??**, used:  
**??**
- END*, **??**, **??**, **??**, **??**, used: **??**,  
**??**, **70**, **566**
- END* (camlyacc token), **71**, **567**,  
used: **71**, **567**
- end\_step*, **734**, **732**, used: **133**
- enumerate*, **743**, **740**, used: **747**
- EPowSet* (module), **784**, used:  
**784**, **784**, **784**, **785**, **785**,  
**785**, **786**, **786**, **786**
- equal*, **769**, **769**, **772**, **81**, **84**, **85**,  
**218**, **219**, **219**, **767**, **768**,  
used: **82**, **82**

- EResult*, ??, ??, used: ??  
*ESet* (module), **784**, used: **784**,  
**784**, **784**, **785**, **785**, **785**,  
**785**  
*EStart*, ??, ??, used: ??  
*Eta*, **274**, **297**, **319**, used: **275**,  
**277**, **283**, **290**, **291**, **298**,  
**299**, **304**, **311**, **312**, **319**,  
**320**, **325**, **326**, **327**, **327**  
*eta\_higgs\_gauge*, **327**, used: **327**  
*eval*, **41**, **47**, **692**, **695**, **39**, **691**,  
used: **47**, **47**  
*eval\_decay*, **692**, **693**, **691**, used:  
**693**, **695**  
*eval\_memoized*, **41**, **48**, **39**, used:  
**48**, **123**  
*eval\_memoized'*, **48**, used: **48**  
*eval\_offspring*, **47**, used: **48**  
*ew\_order*, **98**, used: **98**, **98**  
*ew\_order* (type), **98**, used:  
*EW\_order*, **98**, used: **98**, **98**  
*exists*, **737**, **738**, **736**, used: **746**,  
**32**, **205**  
*expand\_decays*, **210**, **213**, **209**,  
used: **714**  
*expand\_home*, **735**, **735**, used:  
**737**  
*expand\_scatterings*, **210**, **212**,  
**209**, used: **714**  
*export*, **769**, **772**, **772**, **775**, **768**,  
**769**, used:  
*export'*, **772**, **774**, used: **772**, **772**,  
**774**, **775**  
*expr*, ??, ??, used: **573**  
*expr* (type), **166**, used: **166**, **171**,  
**175**, **175**  
*expr* (camlyacc non-terminal),  
**567**, used: **567**  
*ext* (field), **28**, used: **29**, **29**, **30**,  
**30**, **30**  
*extend*, **730**, **730**, used: **730**, **730**,  
**128**  
*externals*, **94**, **101**, **103**, **122**, **90**,  
used: **700**, **122**, **709**, **709**,  
**711**, **716**, **717**  
*externals* (field), **100**, **103**, used:  
**103**, **116**  
*external\_color\_flows*, **204**, used:  
**206**  
*external\_edges*, **816**, used: **817**  
*external\_edges\_from*, **816**, used:  
**816**, **816**  
*external\_flavors*, **222**, **571**, **186**,  
**207**, **225**, **226**, **228**, **230**,  
**237**, **266**, **269**, **447**, ??,  
??, **498**, **529**, **275**, **298**,  
**319**, **333**, **344**, **363**, **375**,  
**385**, **407**, **411**, **428**, ??,  
??, **719**, **175**, used: **571**,  
**207**, **713**, **225**, **226**, **228**,  
**230**, **237**, **266**, **269**, **448**,  
??, ??, **498**, **529**, **275**, **298**,  
**319**, **333**, **345**, **364**, **375**,  
**385**, **411**, **428**, ??, ??, **719**  
*external\_flavors'*, **447**, used: **447**  
*external\_flavors''*, **447**, used: **447**  
*external\_ghosts*, **205**, used: **206**  
*external\_wfs*, **100**, **101**, **112**,  
used: **116**, **120**  
*ExtMSSM* (module), **526**, **525**,  
used: ??  
*extMSSM\_flags* (sig), **526**, **525**,  
used: **526**, **526**, **526**, **525**  
*ext\_edges* (field), **816**, used: **817**,  
**817**, **819**  
*ext\_incidence*, **817**, used: **819**  
*ext\_layout* (type), **818**, **807**,  
used: **818**, **807**, **807**  
*ext\_nodes* (field), **816**, used: **817**,  
**818**, **819**, **819**, **819**, **819**,  
**819**  
*f* (type), **218**, **218**, **218**, **222**,  
**571**, **575**, **225**, **226**, **228**,  
**231**, **245**, **266**, **269**, **455**,  
??, ??, **503**, **534**, **280**,  
**302**, **323**, **337**, **350**, **368**,  
**379**, **389**, **406**, **416**, **428**,  
??, ??, **720**, **217**, **217**,  
**217**, used: **218**, **218**, **218**,  
**218**, **218**, **219**, **219**, **219**,  
**222**, **217**, **217**, **217**, **217**  
*F* (module), **699**, **575**, **109**, **128**,  
**708**, **225**, **226**, **228**, **231**,  
**245**, **266**, **269**, **455**, ??,  
??, **503**, **534**, **280**, **302**,  
**323**, **337**, **350**, **368**, **379**,  
**389**, **406**, **416**, **428**, ??,  
??, **720**, used: **699**, **699**,  
**699**, **699**, **700**, **700**, **575**,  
**109**, **128**, **128**, **129**, **129**,

- 131, 131, 132, 133, 134,  
709, 709, 709, 709, 709,  
710, 710, 711, 712, 715,  
715, 716, 716, 716, 716,  
717, 717, 225, 229, 232,  
259, 267, 270, 479, ??, ??,  
514, 549, 291, 312, 327,  
340, 353, 370, 381, 391,  
406, 422, 437, ??, ??, 721
- F12*, 140, used: 220  
*F123*, 140, used: 221  
*F124*, 140, used: 221  
*F13*, 140, used: 220  
*F132*, 140, used: 221  
*F134*, 140, used: 221  
*F142*, 140, used: 221  
*F143*, 140, used: 221  
*F2* (module), 218, used: 219, 220  
*F2'* (module), 220, used: 220,  
220  
*F21*, 140, used: 220  
*F213*, 140, used: 221  
*F214*, 140, used: 221  
*F23*, 140, used: 220, 227  
*F231*, 140, used: 221  
*F234*, 140, used: 221, 227  
*F241*, 140, used: 221  
*F243*, 140, used: 221  
*F3* (module), 219, used: 219, 221  
*F3'* (module), 221, used: 221,  
221  
*F31*, 140, used: 220  
*F312*, 140, used: 221  
*F314*, 140, used: 221  
*F32*, 140, used: 220  
*F321*, 140, used: 221  
*F324*, 140, used: 221  
*F341*, 140, used: 221  
*F342*, 140, used: 221  
*F412*, 140, used: 221  
*F413*, 140, used: 221  
*F421*, 140, used: 221  
*F423*, 140, used: 221  
*F431*, 140, used: 221  
*F432*, 140, used: 221  
*factor*, 83, 86, 81, used: 134  
*factor* (type), 83, 84, 80, used:  
83, 127, 129, 81, 92  
*factorial*, 789, 27, 27, 787, 19,  
used: 790, 790, 27, 32, 32
- factorial'*, 789, used: 789, 789  
*factorize*, 745, 741, used: 793,  
794  
*factorized\_keystones*, 794, 788,  
used: 24, 24  
*factorized\_partitions*, 793, 788,  
used:  
*factorize\_brackets*, 120, used: 120  
*Fake\_Graded\_Map* (module), 48,  
used: 49  
*Fake\_Grading* (module), 43,  
used: 49  
*False*, 69, 74, 68, used: 69, 69,  
75  
*family*, 237, 447, ??, ??, 498,  
529, 275, 297, 319, 333,  
344, 363, 375, 385, 411,  
428, ??, ??, used: 237,  
447, ??, ??, 498, 529, 275,  
298, 319, 333, 344, 363,  
375, 385, 411, 428, ??, ??
- fan*, 810, 806, used: 810  
*FBF*, 138, used: 188, 229, 231,  
245, 245, 246, 246, 246,  
246, 246, 253, 254, 254,  
254, 254, 254, 254, 255,  
255, 255, 255, 256, 256,  
256, 256, 256, 257, 257,  
257, 257, 257, 257, 258,  
258, 258, 455, 455, 455,  
456, 456, 456, 457, 457,  
457, 457, 457, 457, 458,  
458, 458, 458, 458, 459,  
459, 459, 461, 461, 462,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
503, 503, 503, 504, 504,  
504, 505, 505, 505, 505,  
505, 506, 506, 506, 506,  
506, 507, 507, 507, 508,  
534, 535, 535, 535, 535,  
535, 536, 536, 536, 536,  
537, 537, 537, 537, 537,  
537, 538, 538, 538, 539,  
539, 539, 539, 540, 540,  
540, 540, 540, 540, 541,

- 541, 541, 541, 541, 542,  
542, 542, 281, 281, 281,  
281, 281, 282, 282, 282,  
282, 283, 302, 303, 303,  
303, 303, 303, 304, 304,  
304, 304, 323, 323, 323,  
323, 324, 325, 325, 325,  
325, 338, 338, 338, 338,  
338, 350, 350, 350, 351,  
351, 368, 368, 368, 368,  
379, 379, 379, 379, 379,  
389, 389, 389, 389, 390,  
403, 403, 403, 403, 404,  
404, 404, 404, 417, 417,  
417, 417, 417, 418, 418,  
418, 418, 418, 418, 419,  
428, 432, 433, 433, 433,  
433, 433, 434, 434, 434,  
434, 435, 435, 435, 435,  
435, 435, 435, 436, 436,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, 720  
*fermion*, **222, 571, 186, 207,**  
**225, 226, 228, 231, 239,**  
**266, 267, 450, ??, ??,**  
**500, 531, 277, 299, 320,**  
**335, 347, 365, 377, 387,**  
**400, 413, 428, ??, ??,**  
**720, 174,** used: 571, 186,  
207, 95, 125, 266, 267  
*fermion* (label), **223, 175,** used:  
575  
*fermion* (type), **397, 137,** used:  
397, 138, 139  
*Fermion*, **95, 125, 397,** used: 95,  
96, 125, 126, 397, 400,  
403, 403, 403, 403, 404,  
404, 404, 404  
*fermionbar* (type), **137,** used:  
138, 139  
*fermion\_of\_lorentz*, **570,** used:  
570, 573, 573  
*ferm\_of\_sff*, **453,** used:  
*feynmf* (type), **811, 806,** used:  
813, 806, 807  
*feynmf\_footer*, **814,** used: 815,  
815  
*feynmf\_header*, **814,** used: 815,  
815  
*feynmf\_levels*, **815,** used: 815,  
815, 815  
*feynmf\_levels* (type), **813, 807,**  
used: 813, 807, 807, 807  
*feynmf\_levels\_plain*, **815, 807,**  
used:  
*feynmf\_levels\_wrapped*, **815,**  
**807,** used:  
*feynmf\_set*, **814, 711,** used: 814,  
711, 712  
*feynmf\_set* (type), **813, 807,**  
used: 813, 813, 807, 807  
*feynmf\_sets*, **814,** used: 814, 815  
*feynmf\_sets* (type), **813, 807,**  
used: 807, 807  
*feynmf\_sets\_plain*, **814, 807,**  
used:  
*feynmf\_sets\_wrapped*, **815, 807,**  
used: 712, 712, 712  
*feynmf\_set\_sans\_color*, **711,**  
used: 711, 711  
*feynmf\_set\_sans\_color\_empty*,  
**711,** used: 712  
*feynmf\_style*, **709,** used: 710, 710  
*fiber*, **780, 781, 781, 782, 780,**  
**780,** used:  
*fiber* (type), **780, 781, 781, 782,**  
**779, 780,** used: 780, 781,  
782, 780, 780, 780, 780  
*Fiber* (module), **781,** used: 781,  
781, 781, 781  
*fibered\_dag* (type), **118,** used:  
*fibers*, **780, 781, 781, 782, 780,**  
**780,** used: 782  
*fiber\_to\_string*, **214,** used: 214  
*field*, **208, 237, 267, ??, ??, 274,**  
**333, 344, 363, 375, 385,**  
**411, 428, ??, ??, 177,**  
used: 267, 269, 269, 269,  
270  
*field* (type), **208, 237, 267, ??,**  
**??, 274, 333, 344, 363,**  
**375, 385, 411, 428, ??,**  
**??, 177,** used: 177  
*file*, **733, 732,** used: 133  
*File*, **732, 128,** used: 733, 128  
*filter\_keystone*, **112,** used: 117  
*filter\_offspring*, **110,** used: 110  
*filter\_sign*, **795,** used: 795, 795,  
795, 795

- finalize*, **697**, used: 697  
*finalize1*, **694**, used: 694, 697  
*finalize\_decay*, **694**, used: 694  
*find*, **755, 757, 762, 737, 738, 769, 769, 770, 772, 773, 43, 44, 48, 754, 736, 767, 768, 768**, used: 765, 757, 762, 781, 781, 738, 770, 770, 770, 773, 773, 773, 828, 830, 831, 730, 817, 29, 44, 44, 45, 46, 46, 46, 47, 47, 47, 48, 219, 219, 219, 699, 700, 575, 104, 111, 116, 117, 119, 121, 124, 131, 133, 408  
*find1*, **770, 773**, used: 770, 771, 771, 771, 773, 773, 774, 774  
*find\_first*, **737**, used: 738  
*findfst*, **82**, used: 82, 82  
*find\_opt*, **755, 757, 762, 754**, used: 757, 762, 749  
*find\_snd*, **82**, used: 82, 82, 82  
*first\_match*, **808, 692**, used: 809, 692  
*first\_match'*, **692**, used: 692, 692  
*first\_non\_white*, **568**, used: 569  
*first\_pair*, **692**, used: 696  
*first\_pair'*, **692**, used: 692, 692  
*flatmap*, **743, 741**, used: 743, 830, 832, 795, 808, 808, 816, 816, 816, 816, 17, 24, 24, 33, 34, 223, 701, 74, 204, 204, 204, 212, 213, 108, 119, 120, 120, 123, 123, 131, 133, 709, 712, 713, 225, 226, 228, 230, 237, 237, 246, 246, 256, 257, 257, 258, 258, 258, 269, 269, 270, 447, 448, 458, 458, 459, 459, 459, 461, 461, 463, 465, 466, 466, 466, 469, 470, 470, 470, 471, 472, 474, 474, 475, 475, 476, 477, 478, ??, ??, ??, ??, ??, ??, ??, ??, ??, ??, ??, ??, 498, 498, 507, 509, 510, 511, 511, 511, 512, 512, 513, 513, 514, 529, 529, 538, 539, 540, 540, 540, 540, 540, 540, 541, 541, 541, 541, 542, 542, 542, 543, 544, 545, 545, 545, 546, 546, 547, 548, 549, 275, 275, 291, 298, 298, 312, 319, 319, 323, 325, 327, 333, 333, 340, 344, 345, 353, 363, 364, 370, 375, 375, 380, 385, 385, 391, 398, 411, 411, 422, 428, 435, 435, 436, 436, ??, ??, ??, ??, ??, ??, ??, ??, ??, ??, ??, ??, 719  
*flatten\_keystones*, **108**, used: 124  
*flavor*, **94, 100, 101, 121, 88**, used: 699, 700, 108, 112, 117, 119, 121, 709, 710, 710, 717  
*flavor* (field), **100, 101**, used: 101, 101, 102, 104, 108, 108, 111, 112, 117, 118, 119, 119, 123, 124  
*flavor* (type), **222, 571, 73, 74, 184, 207, 210, 210, 94, 95, 95, 100, 101, 121, 125, 127, 128, 707, 708, 225, 226, 227, 230, 236, 266, 267, 447, ??, ??, 498, 529, 274, 297, 319, 333, 344, 363, 374, 384, 397, 411, 428, ??, ??, 718, 172, 72, 209, 88, 91, 707**, used: 699, 699, 700, 571, 575, 73, 74, 74, 74, 76, 184, 184, 207, 210, 210, 210, 211, 214, 216, 94, 95, 95, 95, 95, 95, 97, 100, 100, 100, 101, 101, 101, 101, 103, 104, 104, 105, 121, 125, 125, 127, 128, 128, 129, 707, 708, 225, 226, 228, 231, 241, 245, 266, 266, 269, 450, 455, ??, ??, 501, 503, 532, 534, 278, 280, 300, 302, 321, 323, 337, 337, 349, 350, 367, 368, 378, 379, 388, 389, 406, 414, 416, 428, ??, ??, ??, ??, 720, 172, 172, 172, 172, 174,



- 174, 174, 174, 174, 175,  
175, 175, 175, 175, 175,  
175, 177, 177, 178, 178,  
178, 178, 217, 73, 73, 73,  
73, 183, 183, 209, 209,  
210, 210, 88, 90, 91, 91,  
93, 93, 707, 707
- Flavor* (sig), **218, 217**, used:  
218, 217
- FLAVOR*, ??, ??, used: ??, ??,  
70
- FLAVOR* (camlyacc token), **71**,  
used: 72
- flavors*, **222, 571, 186, 207**,  
**214, 127, 129, 225, 226**,  
**228, 230, 237, 266, 269**,  
**448, ??, ??, 498, 529**,  
**275, 298, 319, 333, 345**,  
**364, 375, 385, 406, 411**,  
**428, ??, ??, 719, 175**,  
**92**, used: 571, 576, 186,  
207, 215, 105, 117, 266,  
269, 408
- flavors* (field), **129**, used: 129,  
134
- flavors* (label), **223, 175**, used:
- flavors* (type), **129**, used:
- flavors\_of\_particles*, **574**, used:  
576
- flavors\_to\_string*, **701, 75**, used:  
701, 701, 701, 75
- flavor\_keystone*, **108**, used: 108
- flavor\_keystones*, **108**, used: 117
- flavor\_list* (camlyacc  
non-terminal), **72**, used:  
71, 72
- flavor\_of\_antiparticle*, **573**, used:  
574
- flavor\_of\_b*, **397**, used: 406, 407
- flavor\_of\_f*, **397**, used: 406, 407
- flavor\_of\_particle*, **573**, used:  
574
- flavor\_of\_string*, **222, 571, 186**,  
**207, 226, 227, 229, 232**,  
**259, 267, 268, 479, ??**,  
**??, 514, 549, 291, 312**,  
**327, 340, 353, 370, 381**,  
**391, 408, 422, 437, ??**,  
**??, 721, 175**, used: 571,  
75, 186, 207, 211, 267, 268
- flavor\_of\_string* (label), **223**,  
**175**, used:
- flavor\_sans\_color*, **184, 207, 94**,  
**121, 178, 178, 88**, used:  
184, 204, 204, 204, 207,  
117, 118, 119, 121, 129,  
709, 709
- flavor\_sans\_color* (type), **184**,  
**207, 94, 121, 178, 178**,  
**88**, used: 207, 94, 95, 97,  
178, 178, 178, 178, 183,  
183, 88, 89, 90, 91, 93
- Flavor\_Set* (module), **700**, used:  
700, 700, 700
- flavor\_sums*, **214**, used: 215
- flavor\_symbol*, **222, 571, 187**,  
**207, 226, 227, 229, 233**,  
**262, 267, 267, 481, ??**,  
**??, 518, 554, 293, 315**,  
**330, 342, 360, 372, 383**,  
**393, 408, 424, 440, ??**,  
**??, 723, 175**, used: 571,  
187, 207, 124, 264, 267,  
267, 487, ??, ??, 294, 316,  
331, 343, 362, 374, 384,  
394, 425, 441, ??, ??
- flavor\_symbol* (label), **223, 175**,  
used: 575
- flavor\_to\_string*, **222, 571, 187**,  
**207, 226, 227, 229, 232**,  
**260, 267, 268, 480, ??**,  
**??, 515, 551, 292, 313**,  
**328, 340, 354, 371, 381**,  
**392, 407, 422, 438, ??**,  
**??, 722, 175**, used: 701,  
571, 576, 75, 187, 203,  
207, 213, 129, 709, 713,  
715, 267, 268, 408
- flavor\_to\_string* (label), **223**,  
**175**, used: 575
- flavor\_to\_TeX*, **222, 571, 187**,  
**207, 226, 227, 229, 232**,  
**261, 267, 268, 482, ??**,  
**??, 516, 552, 292, 314**,  
**329, 341, 357, 372, 382**,  
**392, 408, 423, 439, ??**,  
**??, 722, 175**, used: 571,  
187, 207, 709, 710, 710,  
712, 267, 268
- flavor\_to\_TeX* (label), **223, 175**,

- used: 575
- flip\_incoming*, **696**, used: 696
- flip\_s\_channel\_in*, **54, 59, 64, 53**, used: 696, 699
- flow*, **207, 208, 178, 178**, used: 208, 129
- Flow* (module), **83, 81**, used: 207, 127, 129, 129, 129, 134, 134, 134, 178, 178, 92, 92
- Flow* (sig), **83, 80**, used: 81
- FMap* (module), **129**, used: 133, 133
- Fn* (module), **219**, used: 219
- fold*, **755, 760, 764, 769, 769, 771, 772, 774, 777, 810, 41, 41, 42, 42, 43, 43, 44, 46, 48, 109, 754, 767, 768, 768, 776, 806, 36, 38, 40**, used: 760, 761, 764, 781, 781, 786, 786, 771, 774, 828, 829, 829, 829, 830, 830, 830, 830, 830, 831, 831, 831, 832, 777, 810, 810, 810, 16, 17, 17, 30, 43, 44, 44, 44, 45, 46, 46, 46, 46, 46, 47, 47, 47, 47, 47, 48, 48, 700, 212, 213, 104, 109, 116, 117, 118, 120, 120, 124, 131
- fold* (type), **778, 776**, used: 776
- fold'*, **771, 774**, used: 771, 774
- fold2*, **830, 777, 776**, used: 830, 777, 777, 11, 11, 12, 15, 47, 108, 108, 119, 123
- fold2* (type), **778, 776**, used: 776
- fold2\_rev*, **777**, used: 777
- fold3*, **777, 776**, used: 777, 12, 12, 15
- fold3\_rev*, **777**, used: 777
- fold\_left*, **9, 11, 12, 14, 16, 6**, used: ??, ??, ??, 765, 743, 743, 744, 744, 746, 746, 785, 735, 829, 830, 830, 830, 830, 831, 831, 730, 777, 777, 777, 777, 790, 790, 792, 792, 792, 792, 793, 793, 793, 793, 793, 794, 795, 795, 796, 816, 817, 818, 16, 26, 26, 29, 29, 29, 31, 31, 32, 32, 32, 32, 32, 47, 48, 61, 181, 181, 181, 182, 84, 220, 221, 699, 700, 700, 572, 574, 575, 74, 186, 214, 97, 98, 103, 108, 110, 111, 111, 112, 119, 120, 121, 122, 122, 131, 132, 132, 133
- fold\_left2*, **743, 741**, used: 743, 741
- fold\_lefti*, **??**, used: ??, ??
- fold\_left\_internal*, **9, 11, 12, 14, 16, 6**, used: 108
- fold\_lines*, **569**, used: 570
- fold\_nodes*, **41, 46, 37**, used: 111, 118, 124
- fold\_rev*, **777**, used: 777, 777
- fold\_right*, **9, 11, 12, 14, 16, 6**, used: 744, 746, 746, 781, 784, 785, 785, 803, 812, 11, 11, 12, 13, 15, 16, 16, 17, 42, 694, 696, 700, 700, 702, 565, 570, 75, 214, 214, 214, 215, 215, 216, 103, 104, 118, 119, 124
- fold\_right2*, **744, 741**, used: 123
- fold\_right\_internal*, **9, 11, 12, 14, 16, 6**, used: 99
- forest*, **41, 47, 94, 123, 39, 91**, used: 709, 711, 716, 717
- Forest* (module), **42, 36**, used: 103, 109
- Forest* (sig), **41, 36**, used: 42, 42, 43, 49, 36, 39, 40
- forest'*, **123**, used: 123
- Forest\_Grader* (sig), **42, 40**, used: 40
- forest\_memoized*, **41, 48, 39**, used: 123
- forest\_sans\_color*, **709**, used: 711, 711, 712
- format\_flavor*, **701**, used: 702
- format\_generation*, **268**, used: 268, 268
- format\_maps*, **701**, used: 701
- format\_p*, **709**, used: 709, 709, 712, 712, 712
- Fortran* (module), **678, 678, 578**, used: 718, ??, 718,

- ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??
- Fortran77* (module), **578**, used:  
*Fortran\_Majorana* (module),  
**578**, used: ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, **723**
- for\_all*, **9, 11, 12, 14, 16, 41,**  
**42, 42, 43, 109, 6, 36,**  
**40**, used: **744, 16, 31, 42,**  
**43, 45, 181, 182, 74, 76,**  
**76, 77, 78, 203, 205, 211,**  
**108, 109, 112**
- four\_gluon*, **232, 721**, used: **232,**  
**721**
- FSet* (module), **214**, used: **214,**  
**214, 214, 214, 215**
- fspec\_of\_gen*, **397**, used: **409**  
*fspec\_of\_iso*, **397**, used: **409**  
*fspec\_of\_kk2*, **397**, used: **409**  
*fspec\_of\_kkmode*, **397**, used: **409**
- Fudged*, **137**, used: **239, 449, ??,**  
**??, 499, 531, 276, 299,**  
**320, 334, 346, 365, 376,**  
**386, 412, 428, ??**
- functions\_file*, **576**, used: **576,**  
**576**
- fuse*, **809, 218, 220, 222, 571,**  
**204, 207, 97, 97, 97, 98,**  
**108, 225, 227, 229, 232,**  
**259, 267, 270, 479, ??,**  
**??, 514, 549, 291, 312,**  
**327, 340, 353, 370, 381,**  
**391, 406, 422, 437, ??,**  
**??, 721, 174, 806, 217,**  
**93**, used: **571, 575, 204,**  
**207, 104, 110, 119, 123,**  
**225, 229, 232, 259, 267,**  
**270, 479, ??, ??, 514, 549,**  
**291, 312, 327, 340, 353,**  
**370, 381, 391, 406, 422,**  
**437, ??, ??, 721**
- fuse* (label), **223, 175**, used: **575**
- fuse2*, **11, 218, 219, 222, 571,**  
**204, 207, 225, 227, 229,**  
**232, 259, 267, 270, 479,**  
**??, ??, 514, 549, 291,**  
**312, 327, 340, 353, 370,**  
**381, 391, 406, 422, 437,**  
**??, ??, 721, 174, 217,**  
 used: **11, 15, 220, 220,**  
**571, 575, 204, 204, 207,**  
**225, 229, 232, 259, 267,**  
**270, 271, 479, ??, ??, 514,**  
**549, 291, 312, 327, 340,**  
**353, 370, 381, 391, 406,**  
**422, 437, ??, ??, 721**
- fuse2* (type), **140**, used: **140**
- fuse3*, **12, 218, 219, 222, 571,**  
**204, 207, 225, 227, 229,**  
**232, 259, 267, 270, 479,**  
**??, ??, 514, 549, 291,**  
**312, 327, 340, 353, 370,**  
**381, 391, 406, 422, 437,**  
**??, ??, 721, 174, 217,**  
 used: **13, 15, 220, 220,**  
**571, 575, 204, 204, 207,**  
**225, 229, 232, 259, 267,**  
**270, 271, 479, ??, ??, 514,**  
**549, 291, 312, 327, 340,**  
**353, 370, 381, 391, 406,**  
**422, 437, ??, ??, 721**
- fuse3* (type), **140**, used: **140**
- fusen*, **219**, used: **220, 220**
- fusen* (type), **140**, used: **140**
- fuse\_c\_wf*, **119**, used: **119, 119**
- fuse\_list*, **204**, used: **204**
- fuse\_n*, **17, 17**, used: **17**
- fuse\_rhs*, **104**, used: **104, 108**
- fuse\_trees*, **123**, used: **123**
- fusion* (type), **94, 100, 103, 121,**  
**127, 128, 89, 91**, used:  
**94, 100, 100, 101, 103,**  
**121, 127, 128, 128, 129,**  
**89, 90, 92, 93**
- Fusion* (module), **93, 88**, used:  
**699, 708, 708, 718, ??, ??,**  
**??, 718, ??, ??, ??, ??,**  
**??, ??, ??, ??, ??, ??, ??,**  
**??, ??, ??, ??, ??, ??, ??,**  
**??, ??, ??, ??, ??, ??, ??,**  
**??, ??, ??, ??, ??, ??, ??,**  
**??, ??, ??, ??, ??, ??, ??,**  
**??, ??, ??, ??, ??, ??, ??,**  
**??, ??, 723, 179, 698, 707**
- fusions*, **94, 101, 103, 122, 127,**  
**129, 90, 92**, used: **122,**  
**131, 132**
- fusions* (field), **100, 103, 129,**  
 used: **103, 116, 122, 122,**

- 124, 129, 134
- Fusions* (module), **218, 217**,  
used: 575, 225, 226, 228,  
231, 245, 266, 269, 455,  
??, ??, 503, 534, 280, 302,  
323, 337, 350, 368, 379,  
389, 406, 416, 428, ??, ??,  
720
- Fusions* (sig), **218, 217**, used:  
**218, 217**
- fusion\_dag*, **101, 103**, used:
- fusion\_dag* (field), **100, 103**,  
used: 103, 116, 117, 120,  
121, 122, 123, 123, 125
- fusion\_tower*, **111**, used: 111,  
111
- fusion\_tower* (field), **100, 103**,  
used: 116, 117, 121, 125
- fusion\_tower'*, **110**, used: 110,  
111
- f\_aux* (field), **572**, used: 572,  
573, 573
- f\_aux\_top* (type), **236**, ??, ??,  
**428**, used: 236, ??, ??,  
428
- f\_color* (field), **572**, used: 572,  
573, 573, 575
- f\_conjugate* (field), **572**, used:  
572, 573, 573, 575
- f\_fermion* (field), **572**, used: 572,  
573, 573, 575
- f\_mass* (field), **572**, used: 572,  
573, 573, 575
- f\_name* (field), **572**, used: 572,  
573, 573, 575
- f\_pdg* (field), **572**, used: 572,  
573, 573, 575
- f\_propagator* (field), **572**, used:  
572, 573, 573, 575
- f\_spin* (field), **572**, used: 572,  
573, 573, 575
- f\_symbol* (field), **572**, used: 572,  
573, 573, 575
- f\_width* (field), **572**, used: 572,  
573, 573, 575
- g* (type), **222, 571, 217**, used:  
222, 217
- G*, **225, 236, 267, 446, 450, ??**,  
**??, 497, 501, 527, 532**,  
**274, 333, 344, 363, 374**,  
**384, 397, 411, 428, ??**,  
**??, 718**, used: 225, 225,  
237, 239, 243, 244, 245,  
246, 248, 251, 251, 252,  
253, 253, 253, 254, 254,  
254, 254, 254, 254, 255,  
255, 255, 256, 256, 256,  
259, 267, 269, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, 274, 277,  
281, 291, 333, 335, 337,  
338, 338, 339, 339, 339,  
339, 340, 340, 344, 347,  
350, 351, 351, 352, 352,  
352, 352, 353, 353, 363,  
365, 368, 368, 369, 369,  
369, 369, 369, 370, 370,  
375, 376, 379, 380, 380,  
380, 380, 380, 381, 385,  
386, 389, 390, 390, 390,  
390, 391, 391, 391, 398,  
404, 405, 406, 407, 408,  
411, 412, 417, 419, 420,  
420, 420, 422, 422, 428,  
428, 429, 430, 430, 431,  
431, 431, 432, 432, 432,  
432, 432, 432, 433, 433,  
433, 433, 433, 434, 434,  
434, 435, 435, 437, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, 719, 720, 720, 720,  
720, 721, 721, 721
- G* (module), **42, 43, 43, 43, 45**,  
**109, 39**, used: 42, 44, 44,  
44, 44, 45, 45, 48, 49, 39,  
40
- G2*, **230, 241, ??, ??, 278, 300**,  
**321, 337, 349, 378, 388**,  
**414, 428, ??, ??**, used:  
232, 248, ??, ??, 284, 305,  
326, 338, 351, 380, 390,  
420, 428, ??, ??
- G22*, **349**, used: 351
- G3*, **226, 719**, used: 227, 227,  
720, 720
- G4*, **226, 719**, used: 227, 227,

- 721, 721  
*G5\_AWW*, 241, ??, ??, 428,  
 used: 247, ??, ??, 428  
*G5\_ZWW*, 241, ??, ??, 428,  
 used: 247, ??, ??, 428  
*Ga*, 236, 447, ??, ??, 498, 529,  
 274, 297, 319, 333, 344,  
 363, 374, 384, 411, 428,  
 ??, ??, used: 237, 239,  
 245, 246, 247, 248, 252,  
 253, 253, 253, 254, 254,  
 255, 259, 447, 449, 455,  
 455, 455, 462, 463, 463,  
 463, 464, 464, 465, 465,  
 466, 466, 476, 476, 479,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, 498,  
 500, 503, 503, 503, 508,  
 508, 508, 509, 509, 510,  
 510, 510, 510, 511, 511,  
 514, 529, 531, 534, 534,  
 535, 542, 542, 542, 542,  
 542, 542, 543, 543, 543,  
 544, 544, 544, 545, 545,  
 546, 549, 275, 277, 281,  
 281, 283, 283, 284, 284,  
 286, 287, 290, 290, 291,  
 298, 299, 302, 303, 305,  
 305, 305, 305, 307, 308,  
 311, 312, 312, 319, 320,  
 323, 325, 325, 325, 326,  
 326, 327, 327, 333, 335,  
 338, 338, 338, 339, 339,  
 340, 340, 344, 347, 350,  
 351, 351, 352, 352, 353,  
 353, 363, 365, 368, 368,  
 369, 369, 369, 370, 370,  
 375, 376, 379, 380, 380,  
 380, 381, 385, 386, 389,  
 390, 390, 391, 391, 391,  
 411, 412, 417, 419, 420,  
 420, 420, 422, 422, 428,  
 430, 430, 431, 432, 433,  
 434, 437, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??  
*gauge* (type), 222, 571, 184,  
 207, 225, 226, 228, 230,  
 237, 266, 267, 447, ??,  
 ??, 498, 529, 274, 297,  
 319, 333, 344, 363, 375,  
 385, 400, 411, 428, ??,  
 ??, 719, 174, used: 571,  
 572, 184, 207, 267, 174,  
 175, 175, 217  
*Gauge*, 208, 237, 267, ??, ??,  
 274, 333, 344, 363, 375,  
 385, 411, 428, ??, ??,  
 177, 178, used: 713, 237,  
 267, ??, ??, 274, 333, 344,  
 363, 375, 385, 411, 428,  
 ??, ??  
*Gauge* (module), 207, 183, used:  
  
*Gauge* (sig), 176, used: 207, 267,  
 177, 177, 178, 183, 224,  
 224, ??, 272, 273, ??  
*gauge4*, 232, 248, 463, ??, ??,  
 508, 542, 284, 305, 326,  
 338, 351, 369, 380, 390,  
 405, 420, 428, ??, ??,  
 721, used: 232, 248, 463,  
 ??, ??, 508, 542, 284, 284,  
 305, 305, 326, 338, 351,  
 369, 380, 390, 405, 406,  
 420, 428, ??, ??, 721  
*gauge\_boson*, 208, 237, 267, ??,  
 ??, 274, 333, 344, 363,  
 375, 385, 411, 428, ??,  
 ??, 177, used: 237, 267,  
 ??, ??, 275, 333, 344, 363,  
 375, 385, 411, 428, ??, ??  
*gauge\_boson* (type), 208, 236,  
 267, ??, ??, 274, 333,  
 344, 363, 374, 384, 411,  
 428, ??, ??, 176, used:  
 208, 208, 236, 237, 267,  
 ??, ??, 274, 274, 333, 333,  
 344, 344, 363, 363, 374,  
 375, 384, 385, 411, 411,  
 428, ??, ??, ??, ??, 177,  
 177, 177, 177, 177, 178  
*Gauge\_Gauge\_Gauge*, 138, used:  
 188, 231, 246, 463, ??, ??,  
 508, 542, 283, 283, 305,  
 305, 325, 325, 338, 351,  
 368, 380, 390, 404, 405,  
 405, 419, 428, ??, ??, 720  
*gauge\_higgs*, 253, 463, 509, 543,  
 290, 311, 327, 339, 352,

- 369, 380, 390, 420, 430,**  
 ??, ??, used: **258, 477,**  
**513, 548, 291, 312, 327,**  
**340, 353, 370, 380, 391,**  
**422, 436, ??, ??**  
*gauge\_higgs4*, **253, 464, 510,**  
**544, 290, 311, 327, 339,**  
**352, 370, 380, 390, 420,**  
**430, ??, ??,** used: **259,**  
**478, 514, 549, 291, 312,**  
**327, 340, 353, 370, 381,**  
**391, 422, 437, ??, ??**  
*gauge\_higgs4\_GaGaCC*, **509,**  
**543,** used: **510, 544**  
*gauge\_higgs4\_GaWPC*, **510,**  
**544,** used: **510, 544**  
*gauge\_higgs4\_GaWSC*, **510,**  
**544,** used: **510, 544**  
*gauge\_higgs4\_WWCC*, **509, 544,**  
 used: **510, 544**  
*gauge\_higgs4\_WWPP*, **509, 544,**  
 used: **510, 544**  
*gauge\_higgs4\_WWSS*, **509, 544,**  
 used: **510, 544**  
*gauge\_higgs4\_ZGaCC*, **509, 543,**  
 used: **510, 544**  
*gauge\_higgs4\_ZWPC*, **510, 544,**  
 used: **510, 544**  
*gauge\_higgs4\_ZWSC*, **509, 544,**  
 used: **510, 544**  
*gauge\_higgs4\_ZZCC*, **509, 543,**  
 used: **510, 544**  
*gauge\_higgs4\_ZZPP*, **509, 543,**  
 used: **510, 544**  
*gauge\_higgs4\_ZZSS*, **509, 543,**  
 used: **510, 544**  
*gauge\_higgs\_GaCC*, **508, 543,**  
 used: **509, 543**  
*gauge\_higgs\_GlGIP*, **508,** used:  
**509**  
*gauge\_higgs\_GlGIS*, **508,** used:  
**509**  
*gauge\_higgs\_gold*, **464,** used: **478**  
*gauge\_higgs\_gold4*, **465,** used:  
**478**  
*gauge\_higgs\_WPC*, **508, 543,**  
 used: **509, 543**  
*gauge\_higgs\_WSC*, **508, 543,**  
 used: **509, 543**  
*gauge\_higgs\_WWS*, **508, 543,**  
 used: **509, 543**  
*gauge\_higgs\_ZCC*, **508, 543,**  
 used: **509, 543**  
*gauge\_higgs\_ZSP*, **508, 543,**  
 used: **509, 543**  
*gauge\_higgs\_ZZS*, **508, 543,**  
 used: **509, 543**  
*gauge\_sfermion4*, **465, 511, 545,**  
 used: **478, 514, 549**  
*gauge\_sfermion4'*, **465, 510,**  
**544,** used: **465, 511, 545**  
*gauge\_sfermion4''*, **465, 510,**  
**545,** used: **465, 511, 545**  
*gauge\_squark4*, **466, 511, 545,**  
 used: **478, 514, 549**  
*gauge\_squark4'*, **466, 511, 545,**  
 used: **466, 511, 545**  
*gauge\_squark4''*, **466, 511, 545,**  
 used: **466, 511, 545**  
*gauge\_symbol*, **222, 571, 188,**  
**207, 226, 227, 229, 233,**  
**237, 266, 267, 447, ??,**  
**??, 498, 529, 274, 274,**  
**297, 319, 333, 344, 363,**  
**375, 385, 400, 411, 428,**  
**??, ??, 723, 175,** used:  
**571, 188, 207, 267**  
*gauge\_symbol* (label), **223, 175,**  
 used: **575**  
*Gauss*, **69, 74, 68,** used: **69, 75**  
*GAUSS*, ??, ??, used: ??, 70  
*GAUSS* (camlyacc token), **71,**  
 used: **71**  
*Gauss\_not*, **69, 74, 68,** used: **69**  
*GBBG*, **139,** used: **189, 476, 476,**  
**476, 476, 476, 290, 312,**  
**327**  
*GBG*, **138,** used: **188, 462, 462,**  
**462, 462, 462, 369, 369**  
*gcd*, **826,** used: **826, 826, 826**  
*gen* (type), **446, 497, 527,** used:  
**446, 497, 527**  
*Gen0*, **397,** used: **398**  
*Gen1*, **397,** used: **398**  
*Gen2*, **397,** used: **398**  
*General\_Flow* (module), **86,**  
 used:  
*generation*, **240, 454, ??, ??,**  
**500, 336, 348, 366, 377,**

- 387, 413, 428, ??, ??,**  
 used: **241, 454, ??, ??,**  
**501, 336, 349, 367, 378,**  
**388, 414, 428, ??, ??**
- generation* (type), **397**, used:  
**397, 401**
- generation'*, **240, 454, ??, ??,**  
**500, 335, 348, 366, 377,**  
**387, 413, 428, ??, ??,**  
 used: **240, 454, ??, ??,**  
**500, 336, 348, 366, 377,**  
**387, 413, 428, ??, ??**
- generations*, **269, 718**, used: **269,**  
**269, 269, 269, 718, 718,**  
**718, 719**
- generations\_pairs*, **718**, used: **720**
- generations\_quadruples*, **718**,  
 used: **721, 721**
- generations\_triples*, **718**, used:  
**720, 720, 720**
- get\_kk2*, **402**, used: **404, 404,**  
**405, 405, 405**
- GF* (module), **109**, used: **110**
- GG*, **446, 497, 527**, used:
- ghh*, **281**, used: **286**
- ghost*, **83, 83, 80**, used: **207**
- Ghost*, **83, 86**, used: **83, 84**
- ghost\_flag*, **84**, used: **84, 84, 84**
- ghost\_flags*, **83, 84, 80**, used:
- Gl*, **230, 236, 447, ??, ??, 498,**  
**529, 274, 297, 319, 333,**  
**344, 363, 374, 384, 411,**  
**428, ??, ??, used: 230,**  
**230, 231, 231, 232, 232,**  
**237, 239, 245, 246, 248,**  
**253, 254, 255, 259, 447,**  
**449, 457, 462, 462, 462,**  
**463, 463, 463, 466, 466,**  
**467, 476, 476, 479, ??, ??,**  
**??, ??, ??, ??, ??, ??,**  
**498, 500, 505, 508, 508,**  
**508, 508, 508, 511, 511,**  
**512, 514, 529, 531, 536,**  
**539, 542, 542, 542, 542,**  
**542, 542, 542, 545, 546,**  
**546, 549, 275, 277, 281,**  
**283, 284, 290, 291, 298,**  
**299, 303, 305, 305, 311,**  
**312, 319, 320, 323, 325,**  
**326, 326, 327, 333, 335,**  
**338, 338, 338, 339, 339,**  
**340, 344, 347, 351, 351,**  
**351, 352, 352, 353, 363,**  
**365, 369, 370, 375, 376,**  
**379, 380, 380, 381, 385,**  
**386, 389, 390, 390, 391,**  
**391, 411, 412, 417, 419,**  
**420, 422, 428, 430, 433,**  
**434, 437, ??, ??, ??, ??,**  
**??, ??, ??, ??, ??, ??, ??,**  
**??**
- global\_verbos*e, **??**, used: **??, ??,**  
**??, ??**
- Gluino*, **447, 498, 529**, used:  
**447, 449, 457, 459, 462,**  
**476, 479, 498, 500, 505,**  
**507, 514, 529, 531, 536,**  
**538, 541, 549**
- gluon2\_lq2*, **542**, used: **549**
- gluon2\_lq2'*, **542**, used: **542**
- gluon2\_phi*, **720**, used: **721**
- gluon2\_squark2*, **467, 512, 546,**  
 used: **478, 514, 549**
- gluon2\_squark2'*, **512, 546**, used:  
**512, 546**
- gluon3\_phi*, **721**, used: **721**
- gluon4*, **463**, used:
- gluon\_gauge\_squark*, **466, 512,**  
**546**, used: **478, 514, 549**
- gluon\_gauge\_squark'*, **466, 511,**  
**546**, used: **466, 512, 546**
- gluon\_gauge\_squark''*, **466, 511,**  
**546**, used: **466, 512, 546**
- gluon\_w\_squark*, **466, 511, 545,**  
 used: **478, 514, 549**
- gluon\_w\_squark'*, **466, 511, 545,**  
 used: **466, 511, 545**
- gluon\_w\_squark''*, **466, 511,**  
**545**, used: **466, 511, 545**
- Gl\_K1*, **344**, used: **344, 347, 351,**  
**351, 353**
- Gl\_K2*, **344**, used: **344, 347, 351,**  
**351, 353**
- gobble\_arrows*, **569**, used: **570**
- gobble\_white*, **569**, used: **569,**  
**569, 570**
- goldstone*, **222, 571, 185, 207,**  
**225, 226, 228, 230, 239,**  
**266, 268, 449, ??, ??,**  
**500, 531, 276, 299, 320,**

- 335, 346, 365, 376, 386,**  
**407, 412, 428, ??, ??,**  
**720, 175, 177, used: 571,**  
185, 207, 104, 111, 266,  
268  
*goldstone* (label), **223, 175, used:**  
575  
*goldstone* (type), **177, used: 177,**  
177  
*Goldstone*, **177, used:**  
*goldstone4*, **468, used: 478**  
*goldstone\_charg\_neutr*, **458,**  
used: **478**  
*goldstone\_neutr*, **459, used: 478**  
*goldstone\_neutr'*, **459, used: 459**  
*goldstone\_neutr''*, **459, used: 459**  
*goldstone\_sfermion*, **470, used:**  
478  
*goldstone\_sfermion'*, **470, used:**  
470  
*goldstone\_sfermion''*, **470, used:**  
470  
*goldstone\_sfermion'''*, **470, used:**  
470  
*goldstone\_squark*, **470, used: 478**  
*goldstone\_squark'*, **470, used:**  
470  
*goldstone\_squark\_a*, **470, used:**  
470  
*goldstone\_squark\_b*, **470, used:**  
470  
*goldstone\_vertices*, **253, ??, ??,**  
**290, 312, 327, 340, 353,**  
**370, 380, 391, 422, 431,**  
**??, ??, used: 258, ??, ??,**  
**291, 312, 327, 340, 353,**  
**370, 380, 391, 422, 436,**  
**??, ??**  
*graded* (type), **9, 11, 12, 15, 17,**  
**7, used: 9, 7**  
*Graded* (module), **48, 40, used:**  
110  
*Graded* (sig), **48, 40, used: 40**  
*Graded\_Forest* (sig), **42, 40,**  
used: **42, 45, 48, 40, 40**  
*Graded\_Map* (module), **44, used:**  
48  
*Graded\_Map* (sig), **43, used: 44,**  
**44, 48**
- Graded\_Map\_Maker* (sig), **44,**  
used: **45**  
*Graded\_Ord* (sig), **42, 39, used:**  
**42, 42, 44, 44, 48, 39, 40**  
*graded\_sym\_power*, **9, 11, 13,**  
**15, 17, 7, used:**  
*graded\_sym\_power\_fold*, **9, 11,**  
**13, 15, 17, 7, used: 11,**  
**13, 15, 17, 110**  
*Grader* (sig), **42, 39, used: 42,**  
**43, 39, 40**  
*Grade\_Forest* (module), **43, 40,**  
used: **49**  
*graph* (type), **816, 807, used:**  
818, 807, 807  
*graph\_of\_tree*, **817, 807, used:**  
*Grav*, **333, 344, 137, used: 462,**  
462, 462, 462, 476, 476,  
476, 333, 335, 338, 339,  
339, 340, 344, 347, 351,  
352, 352, 353, 369  
*Gravbar*, **137, used: 462, 462,**  
462, 462, 462, 476, 476,  
476, 476, 476, 369, 369  
*gravitino*, **444, 444, 444, 445,**  
**445, 445, 445, 443,**  
used: **447, 478, 478**  
*gravitino\_coup*, **369, used: 370**  
*gravitino\_gauge*, **369, used: 370**  
*gravitino\_gaugino\_3*, **462, used:**  
463  
*Graviton\_Scalar\_Scalar*, **138,**  
used: **188, 339, 352**  
*Graviton\_Spinor\_Spinor*, **138,**  
used: **188, 338, 351**  
*Graviton\_Vector\_Vector*, **138,**  
used: **188, 339, 352**  
*gravity\_currents*, **338, 351, used:**  
340, 353  
*gravity\_gauge*, **339, 352, used:**  
340, 353  
*gravity\_higgs*, **339, 352, used:**  
339, 352  
*GravTest* (module), **363, 272,**  
used: **??**  
*Grino*, **447, 363, used: 447, 449,**  
462, 462, 462, 462, 462,  
476, 476, 476, 476, 476,  
479, 363, 365, 369, 369,  
370



- Groves* (module), **267, 224**, used: **272**
- grow*, **110**, used: **110**
- Gs*, **230, 241, 450, ??, ??, 501, 532, 278, 300, 321, 337, 349, 378, 388, 414, 428, ??, ??**, used: **231, 232, 245, 457, 462, 462, ??, ??, 505, 508, 508, 536, 539, 542, 542, 542, 281, 303, 323, 338, 351, 379, 389, 417, 428, ??, ??**
- G\_AASFSF*, **450**, used: **471**
- G\_aaww*, **401**, used: **402, 405**
- G\_AAWW*, **241, ??, ??, 278, 300, 321, 337, 349, 367, 378, 388, 414, 428, ??, ??**, used: **248, ??, ??, 284, 284, 287, 305, 305, 308, 326, 338, 351, 369, 380, 390, 420, 428, ??, ??**
- G\_AG0SFSF*, **450**, used: **472, 473**
- G\_AGSNSL*, **450**, used: **472**
- G\_AGSUSD*, **450**, used: **473**
- G\_AHpHm*, **414**, used: **420**
- G\_AHPsip*, **278, 300**, used: **286, 307**
- G\_AHTHT*, **278, 300**, used: **281, 303**
- G\_AHTHTH*, **278, 300**, used: **281, 303**
- G\_AHTT*, **278, 300**, used: **281, 303**
- G\_ASFSF*, **450**, used: **469**
- G\_auw*, **401**, used: **402, 404**
- G\_AZWW*, **241, ??, ??, 278, 300, 321, 337, 349, 367, 378, 388, 414, 428, ??, ??**, used: **248, ??, ??, 284, 284, 305, 305, 326, 338, 351, 369, 380, 390, 420, 428, ??, ??**
- G\_a-lep*, **401**, used: **402, 403**
- g\_a-quark*, **402**, used: **402**
- G\_a-quark*, **401**, used: **402, 403**
- G\_CAC*, **450**, used: **458**
- G\_CC*, **241, 450, ??, ??, 501, 532, 278, 300, 321, 337, 349, 367, 378, 388, 414, 428, ??, ??**, used: **244, 246, 246, 456, ??, ??, 504, 535, 282, 303, 304, 323, 325, 327, 338, 350, 368, 379, 389, 417, 428, ??, ??**
- G\_CCQ*, **241, 450, ??, ??, 501, 532, 337, 349, 367, 428**, used: **246, 456, ??, ??, 504, 535, 428**
- G\_CCtop*, **278, 300**, used: **281, 303**
- G\_CC\_heavy*, **278, 300**, used: **282, 303**
- G\_CC\_W*, **278, 300**, used: **281, 303**
- G\_CC\_WH*, **278, 300**, used: **281, 303**
- G\_CGC*, **450**, used: **458**
- G\_CGN*, **450**, used: **458**
- G\_CH1C*, **450**, used: **458**
- G\_CH2C*, **450**, used: **458**
- G\_CHN*, **450**, used: **458**
- G\_CICIA*, **450**, used: **459**
- G\_CICIG*, **450**, used: **459**
- G\_CICIH1*, **450**, used: **459**
- G\_CICIH2*, **450**, used: **459**
- G\_CICIP*, **501, 532**, used: **506, 537**
- G\_CICIS*, **501, 532**, used: **506, 537**
- G\_CPC*, **501, 532**, used: **506, 537**
- G\_CSC*, **501, 532**, used: **506, 537**
- G\_CWN*, **450, 501, 532**, used: **456, 504, 535**
- G\_CZC*, **450, 501, 532**, used: **457, 505, 536**
- G\_Ebb*, **278, 300, 321**, used: **283, 304, 325**
- G\_EGaGa*, **278, 300, 321**, used: **290, 311, 326**
- G\_EGaZ*, **278, 300, 321**, used: **290, 311, 326**
- G\_EGIGl*, **278, 300, 321**, used: **290, 311, 326**
- G\_Etht*, **278, 300, 321**, used: **283, 304, 325**
- G\_Ethth*, **278, 300, 321**, used:

- G\_Ett*, **278, 300, 321**, used: **283, 304, 325**  
*G\_FWW*, **??, 428**, used: **??, 432**  
*G\_FWW\_T*, **??, 428**, used: **??, 432**  
*G\_FZZ*, **??, 428**, used: **??, 432**  
*G\_FZZ\_T*, **??, 428**, used: **??, 432**  
*G\_G0G0SFSF*, **450**, used: **472, 473**  
*G\_GG4*, **450**, used: **468**  
*G\_GGSFSF*, **450**, used: **472, 473**  
*G\_GGSNSL*, **450**, used: **472**  
*G\_GGSUSD*, **450**, used: **473**  
*G\_GH*, **450**, used: **463, 464**  
*G\_GH4*, **450**, used: **464**  
*G\_GH4\_GaGaCC*, **501, 532**, used: **509, 543**  
*G\_GH4\_GaWPC*, **501, 532**, used: **510, 544**  
*G\_GH4\_GaWSC*, **501, 532**, used: **510, 544**  
*G\_GH4\_WWCC*, **501, 532**, used: **509, 544**  
*G\_GH4\_WWPP*, **501, 532**, used: **509, 544**  
*G\_GH4\_WWSS*, **501, 532**, used: **509, 544**  
*G\_GH4\_ZGaCC*, **501, 532**, used: **509, 543**  
*G\_GH4\_ZWPC*, **501, 532**, used: **510, 544**  
*G\_GH4\_ZWSC*, **501, 532**, used: **509, 544**  
*G\_GH4\_ZZCC*, **501, 532**, used: **509, 543**  
*G\_GH4\_ZZPP*, **501, 532**, used: **509, 543**  
*G\_GH4\_ZZSS*, **501, 532**, used: **509, 543**  
*G\_GHGo*, **450**, used: **464**  
*G\_GHGo4*, **450**, used: **465**  
*G\_GH\_GaCC*, **501, 532**, used: **508, 543**  
*G\_GH\_WPC*, **501, 532**, used: **508, 543**  
*G\_GH\_WSC*, **501, 532**, used: **508, 543**  
*G\_GH\_WWS*, **501, 532**, used: **508, 543**  
*G\_GH\_ZCC*, **501, 532**, used: **508, 543**  
*G\_GH\_ZSP*, **501, 532**, used: **508, 543**  
*G\_GH\_ZZS*, **501, 532**, used: **508, 543**  
*G\_GLGLA*, **450**, used: **463**  
*G\_GLGLH*, **450**, used: **463**  
*G\_GLGLHH*, **450**, used: **463**  
*G\_GLGLQLQ*, **532**, used: **542**  
*G\_GLGLSQSQ*, **450, 501, 532**, used: **467, 512, 546**  
*G\_GLPSQSQ*, **450, 501, 532**, used: **466, 511, 546**  
*G\_GLUGLUA0*, **501**, used: **508**  
*G\_GLUGLUH0*, **501**, used: **508**  
*G\_GLWSUSD*, **450, 501, 532**, used: **466, 511, 545**  
*G\_GLZSFSF*, **450, 501, 532**, used: **466, 511, 546**  
*G\_GoSFSF*, **450**, used: **470**  
*G\_GoNSL*, **450**, used: **470**  
*G\_Gr4A\_Sd*, **450**, used: **476**  
*G\_Gr4A\_Sdc*, **450**, used: **476**  
*G\_Gr4A\_Sl*, **450**, used: **476**  
*G\_Gr4A\_Slc*, **450**, used: **476**  
*G\_Gr4A\_Su*, **450**, used: **476**  
*G\_Gr4A\_Suc*, **450**, used: **476**  
*G\_Gr4Gl\_Sd*, **450**, used: **476**  
*G\_Gr4Gl\_Sdc*, **450**, used: **476**  
*G\_Gr4Gl\_Su*, **450**, used: **476**  
*G\_Gr4Gl\_Suc*, **450**, used: **476**  
*G\_Gr4W\_Sd*, **450**, used: **476**  
*G\_Gr4W\_Sdc*, **450**, used: **476**  
*G\_Gr4W\_Sl*, **450**, used: **476**  
*G\_Gr4W\_Slc*, **450**, used: **476**  
*G\_Gr4W\_Sn*, **450**, used: **476**  
*G\_Gr4W\_Snc*, **450**, used: **476**  
*G\_Gr4W\_Su*, **450**, used: **476**  
*G\_Gr4W\_Suc*, **450**, used: **476**  
*G\_Gr4Z\_Sd*, **450**, used: **476**  
*G\_Gr4Z\_Sdc*, **450**, used: **476**  
*G\_Gr4Z\_Sl*, **450**, used: **476**  
*G\_Gr4Z\_Slc*, **450**, used: **476**  
*G\_Gr4Z\_Sn*, **450**, used: **476**  
*G\_Gr4Z\_Snc*, **450**, used: **476**  
*G\_Gr4Z\_Su*, **450**, used: **476**  
*G\_Gr4Z\_Suc*, **450**, used: **476**  
*G\_Gr4\_A\_Ch*, **450**, used: **476**  
*G\_Gr4\_H\_A*, **450**, used: **476**

- G\_Gr4\_H\_Z*, 450, used: 476  
*G\_Gr4\_Neu*, 450, used: 476  
*G\_Gr4\_W\_H*, 450, used: 476  
*G\_Gr4\_W\_Hc*, 450, used: 476  
*G\_Gr4\_Z\_Ch*, 450, used: 476  
*G\_Gr4\_Z\_H1*, 450, used: 476  
*G\_Gr4\_Z\_H2*, 450, used: 476  
*G\_Gr4\_Z\_H3*, 450, used: 476  
*G\_Grav*, 450, 337, 349, 367, used: 462, 338, 339, 339, 351, 352, 352, 369, 369  
*G\_GravGl*, 450, used: 476  
*G\_Grav\_D*, 450, used: 462  
*G\_Grav\_Dc*, 450, used: 462  
*G\_Grav\_L*, 450, used: 462  
*G\_Grav\_Lc*, 450, used: 462  
*G\_Grav\_N*, 450, used: 462  
*G\_Grav\_U*, 450, used: 462  
*G\_Grav\_Uc*, 450, used: 462  
*G\_Gr\_A\_Neu*, 450, used: 462  
*G\_Gr\_Ch*, 450, used: 462  
*G\_Gr\_H1\_Neu*, 450, used: 462  
*G\_Gr\_H2\_Neu*, 450, used: 462  
*G\_Gr\_H3\_Neu*, 450, used: 462  
*G\_Gr\_H\_Ch*, 450, used: 462  
*G\_Gr\_Z\_Neu*, 450, used: 462  
*G\_GSUSD*, 450, used: 470  
*G\_h111*, 414, used: 421  
*G\_h1111*, 414, used: 421  
*G\_h1112*, 414, used: 421  
*G\_h1113*, 414, used: 421  
*G\_h112*, 414, used: 421  
*G\_h1122*, 414, used: 421  
*G\_h1123*, 414, used: 421  
*G\_h113*, 414, used: 421  
*G\_h1133*, 414, used: 421  
*G\_h1222*, 414, used: 421  
*G\_h1223*, 414, used: 421  
*G\_h123*, 414, used: 421  
*G\_h1233*, 414, used: 421  
*G\_h1333*, 414, used: 421  
*G\_h1bb*, 414, used: 416, 418  
*G\_h1bd*, 414, used: 416  
*G\_h1bs*, 414, used: 416  
*G\_h1cc*, 414, used: 416, 417  
*G\_h1ct*, 414, used: 416, 418  
*G\_h1cu*, 414, used: 416, 418  
*G\_h1db*, 414, used: 416, 418  
*G\_h1dd*, 414, used: 416, 418  
*G\_h1ds*, 414, used: 416, 418  
*G\_h1e1e1*, 414, used: 416, 418  
*G\_h1e1e2*, 414, used: 416, 419  
*G\_h1e1e3*, 414, used: 416, 419  
*G\_h1e2e1*, 414, used: 416, 419  
*G\_h1e2e2*, 414, used: 416, 418  
*G\_h1e2e3*, 414, used: 416, 419  
*G\_h1e3e1*, 414, used: 416, 419  
*G\_h1e3e2*, 414, used: 416, 419  
*G\_h1e3e3*, 414, used: 416, 418  
*G\_H1GSNSL*, 450, used: 472  
*G\_H1GSUSD*, 450, used: 473  
*G\_H1H1SFSF*, 450, used: 471, 471  
*G\_H1H2SFSF*, 450, used: 471, 471  
*G\_h1HpAWm*, 414, used: 420  
*G\_h1HpAWmC*, 414, used: 420  
*G\_h1HpHm*, 414, used: 421  
*G\_h1HpZWm*, 414, used: 420  
*G\_h1HpZWmC*, 414, used: 420  
*G\_h1sb*, 414, used: 416, 418  
*G\_h1sd*, 414, used: 416, 418  
*G\_H1SFSF*, 450, used: 469, 469  
*G\_h1ss*, 414, used: 416, 418  
*G\_h1tc*, 414, used: 416, 418  
*G\_h1tt*, 414, used: 416, 417  
*G\_h1tu*, 414, used: 416, 418  
*G\_h1uc*, 414, used: 416, 418  
*G\_h1ut*, 414, used: 416, 418  
*G\_h1uu*, 414, used: 416, 417  
*G\_h1WpWm*, 414, used: 420  
*G\_h1ZZ*, 414, used: 420  
*G\_h221*, 414, used: 421  
*G\_h222*, 414, used: 421  
*G\_h2222*, 414, used: 421  
*G\_h2223*, 414, used: 421  
*G\_h223*, 414, used: 421  
*G\_h2233*, 414, used: 421  
*G\_h2333*, 414, used: 421  
*G\_h2bb*, 414, used: 416, 418  
*G\_h2bd*, 414, used: 416  
*G\_h2bs*, 414, used: 416  
*G\_h2cc*, 414, used: 416, 417  
*G\_h2ct*, 414, used: 416, 418  
*G\_h2cu*, 414, used: 416, 418  
*G\_h2db*, 414, used: 416, 418  
*G\_h2dd*, 414, used: 416, 418  
*G\_h2ds*, 414, used: 416, 418  
*G\_h2e1e1*, 414, used: 416, 418  
*G\_h2e1e2*, 414, used: 416, 419

- G\_h2e1e3*, **414**, used: **416**, **419**  
*G\_h2e2e1*, **414**, used: **416**, **419**  
*G\_h2e2e2*, **414**, used: **416**, **418**  
*G\_h2e2e3*, **414**, used: **416**, **419**  
*G\_h2e3e1*, **414**, used: **416**, **419**  
*G\_h2e3e2*, **414**, used: **416**, **419**  
*G\_h2e3e3*, **414**, used: **416**, **418**  
*G\_H2GSNSL*, **450**, used: **472**  
*G\_H2GSUSD*, **450**, used: **473**  
*G\_H2H2SFSF*, **450**, used: **471**,  
**471**  
*G\_h2HpAWm*, **414**, used: **420**  
*G\_h2HpAWmC*, **414**, used: **420**  
*G\_h2HpHm*, **414**, used: **421**  
*G\_h2HpZWm*, **414**, used: **420**  
*G\_h2HpZWmC*, **414**, used: **420**  
*G\_h2sb*, **414**, used: **416**, **418**  
*G\_h2sd*, **414**, used: **416**, **418**  
*G\_H2SFSF*, **450**, used: **469**, **469**  
*G\_h2ss*, **414**, used: **416**, **418**  
*G\_h2tc*, **414**, used: **416**, **418**  
*G\_h2tt*, **414**, used: **416**, **417**  
*G\_h2tu*, **414**, used: **416**, **418**  
*G\_h2uc*, **414**, used: **416**, **418**  
*G\_h2ut*, **414**, used: **416**, **418**  
*G\_h2uu*, **414**, used: **416**, **417**  
*G\_h2WpWm*, **414**, used: **420**  
*G\_h2ZZ*, **414**, used: **420**  
*G\_H3*, **241**, **450**, **278**, **300**, **321**,  
**337**, **349**, **367**, **378**, **388**,  
**428**, **??**, **??**, used: **251**,  
**467**, **467**, **290**, **311**, **326**,  
**339**, **352**, **369**, **380**, **390**,  
**429**, **??**, **??**  
*G\_h331*, **414**, used: **421**  
*G\_h332*, **414**, used: **421**  
*G\_h333*, **414**, used: **421**  
*G\_h3333*, **414**, used: **421**  
*G\_h3bb*, **414**, used: **416**, **418**  
*G\_h3bd*, **414**, used: **416**  
*G\_h3bs*, **414**, used: **416**  
*G\_h3cc*, **414**, used: **416**, **417**  
*G\_h3ct*, **414**, used: **416**, **418**  
*G\_h3cu*, **414**, used: **416**, **418**  
*G\_h3db*, **414**, used: **416**, **418**  
*G\_h3dd*, **414**, used: **416**, **418**  
*G\_h3ds*, **414**, used: **416**, **418**  
*G\_h3e1e1*, **414**, used: **416**, **418**  
*G\_h3e1e2*, **414**, used: **416**, **419**  
*G\_h3e1e3*, **414**, used: **416**, **419**  
*G\_h3e2e1*, **414**, used: **416**, **419**  
*G\_h3e2e2*, **414**, used: **416**, **418**  
*G\_h3e2e3*, **414**, used: **416**, **419**  
*G\_h3e3e1*, **414**, used: **416**, **419**  
*G\_h3e3e2*, **414**, used: **416**, **419**  
*G\_h3e3e3*, **414**, used: **416**, **418**  
*G\_h3HpAWm*, **414**, used: **420**  
*G\_h3HpAWmC*, **414**, used: **420**  
*G\_h3HpHm*, **414**, used: **421**  
*G\_h3HpZWm*, **414**, used: **420**  
*G\_h3HpZWmC*, **414**, used: **420**  
*G\_h3sb*, **414**, used: **416**  
*G\_h3sd*, **414**, used: **416**, **418**  
*G\_h3ss*, **414**, used: **416**, **418**  
*G\_h3tc*, **414**, used: **416**, **418**  
*G\_h3tt*, **414**, used: **416**, **417**  
*G\_h3tu*, **414**, used: **416**, **418**  
*G\_h3uc*, **414**, used: **416**, **418**  
*G\_h3ut*, **414**, used: **416**, **418**  
*G\_h3uu*, **414**, used: **416**, **417**  
*G\_h3WpWm*, **414**, used: **420**  
*G\_h3ZZ*, **414**, used: **420**  
*G\_H3\_SCC*, **501**, **532**, used:  
**512**, **546**  
*G\_H3\_SPP*, **501**, **532**, used:  
**512**, **546**  
*G\_H3\_SSS*, **501**, **532**, used: **512**,  
**546**  
*G\_H4*, **241**, **450**, **278**, **300**, **321**,  
**337**, **349**, **367**, **378**, **428**,  
**??**, **??**, used: **251**, **467**,  
**468**, **290**, **311**, **326**, **339**,  
**352**, **369**, **380**, **429**, **??**, **??**  
*G\_H4\_1*, **388**, used: **390**  
*G\_H4\_2*, **388**, used: **390**  
*G\_H4\_3*, **388**, used: **390**  
*G\_H4\_4*, **388**, used: **390**  
*G\_H4\_5*, **388**, used: **390**  
*G\_HAHAH*, **278**, **300**, used:  
**285**, **306**  
*G\_HAHZ*, **278**, **300**, used: **285**,  
**306**  
*G\_HASLSN*, **450**, used: **471**  
*G\_HASUSD*, **450**, used: **472**  
*G\_hbb*, **414**, used:  
*G\_Hbb*, **241**, **278**, **300**, **321**,  
**337**, **349**, **367**, **378**, **388**,  
**414**, **428**, **??**, **??**, used:  
**246**, **282**, **304**, **325**, **338**,

- 351, 368, 379, 390, 428,  
??, ??
- G\_hbc*, 414, used: 416
- G\_hbt*, 414, used: 416, 418
- G\_hbu*, 414, used: 416
- G\_hcb*, 414, used: 416
- G\_hcc*, 414, used:
- G\_Hcc*, 241, 278, 300, 321,  
337, 349, 367, 378, 388,  
414, 428, ??, ??, used:  
246, 282, 304, 325, 338,  
351, 368, 379, 390, 428,  
??, ??
- G\_hcd*, 414, used: 416
- G\_hcs*, 414, used: 416, 418
- G\_Hcs*, 414, used:
- G\_hdc*, 414, used: 416
- G\_hdt*, 414, used: 416
- G\_hdu*, 414, used: 416, 418
- G\_he1n1*, 414, used: 416
- G\_he1n2*, 414, used: 416
- G\_he1n3*, 414, used: 416
- G\_he2n1*, 414, used: 416
- G\_he2n2*, 414, used: 416
- G\_he2n3*, 414, used: 416
- G\_he3n1*, 414, used: 416
- G\_he3n2*, 414, used: 416
- G\_he3n3*, 414, used: 416
- G\_heavy\_HVV*, 321, used: 326
- G\_heavy\_HWW*, 321, used: 326
- G\_heavy\_HZZ*, 321, used:
- G\_HGaGa*, 241, 278, 300, 321,  
337, 349, 367, 378, 388,  
428, used: 253, 339, 352,  
369, 391, 430
- G\_HGaGa\_anom*, 241, 428,  
used: 252, 430
- G\_HGaZ*, 241, 278, 300, 321,  
337, 349, 367, 378, 388,  
428, used: 253, 339, 352,  
369, 391, 430
- G\_HGaZ\_anom*, 241, 428, used:  
252, 430
- G\_HGaZ\_u*, 241, 428, used:  
252, 430
- G\_Hgg*, 241, 321, 337, 349,  
367, 378, 388, 428,  
used: 253, 339, 352, 369,  
391, 430
- G\_HGo3*, 450, used: 467
- G\_HGo4*, 450, used: 468
- G\_HGSFSF*, 450, used: 472, 473
- G\_HGSNSL*, 450, used: 472
- G\_HGSUSD*, 450, used: 473
- G\_HH1SLSN*, 450, used: 471
- G\_HH1SUSD*, 450, used: 472
- G\_HH2SLSN*, 450, used: 471
- G\_HH2SUSD*, 450, used: 472
- G\_HHAA*, 278, 300, used: 287,  
308
- G\_HHAHZ*, 278, 300, used: 287,  
308
- G\_HHS*, 388, used: 390
- G\_HHSFSF*, 450, used: 471, 471
- G\_HHtht*, 278, 300, used: 290,  
312
- G\_HHthth*, 278, 300, 321, used:  
290, 312, 327
- G\_HHtt*, 278, 300, used: 290,  
312
- G\_HHWW*, 278, 300, used:  
287, 308
- G\_hhWpWm*, 414, used: 420
- G\_HHWW*, 241, 278, 300, 321,  
337, 349, 367, 378, 388,  
428, ??, ??, used: 251,  
287, 287, 308, 308, 326,  
326, 339, 352, 369, 380,  
390, 429, ??, ??
- G\_HHZHAA*, 278, 300, used:  
287, 308
- G\_HHZHZ*, 278, 300, used: 287,  
308
- G\_hhZZ*, 414, used: 420
- G\_HHZZ*, 241, 278, 300, 321,  
337, 349, 367, 378, 388,  
428, ??, ??, used: 251,  
287, 287, 308, 308, 326,  
326, 339, 352, 369, 380,  
390, 429, ??, ??
- G\_HHZZH*, 321, used: 326
- G\_Hmm*, 241, 378, 388, 428,  
used: 246, 379, 390, 428
- G\_hmumu*, 414, used:
- G\_Hmumu*, 414, used:
- G\_Hmunu*, 414, used:
- G\_hn1e1*, 414, used: 416
- G\_hn1e2*, 414, used: 416
- G\_hn1e3*, 414, used: 416
- G\_hn2e1*, 414, used: 416

- G\_hn2e2*, **414**, used: **416**  
*G\_hn2e3*, **414**, used: **416**  
*G\_hn3e1*, **414**, used: **416**  
*G\_hn3e2*, **414**, used: **416**  
*G\_hn3e3*, **414**, used: **416**  
*G\_HpHm11*, **414**, used: **421**  
*G\_HpHm12*, **414**, used: **421**  
*G\_HpHm13*, **414**, used: **421**  
*G\_HpHm22*, **414**, used: **421**  
*G\_HpHm23*, **414**, used: **421**  
*G\_HpHm33*, **414**, used: **421**  
*G\_HpHmAA*, **414**, used: **420**  
*G\_HpHmAZ*, **414**, used: **420**  
*G\_HpHmHpHm*, **414**, used: **421**  
*G\_HpHmWpWm*, **414**, used: **420**  
*G\_HpHmZZ*, **414**, used: **420**  
*G\_HPsi0AAH*, **278, 300**, used:  
**287, 308**  
*G\_HPsi0WHW*, **278, 300**, used:  
**287, 308**  
*G\_HPsi0WW*, **278, 300**, used:  
**287, 308**  
*G\_HPsi0ZAH*, **278, 300**, used:  
**287, 308**  
*G\_HPsi0ZHAH*, **278, 300**, used:  
**287, 308**  
*G\_HPsi0ZHZ*, **278, 300**, used:  
**287, 308**  
*G\_HPsi0ZHZH*, **278, 300**, used:  
**287, 308**  
*G\_HPsi0ZZ*, **278, 300**, used:  
**287, 308**  
*G\_HPsippWHW*, **278, 300**,  
used: **287, 308**  
*G\_HPsippWHWH*, **278, 300**,  
used: **287, 308**  
*G\_HPsippWW*, **278, 300**, used:  
**287, 308**  
*G\_HPsipWA*, **278, 300**, used:  
**287, 308**  
*G\_HPsipWAH*, **278, 300**, used:  
**287, 308**  
*G\_HPsipWHA*, **278, 300**, used:  
**287, 308**  
*G\_HPsipWHAH*, **278, 300**,  
used: **287, 308**  
*G\_HPsipWHZ*, **278, 300**, used:  
**287, 308**  
*G\_HPsipWHZH*, **278, 300**, used:  
**287, 308**  
*G\_HPsipWZ*, **278, 300**, used:  
**287, 308**  
*G\_HPsipWZH*, **278, 300**, used:  
**287, 308**  
*G\_Hqh*, **321**, used: **325**  
*G\_hsc*, **414**, used: **416, 418**  
*G\_HSF31*, **450**, used:  
*G\_HSF32*, **450**, used:  
*G\_HSF41*, **450**, used:  
*G\_HSF42*, **450**, used:  
*G\_HSNL*, **450, 501, 532**, used:  
**469, 512, 547**  
*G\_HSS*, **388**, used: **390**  
*G\_hst*, **414**, used: **416**  
*G\_hsu*, **414**, used: **416**  
*G\_HSUSD*, **450, 501, 532**, used:  
**470, 513, 547**  
*G\_HSWW*, **388**, used: **390**  
*G\_HSZZ*, **388**, used: **390**  
*G\_Htaunu*, **414**, used:  
*G\_htautau*, **414**, used:  
*G\_Htautau*, **241, 278, 300, 321,**  
**337, 349, 367, 378, 388,**  
**414, 428, ??, ??**, used:  
**246, 282, 304, 325, 338,**  
**351, 368, 379, 390, 428,**  
**??, ??**  
*G\_htb*, **414**, used: **416, 418**  
*G\_Htb*, **414**, used:  
*G\_htd*, **414**, used: **416**  
*G\_Htht*, **278, 300, 321**, used:  
**282, 304, 325**  
*G\_Hthth*, **278, 300, 321**, used:  
**282, 304**  
*G\_hts*, **414**, used: **416**  
*G\_htt*, **414**, used:  
*G\_Htt*, **241, 278, 300, 321, 337,**  
**349, 367, 378, 388, 414,**  
**428, ??, ??**, used: **246,**  
**282, 304, 325, 338, 351,**  
**368, 379, 390, 428, ??, ??**  
*G\_hub*, **414**, used: **416**  
*G\_hud*, **414**, used: **416, 418**  
*G\_hus*, **414**, used: **416**  
*G\_HWHW*, **278, 300**, used: **285,**  
**306**  
*G\_HWHWH*, **278, 300**, used:  
**285, 306**  
*G\_HWW*, **241, 278, 300, 321,**  
**337, 349, 367, 378, 388,**

- 428**, ??, ??, used: **251**,  
**285**, **306**, **326**, **339**, **352**,  
**369**, **380**, **390**, **428**, ??, ??  
*G\_HWW\_anom*, **241**, **428**, used:  
**252**, **430**  
*G\_HWW\_u*, **241**, **428**, used:  
**252**, **430**  
*G\_HZHAH*, **278**, **300**, used: **285**,  
**306**  
*G\_HZHZ*, **278**, **300**, used: **285**,  
**306**  
*G\_HZZ*, **241**, **278**, **300**, **321**,  
**337**, **349**, **367**, **378**, **388**,  
**428**, ??, ??, used: **251**,  
**285**, **306**, **326**, **339**, **352**,  
**369**, **380**, **390**, **428**, ??, ??  
*G\_HZZ\_anom*, **241**, **428**, used:  
**252**, **430**  
*G\_HZZ\_u*, **241**, **428**, used: **252**,  
**430**  
*G\_LQ\_EC\_UC*, **532**, used: **539**,  
**539**, **540**, **540**, **540**, **540**,  
**540**, **540**, **540**, **540**, **540**,  
**540**  
*G\_LQ\_GG*, **532**, used: **541**  
*G\_LQ\_NEU*, **532**, used: **541**,  
**541**  
*G\_LQ\_P*, **532**, used: **541**  
*G\_LQ\_S*, **532**, used: **541**  
*G\_LQ\_SSD*, **532**, used: **541**  
*G\_LQ\_SSU*, **532**, used: **540**  
*G\_NCHt*, **321**, used: **323**  
*G\_NCH\_D*, **321**, used: **324**  
*G\_NCH\_N*, **321**, used: **324**  
*G\_NCH\_U*, **321**, used: **324**  
*G\_NC\_down*, **241**, **450**, ??, ??,  
**501**, **532**, **278**, **300**, **321**,  
**337**, **349**, **367**, **378**, **388**,  
**414**, **428**, ??, ??, used:  
**245**, **246**, **455**, ??, ??, **503**,  
**535**, **280**, **281**, **302**, **303**,  
**322**, **323**, **337**, **338**, **350**,  
**350**, **368**, **368**, **379**, **379**,  
**389**, **389**, **416**, **417**, **428**,  
??, ??, ??  
*G\_NC\_H*, **321**, used: **323**  
*G\_NC\_heavy*, **278**, **300**, used:  
**281**, **303**  
*G\_NC\_h\_bot*, **321**, used: **324**  
*G\_NC\_h\_down*, **278**, **300**, **321**,  
??, used: **280**, **281**, **302**,  
**303**, **322**, **324**, ??, ??  
*G\_NC\_h\_lepton*, **278**, **300**, **321**,  
??, used: **280**, **281**, **302**,  
**303**, **322**, **324**, ??, ??  
*G\_NC\_h\_neutrino*, **278**, **300**,  
**321**, ??, used: **280**, **281**,  
**302**, **303**, **322**, **324**, ??, ??  
*G\_NC\_h\_top*, **321**, used: **324**  
*G\_NC\_h\_up*, **278**, **300**, **321**, ??,  
used: **280**, **282**, **302**, **304**,  
**322**, **324**, ??, ??  
*G\_NC\_lepton*, **241**, **450**, ??, ??,  
**501**, **532**, **278**, **300**, **321**,  
**337**, **349**, **367**, **378**, **388**,  
**414**, **428**, ??, ??, used:  
**245**, **246**, **455**, ??, ??, **503**,  
**535**, **280**, **281**, **302**, **303**,  
**322**, **323**, **337**, **338**, **350**,  
**350**, **368**, **368**, **379**, **379**,  
**389**, **389**, **416**, **417**, **428**,  
??, ??, ??  
*G\_NC\_neutrino*, **241**, **450**, ??,  
??, **501**, **532**, **278**, **300**,  
**321**, **337**, **349**, **367**, **378**,  
**388**, **414**, **428**, ??, ??,  
used: **245**, **246**, **455**, ??,  
??, **503**, **535**, **280**, **281**,  
**302**, **303**, **322**, **323**, **337**,  
**338**, **350**, **350**, **368**, **368**,  
**379**, **379**, **389**, **389**, **416**,  
**417**, **428**, ??, ??, ??  
*G\_NC\_top*, ??, used: ??  
*G\_NC\_up*, **241**, **450**, ??, ??,  
**501**, **532**, **278**, **300**, **321**,  
**337**, **349**, **367**, **378**, **388**,  
**414**, **428**, ??, ??, used:  
**245**, **246**, **455**, ??, ??, **503**,  
**535**, **280**, **281**, **302**, **303**,  
**322**, **323**, **337**, **338**, **350**,  
**350**, **368**, **368**, **379**, **379**,  
**389**, **389**, **416**, **417**, **428**,  
??, ??, ??  
*G\_NC\_X*, **321**, used: **323**  
*G\_NC\_X\_t*, **321**, used: **323**  
*G\_NC\_Y*, **321**, used: **323**  
*G\_NC\_Y\_t*, **321**, used: **323**  
*G\_NGC*, **450**, used: **458**



- G\_NHC*, **450, 501, 532**, used:  
458, 506, 537  
*G\_NLQC*, **532**, used: 542  
*G\_NWC*, **450, 501, 532**, used:  
456, 504, 535  
*G\_NZN*, **450, 501, 532**, used:  
457, 505, 536  
*g\_over\_2\_csth*, **245**, ??, ??,  
**280, 302, 322, 337, 350,**  
**367, 378, 389, 416, 428,**  
??, used: 245, ??, ??,  
280, 302, 322, 337, 350,  
367, 378, 389, 416, 428, ??  
*G\_PGLQLQ*, **532**, used: 542  
*G\_PNWW*, ??, **428**, used: ??,  
432  
*G\_PNZZ*, ??, **428**, used: ??, 432  
*G\_PPA*, **450**, used: 463  
*G\_PPH*, **450**, used: 463  
*G\_PPHH*, **450**, used: 463  
*G\_PPLQLQ*, **532**, used: 542  
*G\_PPSFSF*, **450, 501, 532**,  
used: 465, 510, 545  
*G\_PPWW*, **450, 501, 532**, used:  
463, 508, 542  
*G\_Psi00AH*, **278, 300**, used:  
287, 308  
*G\_Psi00ZH*, **278, 300**, used:  
287, 308  
*G\_Psi00ZHAH*, **278, 300**, used:  
287, 308  
*G\_Psi01AH*, **278, 300**, used:  
286, 307  
*G\_Psi01Z*, **278, 300**, used: 286,  
307  
*G\_Psi01ZH*, **278, 300**, used:  
286, 307  
*G\_Psi0bb*, **278, 300**, used: 282,  
304  
*G\_Psi0cc*, **278, 300**, used: 282,  
304  
*G\_Psi0ppWHW*, **278, 300**, used:  
287, 308  
*G\_Psi0ppWHWH*, **278, 300**,  
used: 287, 308  
*G\_Psi0ppWW*, **278, 300**, used:  
287, 308  
*G\_Psi0pWA*, **278, 300**, used:  
287, 308  
*G\_Psi0pWAH*, **278, 300**, used:  
287, 308  
*G\_Psi0pWHA*, **278, 300**, used:  
287, 308  
*G\_Psi0pWHAH*, **278, 300**, used:  
287, 308  
*G\_Psi0pWHZ*, **278, 300**, used:  
287, 308  
*G\_Psi0pWHZH*, **278, 300**, used:  
287, 308  
*G\_Psi0pWZ*, **278, 300**, used:  
287, 308  
*G\_Psi0pWZH*, **278, 300**, used:  
287, 308  
*G\_Psi0tautau*, **278, 300**, used:  
282, 304  
*G\_Psi0tt*, **278, 300**, used: 282,  
304  
*G\_Psi0tth*, **278, 300**, used: 282,  
304  
*G\_Psi0W*, **278, 300**, used: 286,  
307  
*G\_Psi0WH*, **278, 300**, used:  
286, 307  
*G\_Psi1bb*, **278, 300**, used: 282,  
304  
*G\_Psi1cc*, **278, 300**, used: 282,  
304  
*G\_Psi1HAH*, **278, 300**, used:  
286, 307  
*G\_Psi1HZ*, **278, 300**, used: 286,  
307  
*G\_Psi1HZH*, **278, 300**, used:  
286, 307  
*G\_Psi1tautau*, **278, 300**, used:  
282, 304  
*G\_Psi1tt*, **278, 300**, used: 282,  
304  
*G\_Psi1tth*, **278, 300**, used: 282,  
304  
*G\_Psi1W*, **278, 300**, used: 286,  
307  
*G\_Psi1WH*, **278, 300**, used:  
286, 307  
*G\_PsiAHAH*, **278, 300**, used:  
285, 307  
*G\_PsiAHW*, **278, 300**, used:  
285, 307  
*G\_PsiAHWH*, **278, 300**, used:  
285, 307



- G\_PsiccAAH*, **278, 300**, used:  
     287, 308  
*G\_PsiccAZ*, **278, 300**, used: 287,  
     308  
*G\_PsiccAZH*, **278, 300**, used:  
     287, 308  
*G\_PsiccZAH*, **278, 300**, used:  
     287, 308  
*G\_PsiccZZ*, **278, 300**, used: 287,  
     308  
*G\_PsiccZZH*, **278, 300**, used:  
     287, 308  
*G\_PsiHW*, **278, 300**, used: 286,  
     307  
*G\_PsiHWH*, **278, 300**, used:  
     286, 307  
*G\_Psipbth*, **278, 300**, used: 282,  
     304  
*G\_Psipl3*, **278, 300**, used: 282,  
     304  
*G\_PsippAAH*, **278, 300**, used:  
     287, 308  
*G\_PsippAZ*, **278, 300**, used:  
     287, 308  
*G\_PsiPPW*, **278, 300**, used:  
     286, 307  
*G\_PsippWA*, **278, 300**, used:  
     287, 308  
*G\_PsippWAH*, **278, 300**, used:  
     287, 308  
*G\_PsiPPWH*, **278, 300**, used:  
     286, 307  
*G\_PsippWHA*, **278, 300**, used:  
     287, 308  
*G\_PsippWHAH*, **278, 300**, used:  
     287, 308  
*G\_PsippWHW*, **278, 300**, used:  
     285, 307  
*G\_PsippWHWH*, **278, 300**,  
     used: 285, 307  
*G\_PsippWHZ*, **278, 300**, used:  
     287, 308  
*G\_PsippWHZH*, **278, 300**, used:  
     287, 308  
*G\_PsippWW*, **278, 300**, used:  
     285, 307  
*G\_PsippWZ*, **278, 300**, used:  
     287, 308  
*G\_PsippWZH*, **278, 300**, used:  
     287, 308  
*G\_PsippZAH*, **278, 300**, used:  
     287, 308  
*G\_PsippZHZH*, **278, 300**, used:  
     287, 308  
*G\_PsippZZ*, **278, 300**, used:  
     287, 308  
*G\_Psipq2*, **278, 300**, used: 282,  
     304  
*G\_Psipq3*, **278, 300**, used: 282,  
     304  
*G\_PsiWHW*, **278, 300**, used:  
     285, 307  
*G\_PsiWW*, **278, 300**, used: 285,  
     307  
*G\_PsiZAH*, **278, 300**, used: 285,  
     307  
*G\_PsiZHAH*, **278, 300**, used:  
     285, 307  
*G\_PsiZHW*, **278, 300**, used:  
     285, 307  
*G\_PsiZHWH*, **278, 300**, used:  
     285, 307  
*G\_PsiZHZ*, **278, 300**, used: 285,  
     307  
*G\_PsiZHZH*, **278, 300**, used:  
     285, 307  
*G\_PsiZW*, **278, 300**, used: 285,  
     307  
*G\_PsiZWH*, **278, 300**, used:  
     285, 307  
*G\_PsiZZ*, **278, 300**, used: 285,  
     307  
*G\_PWW*, ??, **428**, used: ??, 432  
*G\_PWZ*, ??, **428**, used: ??, 432  
*G\_PZWW*, **450, 501, 532**, used:  
     463, 508, 542  
*G\_s*, **401**, used: 404  
*G\_s2*, **401**, used: 406  
*G\_saa*, **719**, used: 720  
*G\_saaa*, **719**, used:  
*G\_Sbb*, **388**, used: 390  
*G\_Scc*, **388**, used: 390  
*G\_SD4*, **450**, used: 475  
*G\_SD4-2*, **450**, used: 475  
*G\_SF4*, **450**, used:  
*G\_SF4-3*, **450**, used:  
*G\_SF4-4*, **450**, used:  
*G\_SFSFP*, **501, 532**, used: 513,  
     547

*G\_SFSFS*, **501, 532**, used: **512, 513, 547, 547**  
*G\_SGaGa*, **388**, used: **391**  
*G\_SGaZ*, **388**, used: **391**  
*G\_Sgg*, **388**, used: **391**  
*G\_SL2SQ2*, **450**, used: **474**  
*G\_SL4*, **450**, used: **474**  
*G\_SL4\_2*, **450**, used: **474**  
*G\_SLR\_DbtR*, **241, ??, ??, 428**, used: **257, ??, ??, 436**  
*G\_SLSNW*, **450, 501, 532**, used: **456, 504, 535**  
*G\_SL\_DbtL*, **241, ??, ??, 428**, used: **257, ??, ??, 436**  
*G\_SL\_DttL*, **241, ??, ??, 428**, used: **257, ??, ??, 436**  
*G\_SL\_DttR*, **241, ??, ??, 428**, used: **257, ??, ??, 436**  
*G\_Smm*, **388**, used: **390**  
*G\_SN2SL2\_1*, **450**, used: **474**  
*G\_SN2SL2\_2*, **450**, used: **474**  
*G\_SN2SQ2*, **450**, used: **474**  
*G\_SN4*, **450**, used: **474**  
*G\_SP\_ttH*, **241, 428**, used: **255, 434**  
*G\_SR\_DttR*, **241, ??, ??, 428**, used: **257, ??, ??, 436**  
*G\_SS*, **450, 501, 532**, used: **463, 508, 542**  
*G\_SSWW*, **??, 388, 428**, used: **??, 390, 432**  
*G\_SZZZ*, **??, 388, 428**, used: **??, 390, 432**  
*G\_Stautau*, **388**, used: **390**  
*G\_strong*, **450, 532, 367**, used: **390**  
*G\_Stt*, **388**, used: **390**  
*G\_SU2SD2*, **450**, used: **475**  
*G\_SU4*, **450**, used: **475**  
*G\_SU4\_2*, **450**, used: **475**  
*G\_SUSDSNSL*, **450**, used: **475**  
*G\_SWS*, **450**, used: **456**  
*G\_SWW*, **??, 388, 428**, used: **??, 390, 431**  
*G\_SWW\_T*, **??, 428**, used: **??, 431**  
*G\_SZZ*, **??, 388, 428**, used: **??, 390, 431**  
*G\_SZZ\_T*, **??, 428**, used: **??, 431**  
*G\_S\_Sqrt*, **450**, used: **459**  
*G\_TLR\_btW*, **241, ??, ??, 428**, used: **255, ??, ??, 433**  
*G\_TLR\_btWA*, **241, ??, ??, 428**, used: **255, ??, ??, 434**  
*G\_TLR\_btWZ*, **241, ??, ??, 428**, used: **256, ??, ??, 434**  
*G\_TNWW*, **??, 428**, used: **??, 432**  
*G\_TNZZ*, **??, 428**, used: **??, 432**  
*G\_TRL\_tbW*, **241, ??, ??, 428**, used: **255, ??, ??, 433**  
*G\_TRL\_tbWA*, **241, ??, ??, 428**, used: **255, ??, ??, 434**  
*G\_TRL\_tbWZ*, **241, ??, ??, 428**, used: **256, ??, ??, 434**  
*G\_TVA\_bbA*, **241, ??, ??, 428**, used: **254, ??, ??, 433**  
*G\_TVA\_bbWW*, **241, ??, ??, 428**, used: **256, ??, ??, 435**  
*G\_TVA\_bbZ*, **241, ??, ??, 428**, used: **254, ??, ??, 433**  
*G\_TVA\_ttA*, **241, ??, ??, 428**, used: **253, ??, ??, 432**  
*G\_TVA\_ttG*, **241, ??, ??, 428**, used: **254, ??, ??, 433**  
*G\_TVA\_ttGG*, **241, ??, ??, 428**, used: **255, ??, ??, 434**  
*G\_TVA\_ttWW*, **241, ??, ??, 428**, used: **256, ??, ??, 435**  
*G\_TVA\_ttZ*, **241, ??, ??, 428**, used: **254, ??, ??, 433**  
*G\_TWW*, **??, 428**, used: **??, 432**  
*G\_TWZ*, **??, 428**, used: **??, 432**  
*G\_VLR\_btW*, **241, ??, ??, 428**, used: **255, ??, ??, 433**  
*G\_VLR\_qBuB*, **241, ??, ??, 428**, used: **257, ??, ??, 435**  
*G\_VLR\_qBuB\_d*, **241, ??, ??, 428**, used: **257, ??, ??, 435**  
*G\_VLR\_qBuB\_e*, **241, ??, ??, 428**, used: **257, ??, ??, 435**  
*G\_VLR\_qBuB\_u*, **241, ??, ??, 428**, used: **257, ??, ??, 435**  
*G\_VLR\_qGuG*, **241, ??, ??, 428**, used: **256, ??, ??, 435**

- 435  
*G\_VLR\_tbW*, 241, ??, ??, 428,  
 used: 255, ??, ??, 433  
*G\_VLR\_ttZ*, 241, ??, ??, 428,  
 used: 254, ??, ??, 433  
*G\_VL\_qBuB\_n*, 241, ??, ??,  
 428, used: 257, ??, ??,  
 435  
*G\_VL\_qW*, 241, ??, ??, 428,  
 used: 257, ??, ??, 435  
*G\_VL\_qW\_d*, 241, ??, ??, 428,  
 used: 257, ??, ??, 436  
*G\_VL\_qW\_u*, 241, ??, ??, 428,  
 used: 257, ??, ??, 436  
*G\_weak*, 241, ??, ??, 278, 300,  
 321, 337, 349, 367, 378,  
 388, 414, 428, ??, ??,  
 used: 244, 245, ??, ??,  
 280, 302, 322, 337, 350,  
 367, 378, 389, 416, 428, ??  
*G\_WH3W*, 278, 300, used: 284,  
 305  
*G\_WH4*, 278, 300, used: 284,  
 305  
*G\_WHWAH*, 278, 300, used:  
 284, 305  
*G\_WHWAZ*, 278, 300, used:  
 284, 305  
*G\_WHWAZH*, 278, 300, used:  
 284, 305  
*G\_WHWHAAH*, 278, 300, used:  
 284, 305  
*G\_WHWHAZH*, 278, 300, used:  
 284, 305  
*G\_WHWHWW*, 278, 300, used:  
 284, 305  
*G\_WHWHZAH*, 278, 300, used:  
 284, 305  
*G\_WHWHZHAAH*, 278, 300,  
 used: 284, 305  
*G\_WHWHZZH*, 278, 300, used:  
 284, 305  
*G\_WHWWW*, 278, 300, used:  
 284, 305  
*G\_WHWZAH*, 278, 300, used:  
 284, 305  
*G\_WHWZHAAH*, 278, 300, used:  
 284, 305  
*G\_WHWZHZZH*, 278, 300, used:  
 284, 305  
*G\_WHWZZ*, 278, 300, used:  
 284, 305  
*G\_WHWZZH*, 278, 300, used:  
 284, 305  
*G\_WmHph1*, 414, used: 420  
*G\_WmHph2*, 414, used: 420  
*G\_WmHph3*, 414, used: 420  
*G\_WpHmh1*, 414, used: 420  
*G\_WpHmh2*, 414, used: 420  
*G\_WpHmh3*, 414, used: 420  
*G\_WPSLSN*, 450, 501, 532,  
 used: 465, 510, 545  
*G\_WPSUSD*, 450, 501, 532,  
 used: 466, 511, 545  
*G\_WSQ*, 501, 532, used: 504,  
 536  
*G\_WWAAH*, 278, 300, used:  
 284, 305  
*G\_WWAZH*, 278, 300, used:  
 284, 305  
*G\_WWSFSF*, 450, 501, 532,  
 used: 465, 510, 511, 544,  
 545  
*g\_www*, 402, used: 402  
*G\_www*, 401, used: 402, 405  
*G\_WWWW*, 241, 450, ??, ??,  
 501, 532, 278, 300, 321,  
 337, 349, 367, 378, 388,  
 414, 428, ??, ??, used:  
 248, 463, ??, ??, 508, 542,  
 284, 284, 305, 305, 326,  
 338, 351, 369, 380, 390,  
 420, 428, ??, ??  
*g\_wwz*, 402, used: 402  
*G\_wwz*, 401, used: 402, 405  
*g\_wwza*, 402, used: 402  
*G\_wwza*, 401, used: 402, 405  
*G\_WWZAH*, 278, 300, used:  
 284, 305  
*G\_WWZHAAH*, 278, 300, used:  
 284, 305  
*g\_wwzz*, 402, used: 402  
*G\_wwzz*, 401, used: 402, 405  
*G\_WWZZH*, 278, 300, used:  
 284, 305  
*G\_WZSLSN*, 450, 501, 532,  
 used: 465, 510, 545  
*G\_WZSUSD*, 450, 501, 532,  
 used: 466, 511, 545  
*g\_wlep*, 402, used: 402

- G\_wlep*, **401**, used: **402**, **403**  
*g\_wquark*, **402**, used: **402**  
*G\_wquark*, **401**, used: **402**, **403**,  
**404**  
*G\_YUK*, **450**, used: **457**, **457**  
*G\_YUK\_1*, **450**, used: **457**  
*G\_YUK\_2*, **450**, used: **457**  
*G\_YUK\_3*, **450**, used: **458**  
*G\_YUK\_4*, **450**, used: **458**  
*G\_YUK\_C*, **450**, **501**, **532**,  
used: **461**, **507**, **538**  
*G\_YUK\_DCU*, **501**, **532**, used:  
**505**, **537**  
*G\_YUK\_FFP*, **501**, **532**, used:  
**505**, **536**  
*G\_YUK\_FFS*, **501**, **532**, used:  
**505**, **536**  
*G\_YUK\_G*, **450**, **501**, **532**,  
used: **459**, **507**, **538**  
*G\_YUK\_LCN*, **501**, **532**, used:  
**505**, **537**  
*G\_YUK\_LQ\_P*, **532**, used: **541**  
*G\_YUK\_LQ\_S*, **532**, used: **541**  
*G\_YUK\_N*, **450**, **501**, **532**,  
used: **459**, **506**, **538**  
*G\_YUK\_Q*, **450**, **501**, **532**,  
used: **461**, **507**, **539**  
*G\_YUK\_UCD*, **501**, **532**, used:  
**505**, **537**  
*G\_Z*, **450**, **501**, **532**, used:  
*G\_ZEH*, **321**, used: **327**  
*G\_ZGLQLQ*, **532**, used: **542**  
*G\_Zh1h2*, **414**, used: **420**  
*G\_Zh1h3*, **414**, used: **420**  
*G\_Zh2h3*, **414**, used: **420**  
*G\_ZHEH*, **321**, used: **327**  
*G\_ZHpHm*, **414**, used: **420**  
*G\_ZHPsipp*, **278**, **300**, used:  
**286**, **307**  
*G\_ZHTHT*, **278**, **300**, used: **281**,  
**303**  
*G\_zhthth*, **321**, used:  
*G\_ZLQ*, **532**, used: **542**  
*G\_ZPLQLQ*, **532**, used: **542**  
*G\_ZPSFSF*, **450**, **501**, **532**,  
used: **465**, **510**, **544**  
*G\_ZPsip*, **278**, **300**, used: **286**,  
**307**  
*G\_ZPsipp*, **278**, **300**, used: **286**,  
**307**  
*G\_ZSF*, **450**, **501**, **532**, used:  
**456**, **505**, **536**  
*G\_ZTHT*, **278**, **300**, used: **281**,  
**303**  
*G\_ZZLQLQ*, **532**, used: **542**  
*G\_ZZSFSF*, **450**, **501**, **532**,  
used: **465**, **510**, **511**, **544**,  
**545**  
*G\_ZZWW*, **241**, **450**, **??**, **??**,  
**501**, **532**, **278**, **300**, **321**,  
**337**, **349**, **367**, **378**, **388**,  
**414**, **428**, **??**, **??**, used:  
**248**, **463**, **??**, **??**, **508**, **542**,  
**284**, **284**, **305**, **305**, **326**,  
**338**, **351**, **369**, **380**, **390**,  
**420**, **428**, **??**, **??**  
*g\_zlep*, **402**, used: **402**  
*G\_zlep*, **401**, used: **402**, **404**  
*g\_zquark*, **402**, used: **402**  
*G\_zquark*, **401**, used: **402**, **404**  
*H*, **236**, **274**, **297**, **319**, **333**,  
**344**, **363**, **374**, **384**, **428**,  
**??**, **??**, used: **237**, **239**,  
**246**, **251**, **251**, **251**, **251**,  
**252**, **253**, **255**, **259**, **275**,  
**277**, **282**, **282**, **285**, **285**,  
**286**, **287**, **287**, **290**, **290**,  
**290**, **291**, **298**, **299**, **304**,  
**304**, **306**, **306**, **307**, **308**,  
**308**, **311**, **311**, **312**, **312**,  
**319**, **320**, **325**, **325**, **326**,  
**326**, **326**, **326**, **326**, **326**,  
**327**, **327**, **327**, **333**, **335**,  
**338**, **339**, **339**, **339**, **339**,  
**339**, **339**, **340**, **344**, **347**,  
**351**, **352**, **352**, **352**, **352**,  
**352**, **352**, **353**, **363**, **365**,  
**368**, **369**, **369**, **369**, **369**,  
**369**, **370**, **375**, **376**, **379**,  
**380**, **380**, **380**, **380**, **381**,  
**385**, **386**, **390**, **390**, **390**,  
**390**, **390**, **391**, **391**, **428**,  
**428**, **429**, **429**, **429**, **430**,  
**430**, **434**, **437**, **??**, **??**, **??**,  
**??**, **??**, **??**, **??**, **??**, **??**, **??**,  
**??**, **??**, **??**, **??**, **??**, **??**  
*H1*, **447**, used:  
*H1dm*, **344**, used: **344**, **347**, **353**  
*H1dp*, **344**, used: **344**, **347**, **353**  
*H1um*, **344**, used: **344**, **347**, **353**

- H1up*, **344**, used: 344, 347, 353  
*H2*, **447**, used:  
*H2* (module), **219**, used: 219,  
219, 220, 221  
*H2dm*, **344**, used: 344, 347, 353  
*H2dp*, **344**, used: 344, 347, 353  
*H2um*, **344**, used: 344, 347, 353  
*H2up*, **344**, used: 344, 347, 353  
*H3*, **447**, used:  
*H3* (module), **219**, used: 219,  
219, 220, 221  
*H4*, **447**, used:  
*H5*, **447**, used:  
*H6*, **447**, used:  
*HA*, **411**, used: 411, 412, 417,  
418, 418, 418, 418, 419,  
420, 420, 421, 421, 422  
*half*, **245**, ??, ??, **280, 302, 322**,  
**337, 350, 368, 379, 389**,  
**416, 428**, ??, used: 245,  
??, ??, 280, 302, 322, 337,  
350, 368, 379, 389, 416,  
428, ??  
*Half*, **241**, ??, ??, **428**, used:  
257, 257, 258, 258, ??, ??,  
??, ??, ??, ??, 436, 436  
*harvest*, **41, 47, 38**, used: 47, 47,  
48, 111  
*harvest\_goldstones*, **111**, used:  
*harvest\_list*, **41, 47, 38**, used:  
117, 120  
*hash*, **737, 737, 218, 219, 219**,  
**105, 736**, used: 218, 219,  
219, 105, 105, 105  
*hash* (type), **737, 737, 736**, used:  
737, 737, 736  
*HC1*, **528**, used: 528, 529, 537,  
537, 537, 543, 543, 543,  
543, 544, 544, 544, 544,  
544, 546, 547, 547, 549  
*HC1c*, **528**, used: 528, 529, 537,  
537, 537, 543, 543, 543,  
543, 544, 544, 544, 544,  
544, 546, 547, 547, 549  
*HC2*, **528**, used: 528, 529  
*HC2c*, **528**, used: 528, 529  
*HC3*, **528**, used: 528, 529  
*HC3c*, **528**, used: 528, 529  
*HC4*, **528**, used: 528, 529  
*HC4c*, **528**, used: 528, 529  
*HC5*, **528**, used: 528, 529  
*HC5c*, **528**, used: 528, 529  
*hdn*, **742, 740**, used: 742  
*hdl*, **793**, used: 793, 794  
*header*, **710**, used: 711  
*header* (field), **813, 807**, used:  
814, 815, 711, 711, 711  
*header\_sans\_color*, **710**, used:  
711, 711  
*head\_req*, **205**, used: 205  
*Heavy*, **397**, used: 398, 398, 405,  
405, 407  
*Heavy2*, **397**, used: 398, 402  
*heavy\_currents*, **325**, used: 327  
*heavy\_gauge\_higgs*, **285, 306**,  
**326**, used: 287, 308, 326  
*heavy\_gauge\_higgs4*, **326**, used:  
327  
*heavy\_quartic\_gauge*, **284, 305**,  
**326**, used: 285, 306, 326  
*heavy\_top\_currents*, **281, 303**,  
used: 291, 312  
*heavy\_triple\_gauge*, **283, 305**,  
**325**, used: 284, 305, 326  
*height*, **756**, used: 756, 756, 756  
*Helac* (module), **33, 127, 20, 91**,  
used: 127  
*Helac\_Binary* (module), **33, 20**,  
used:  
*Helac\_Majorana* (module), **127**,  
**91**, used:  
*helicities*, **127, 129, 92**, used:  
*helicities* (field), **129**, used: 129,  
134  
*helicities* (type), **129**, used:  
*helicity\_table*, **131**, used: 133  
*hgg*, **281**, used: 285, 285, 285,  
290, 290  
*Hh*, **411**, used: 411, 412, 417,  
418, 418, 418, 418, 419,  
420, 420, 421, 421, 422  
*HH*, **411**, used: 411, 412, 417,  
418, 418, 418, 418, 419,  
420, 420, 421, 421, 422  
*hhgg*, **281**, used: 287, 287  
*higgs*, **253, 467, 512, 546, 290**,  
**312, 327, 339, 352, 370**,  
**380, 390, 421, 431, ??**,  
??, used: 258, 477, 513,  
548, 291, 312, 327, 340,

- 353, 370, 380, 391, 422,  
 436, ??, ??  
*higgs* (type), 447, used: 447, 450  
*higgs4*, 253, 467, 512, 546, 290,  
 312, 327, 340, 352, 370,  
 380, 390, 421, 431, ??,  
 ??, used: 259, 478, 514,  
 549, 291, 312, 327, 340,  
 353, 370, 381, 391, 422,  
 437, ??, ??  
*higgs\_anom*, 234, 234, 234, 234,  
 235, 235, 235, 235, 236,  
 427, 428, 224, 273,  
 used: 253, 253, 253, 253,  
 430, 430, 431, 431  
*higgs\_charg\_neutr*, 458, 506,  
 537, used: 477, 513, 548  
*higgs\_ch\_gravitino*, 462, used:  
 463  
*higgs\_gold*, 467, used: 478  
*higgs\_gold4*, 468, used: 478  
*higgs\_gold\_sfermion*, 473, used:  
 478  
*higgs\_gold\_sfermion'*, 473, used:  
 473  
*higgs\_gold\_sneutrino*, 472, used:  
 478  
*higgs\_gold\_sneutrino'*, 472, used:  
 472  
*higgs\_gold\_squark*, 473, used:  
 478  
*higgs\_gold\_squark'*, 473, used:  
 473  
*higgs\_hmm*, 234, 234, 234, 234,  
 235, 235, 235, 235, 236,  
 427, 428, 224, 273,  
 used: 246, 428  
*higgs\_neutr*, 459, 506, 538,  
 used: 477, 513, 548  
*higgs\_neutr'*, 459, used: 459  
*higgs\_neutr''*, 459, used: 459  
*higgs\_neu\_gravitino*, 462, used:  
 463  
*higgs\_SCC*, 512, 546, used: 512,  
 546  
*higgs\_sfermion*, 469, 513, 547,  
 used: 477, 513, 548  
*higgs\_sfermion'*, 469, 513, 547,  
 used: 469, 513, 547  
*higgs\_sfermion''*, 469, 513, 547,  
 used: 469, 513, 547  
*higgs\_sfermion4*, 471, used: 478  
*higgs\_sfermion4'*, 471, used: 471  
*higgs\_sfermion\_P*, 513, 547,  
 used: 513, 547  
*higgs\_sfermion\_S*, 513, 547,  
 used: 513, 547  
*higgs\_sneutrino*, 469, 512, 547,  
 used: 477, 513, 548  
*higgs\_sneutrino'*, 469, 512, 547,  
 used: 469, 512, 547  
*higgs\_sneutrino''*, 469, 512, 547,  
 used: 469, 512, 547  
*higgs\_sneutrino4*, 471, used: 478  
*higgs\_sneutrino4'*, 471, used:  
 471  
*higgs\_SPP*, 512, 546, used: 512,  
 546  
*higgs\_squark*, 470, 513, 547,  
 used: 477, 513, 548  
*higgs\_squark'*, 470, 513, 547,  
 used: 470, 513, 547  
*higgs\_squark4*, 472, used: 478  
*higgs\_squark4'*, 472, used: 472  
*higgs\_squark\_a*, 470, 513, 547,  
 used: 470, 513, 547  
*higgs\_squark\_b*, 470, 513, 547,  
 used: 470, 513, 547  
*higgs\_SSS*, 512, 546, used: 512,  
 546  
*higgs\_triangle*, 234, 234, 234,  
 234, 235, 235, 235, 235,  
 236, 444, 444, 444, 445,  
 445, 445, 445, 495, 495,  
 496, 496, 427, 428, 224,  
 443, 495, 273, used: 253,  
 463, 509, 430  
*higgs\_triangle\_vertices*, 253,  
 430, used: 258, 436  
*Hit*, 737, 738, 736, used: 739  
*Hm*, 447, 498, 411, used: 447,  
 449, 457, 457, 458, 462,  
 463, 464, 467, 467, 467,  
 468, 469, 470, 471, 471,  
 472, 472, 473, 473, 476,  
 476, 479, 498, 500, 505,  
 505, 506, 508, 509, 509,  
 509, 509, 509, 510, 510,  
 510, 512, 512, 513, 514,

- 411, 412, 418, 420, 420,  
 421, 421  
*Hn* (module), **219**, used: 219,  
 219, 220, 221  
*homogeneous*, **745, 740**, used:  
 745, 131, 133  
*homogeneous\_final\_state*, **213**,  
 used: 213, 215  
*Hp*, **447, 498, 411**, used: 447,  
 449, 457, 457, 458, 462,  
 463, 464, 467, 467, 467,  
 468, 469, 470, 471, 471,  
 472, 472, 473, 473, 476,  
 476, 479, 498, 500, 505,  
 505, 506, 508, 509, 509,  
 509, 509, 509, 510, 510,  
 510, 512, 512, 513, 514,  
 411, 412, 418, 420, 420,  
 421, 421  
*HSExt* (module), **384, 272**, used:  
 ??, ??  
*hs\_of\_flavor*, **130**, used: 130, 131  
*hs\_of\_flavors*, **130**, used: 131,  
 133  
*hs\_of\_lorentz*, **130**, used: 130,  
 130  
*H\_Heavy*, **447**, used: 447, 449,  
 457, 458, 459, 462, 463,  
 464, 464, 465, 467, 467,  
 467, 468, 469, 469, 471,  
 471, 472, 472, 473, 476,  
 479  
*H\_Light*, **447**, used: 447, 449,  
 457, 458, 459, 462, 463,  
 464, 464, 465, 467, 467,  
 467, 468, 469, 469, 471,  
 471, 472, 472, 473, 476,  
 479  
*I*, **564**, ??, **166, 564**, ??, used:  
 564, ??, 244, ??, ??, 428,  
 566  
*I* (camlyacc token), **567**, used:  
 567  
*id*, **130**, used: 131  
*IG-s*, **401**, used: 405  
*imag*, **564, 564**, used: ??, 567  
*IMap* (module), **28**, used: 28, 29,  
 29, 29, 29, 30, 30  
*import*, **75**, used: 75  
*import\_prefixed*, **703**, used: 703,  
 703  
*impossible*, **803, 10, 184**, used:  
 803, 10, 10, 194  
*Impossible* (exn), **803, 10, 23**,  
**43, 49, 95, 96, 123, 126**,  
 used:  
*in1* (field), **699**, used:  
*in2* (field), **699**, used:  
*include\_anomalous*, ??, ??, ??,  
 ??, ??, ??, used:  
*include\_ckm*, **395, 395, 395**,  
**395, 395, 396, 396, 272**,  
 used: 396, 401, 406  
*include\_four*, **444, 444, 444**,  
**445, 445, 445, 445, 443**,  
 used: 478  
*include\_goldstone*, **444, 444**,  
**444, 445, 445, 445, 445**,  
**443**, used: 447, 448, 478,  
 478  
*include\_goldstones*, **712**, used:  
 712, 715  
*include\_hf*, **395, 395, 395, 395**,  
**395, 396, 396, 272**,  
 used: 396, 398, 407  
*incoming*, **54, 58, 59, 64, 64**,  
**210, 210, 94, 101, 103**,  
**122, 52, 53, 209, 90**,  
 used: 64, 122, 129, 129  
*incoming* (field), **813, 100, 103**,  
**807**, used: 814, 815, 103,  
 116, 117, 121, 121  
*incomplete*, **183, 208**, used: 190,  
 191, 194, 203, 208, 208,  
 208, 208  
*Incomplete* (exn), **692, 694, 691**,  
 used:  
*Index*, **566**, used: 566  
*Index'*, **566**, used: 566  
*index\_string*, **753, 751**, used:  
 727, 727  
*indices*, **207**, used: 207  
*Infinity*, **810**, used: 811  
*init*, **575**, used: 833, 835, 818,  
 576, 110  
*initialize\_cache*, **94, 105, 127**,  
**134, 90, 92**, used: 134,  
 715

- inject*, **267**, used: 268, 268, 268,  
 269, 269, 271  
*injectl*, **271**, used: 271, 271  
*inner* (field), **813, 807**, used:  
 814, 711, 711, 712  
*input* (field), **171**, used: 575, 225,  
 227, 229, 232, 245, 455,  
 ??, ??, 503, 534, 280, 302,  
 323, 337, 350, 368, 379,  
 389, 407, 416, 428, ??, ??,  
 721  
*input\_functions*, **574**, used: 574,  
 576  
*input\_lagrangian*, **574**, used: 574,  
 576  
*input\_model*, **574**, used:  
*input\_parameters*, **243**, ??, ??,  
 280, 302, 322, 337, 350,  
 367, 378, 388, 428, ??,  
 ??, used: 245, ??, ??,  
 280, 302, 323, 337, 350,  
 368, 379, 389, 428, ??, ??  
*input\_particles*, **574**, used: 574,  
 576  
*input\_table*, **570**, used: 574  
*input\_variables*, **574**, used: 574,  
 576  
*insert*, **795**, used: 795, 795  
*insert1*, **828, 830, 831**, used:  
 828, 830, 830, 830, 831  
*insert\_inorder\_signed*, **795**, used:  
 796  
*insert\_in\_unfinished\_decays*,  
**696**, used: 696  
*insert\_signed*, **795**, used: 795,  
 795  
*inspect\_partition*, **20, 21, 24, 26**,  
**26, 33, 33, 19**, used:  
*Int* (module), **27, 124, 19**, used:  
 124, 124  
*INT*, ??, ??, ??, ??, used: ??,  
 ??, 70, 566  
*INT* (camlyacc token), **71, 567**,  
 used: 72, 567  
*integer*, **564, 564**, used: ??, 572,  
 575, 567  
*integer* (type), **28, 28, 19**, used:  
 28, 28, 28, 20, 20, 20, 20  
*integer* (camllex regexp), **566**,  
 used: 566  
*Integer*, **564, 564**, used: 564  
*Integer* (sig), **27, 19**, used: 27,  
 28, 19, 20  
*integer\_range*, **215**, used: 215  
*interleave*, **745, 741**, used: 746  
*interleave\_nearest*, **746, 741**,  
 used:  
*internal\_edges*, **816**, used: 817  
*internal\_edges\_from*, **816**, used:  
 816, 816  
*int\_edges* (field), **816**, used: 817,  
 817, 819  
*int\_incidence*, **817**, used: 819  
*int\_list\_to\_string*, **70**, used:  
*int\_node*, **812**, used: 812  
*int\_nodes* (field), **816**, used: 817,  
 817, 819, 819, 819, 819  
*int\_of\_char*, **446, 497, 528**,  
 used: 448, 448, 450, 481,  
 499, 499, 500, 518, 528,  
 530, 530, 531, 554  
*int\_of\_csign*, **397**, used: 399,  
 400, 401, 401, 401, 401  
*int\_of\_gen*, **397**, used: 408  
*int\_orders*, **98**, used: 107  
*int\_power*, **86**, used: 86  
*invalid*, **183**, used: 186, 186, 191  
*Invalid* (exn), **730, 730**, used:  
*invalid\_flavor*, **721**, used: 721  
*inverse*, **796, 797, 798, 796**,  
 used: 797, 798, 800, 800  
*inverse\_ok*, **800**, used: 800  
*invert\_array*, **817**, used: 817  
*invert\_array\_unsafe*, **816**, used:  
*InvPi* (module), **781**, used: 781,  
 781, 781, 781, 781, 781  
*inv\_pi*, **780, 781, 781, 782, 780**,  
**780**, used: 781, 782, 782,  
 119, 119, 119  
*in\_ghost\_flags*, **83, 84, 80**, used:  
*in\_to\_lists*, **83, 84, 80**, used:  
*IPowSet* (module), **78, 215**,  
 used: 78, 78, 215  
*ISet* (module), **746, 186, 215**,  
 used: 746, 746, 746, 186,  
 215, 215  
*iset\_list\_union*, **746**, used: 746  
*iset\_of\_list*, **746**, used: 746  
*isospin* (type), **397**, used: 397,  
 401



- Iso-down*, **397**, used: 398, 402, 403  
*Iso-up*, **397**, used: 398, 402  
*is\_empty*, **755, 756, 761, 784, 784, 769, 769, 770, 754, 783, 767, 768**, used: 784, 785, 785, 786, 828, 829, 831, 46, 46, 78, 214  
*is\_error*, **??**, used: ??  
*is\_failure*, **??**, used: ??  
*is\_gauss*, **73, 76, 94, 101, 103, 122, 73, 90**, used: 117, 122  
*is\_gauss* (field), **76, 100, 103**, used: 76, 76, 79, 103, 116, 117, 121  
*is\_goldstone\_of*, **104**, used:  
*is\_node*, **41, 45, 37**, used: 111, 112, 112  
*is\_null*, **826, 826, 827, 829, 831, 181, 181, 181, 181, 181, 181, 182, 823, 824, 180**, used: 829, 830, 831, 831, 831, 832, 181, 182, 211, 122  
*is\_offspring*, **41, 46, 37**, used: 47  
*is\_skip*, **??**, used: ??  
*is\_source*, **104**, used: 108, 112, 112  
*is\_sterile*, **41, 46, 37**, used: 47, 47, 118  
*is\_success*, **??**, used:  
*is\_todo*, **??**, used: ??  
*is\_unit*, **826, 826, 827, 827, 828, 829, 823, 824, 824**, used: 829, 831, 832  
*is\_white*, **203**, used: 203  
*It* (module), **183, 183**, used: 207, 95, 97, 117, 128, 708, 91, 93  
*iter*, **755, 760, 763, 769, 769, 771, 772, 774, 9, 11, 12, 14, 16, 41, 43, 44, 46, 48, 754, 767, 768, 768, 6, 38**, used: ??, ??, ??, ??, ??, ??, ??, 760, 763, 771, 772, 774, 774, 812, 814, 814, 814, 815, 815, 815, 815, 817, 817, 819, 819, 819, 16, 44, 46, 46, 48, 221, 702, 703, 703, 704, 705, 124, 133, 712, 716, 716, 716, 716, 716  
*iter'*, **771, 774**, used: 771, 774  
*iteri*, **744, 741**, used: 744  
*iteri2*, **744, 741**, used:  
*iter\_edges*, **819, 808**, used:  
*iter\_incoming*, **819, 808**, used:  
*iter\_internal*, **819, 808**, used:  
*iter\_nodes*, **41, 46, 37**, used: 124  
*iter\_outgoing*, **819, 808**, used:  
*I\_G1\_AWW*, **241, ??, ??, 428**, used: 247, ??, ??, 428  
*I\_G1\_minus\_kappa\_minus\_G4\_AWW*, **241, ??, ??, 428**, used: 247, ??, ??, 428  
*I\_G1\_minus\_kappa\_minus\_G4\_ZWW*, **241, ??, ??, 428**, used: 247, ??, ??, 428  
*I\_G1\_minus\_kappa\_plus\_G4\_AWW*, **241, ??, ??, 428**, used: 247, ??, ??, 428  
*I\_G1\_minus\_kappa\_plus\_G4\_ZWW*, **241, ??, ??, 428**, used: 247, ??, ??, 428  
*I\_G1\_plus\_kappa\_minus\_G4\_AWW*, **241, ??, ??, 428**, used: 247, ??, ??, 428  
*I\_G1\_plus\_kappa\_minus\_G4\_ZWW*, **241, ??, ??, 428**, used: 247, ??, ??, 428  
*I\_G1\_plus\_kappa\_plus\_G4\_AWW*, **241, ??, ??, 428**, used: 247, ??, ??, 428  
*I\_G1\_plus\_kappa\_plus\_G4\_ZWW*, **241, ??, ??, 428**, used: 247, ??, ??, 428  
*I\_G1\_ZWW*, **241, ??, ??, 428**, used: 247, ??, ??, 428  
*I\_G3*, **719**, used: 720  
*I\_Gs*, **230, 241, ??, ??, 278, 300, 321, 337, 349, 378, 388, 414, 428, ??, ??**, used: 231, 246, 255, ??, ??, ??, ??, 283, 305, 325, 338, 351, 380, 390, 419, 428, 434, ??, ??  
*I\_GsRt2*, **349**, used: 351  
*I\_G\_Abb*, **414**, used:  
*I\_G\_Acc*, **414**, used:

- I\_G-AHWWH*, **278, 300**, used:  
     **283, 305**  
*I\_G-AHWHWH*, **278, 300**,  
     used: **283, 305**  
*I\_G-AHWW*, **278, 300**, used:  
     **283, 305**  
*I\_G-Amumu*, **414**, used:  
*I\_G-Atautau*, **414**, used:  
*I\_G-Att*, **414**, used:  
*I\_G-CC*, **321**, used: **323**  
*I\_G-Psi0ppWHW*, **278, 300**,  
     used: **287, 308**  
*I\_G-Psi0ppWHWH*, **278, 300**,  
     used: **287, 308**  
*I\_G-Psi0ppWW*, **278, 300**,  
     used: **287, 308**  
*I\_G-Psi0pWA*, **278, 300**, used:  
     **287, 308**  
*I\_G-Psi0pWAH*, **278, 300**,  
     used: **287, 308**  
*I\_G-Psi0pWHA*, **278, 300**, used:  
     **287, 308**  
*I\_G-Psi0pWHAH*, **278, 300**,  
     used: **287, 308**  
*I\_G-Psi0pWHZ*, **278, 300**, used:  
     **287, 308**  
*I\_G-Psi0pWHZH*, **278, 300**,  
     used: **287, 308**  
*I\_G-Psi0pWZ*, **278, 300**, used:  
     **287, 308**  
*I\_G-Psi0pWZH*, **278, 300**,  
     used: **287, 308**  
*I\_G-S*, **450, 501, 532**, used:  
     **463, 508, 542**  
*I\_G-weak*, **241, ??, ??, 428**,  
     used: **244, 255, 256, 256,**  
     **256, ??, ??, ??, ??, ??,**  
     **??, ??, ??, ??, ??, 428,**  
     **434, 434, 435, 435**  
*I\_G-WWW*, **278, 300, 321**,  
     **414, ??**, used: **283, 305**  
*I\_G-Z1*, **321**, used: **325**  
*I\_G-Z2*, **321**, used: **325**  
*I\_G-Z3*, **321**, used: **325**  
*I\_G-Z4*, **321**, used: **325**  
*I\_G-Z5*, **321**, used: **325**  
*I\_G-Z6*, **321**, used: **325**  
*I\_G-ZHWHWH*, **278, 300**,  
     used: **283, 305**  
*I\_G-ZHWW*, **278, 300**, used:  
     **283, 305**  
*I\_G-ZWHW*, **278, 300**, used:  
     **283, 305**  
*I\_G-ZWW*, **241, 450, ??, ??,**  
     **501, 532, 278, 300, 321,**  
     **337, 349, 367, 378, 388,**  
     **414, 428, ??, ??**, used:  
     **244, 246, 253, 463, ??, ??,**  
     **??, ??, 508, 542, 283, 283,**  
     **290, 305, 305, 312, 325,**  
     **327, 338, 340, 351, 353,**  
     **368, 370, 380, 380, 390,**  
     **391, 419, 422, 428, 431,**  
     **??, ??, ??, ??**  
*I\_G-ZWW\_K1*, **349**, used: **351**  
*I\_G-ZWW\_K2*, **349**, used: **351**  
*I\_G-ZWW\_K3*, **349**, used: **351**  
*I\_kappa5-AWW*, **241, ??, ??,**  
     **428**, used: **247, ??, ??,**  
     **428**  
*I\_kappa5-ZWW*, **241, ??, ??,**  
     **428**, used: **247, ??, ??,**  
     **428**  
*I\_lambda5-AWW*, **241, ??, ??,**  
     **428**, used: **247, ??, ??,**  
     **428**  
*I\_lambda5-ZWW*, **241, ??, ??,**  
     **428**, used: **247, ??, ??,**  
     **428**  
*I\_lambda-AWW*, **241, ??, ??,**  
     **428**, used: **247, ??, ??,**  
     **428**  
*I\_lambda-ZWW*, **241, ??, ??,**  
     **428**, used: **247, ??, ??,**  
     **428**  
*I\_Q-H*, **278, 300, 321**, used:  
*I\_Q-W*, **241, 450, ??, ??, 501,**  
     **532, 278, 300, 321, 337,**  
     **349, 367, 378, 388, 414,**  
     **428, ??, ??**, used: **244,**  
     **246, 253, 463, ??, ??, ??,**  
     **??, 508, 542, 283, 283,**  
     **290, 305, 305, 312, 325,**  
     **325, 327, 338, 340, 351,**  
     **353, 368, 370, 380, 380,**  
     **390, 391, 419, 422, 428,**  
     **431, ??, ??, ??, ??**  
*I\_Q-W\_K*, **349**, used: **351**  
*I\_Q-ZH*, **321**, used: **325**

- Java* (module), **578**, used:  
*join*, **756, 735, 735**, used: **756**,  
**757, 757, 759, 760, 735**  
*join\_signs*, **795**, used: **795**  
*ket*, **94, 100, 103, 122, 89**, used:  
**122**  
*key* (type), **737, 737, 769, 769**,  
**770, 43, 44, 48, 736**,  
**767, 768**, used: **737, 769**,  
**769, 770, 770, 772, 43, 44**,  
**44, 48, ??, 736, 736, 767**,  
**767, 767, 767, 768, 768**,  
**768**  
*Key* (sig), **737, 736**, used: **737**,  
**736**  
*keys*, **44**, used: **44**  
*keystone*, **24**, used: **24**  
*keystones*, **794, 20, 24, 24, 26**,  
**26, 28, 32, 33, 34, 788**,  
**18, 20**, used: **794, 32, 117**  
*keystones'*, **24, 33, 34**, used: **24**,  
**26, 26, 33, 34**  
*kind*, **177, 177**, used:  
*kind* (type), **177, 177**, used: **177**,  
**177**  
*kk2* (type), **397**, used: **401**  
*kkmode* (type), **397**, used: **397**,  
**397, 401**  
*kmatrix\_cuts*, **107**, used: **108**,  
**108, 119**  
*k\_matrix*, **234, 234, 234, 234**,  
**235, 235, 235, 235, 236**,  
**??, ??, 427, 428, ??, ??**,  
**??, ??, ??, 224, ??, 273**,  
**??**, used: **250, ??, ??, 428**  
*K\_Matrix\_Coeff*, **241, ??, ??**,  
**428**, used:  
*K\_Matrix\_Pole*, **241, ??, ??**,  
**428**, used:  
*k\_matrix\_quartic\_gauge*, **250**,  
**??, ??, 428**, used: **251**,  
**??, ??, 428**  
*L*, **236, 447, ??, ??, 498, 529**,  
**274, 297, 319, 333, 344**,  
**363, 374, 384, 411, 428**,  
**??, ??**, used: **237, 239**,  
**243, 245, 246, 246, 246**,  
**257, 257, 259, 447, 449**,  
**453, 455, 455, 456, 457**,  
**457, 459, 461, 462, 476**,  
**476, 479, ??, ??, ??, ??**,  
**??, ??, ??, ??, 498, 500**,  
**503, 503, 504, 505, 505**,  
**506, 507, 514, 529, 531**,  
**534, 535, 535, 537, 537**,  
**538, 538, 540, 540, 540**,  
**540, 549, 275, 277, 281**,  
**281, 281, 282, 282, 282**,  
**282, 291, 297, 299, 302**,  
**303, 303, 303, 304, 304**,  
**312, 319, 320, 323, 323**,  
**323, 324, 325, 325, 327**,  
**333, 335, 338, 338, 338**,  
**338, 338, 340, 344, 347**,  
**350, 350, 350, 351, 351**,  
**353, 363, 365, 368, 368**,  
**368, 368, 369, 370, 375**,  
**376, 379, 379, 379, 379**,  
**381, 385, 386, 389, 389**,  
**389, 390, 391, 411, 412**,  
**417, 417, 417, 418, 419**,  
**422, 428, 435, 436, 437**,  
**??, ??, ??, ??, ??, ??, ??**,  
**??, ??, ??, ??, ??, ??, ??**,  
**??**  
*label*, **693**, used: **693, 693, 694**,  
**695, 696, 696**  
*label* (field), **811, 806**, used: **811**,  
**812, 813, 813, 709**  
*Label*, **??, ??**, used: **??, ??, ??**  
*lagrangian\_file*, **576**, used: **576**,  
**576**  
*Lambda*, **501**, used:  
*last\_begin* (field), **732**, used: **733**,  
**734, 734, 734**  
*last\_non\_white*, **568**, used: **569**  
*last\_reset* (field), **732**, used: **733**,  
**734, 734**  
*LaTeX* (module), **578**, used:  
*latex\_section*, **813**, used: **814**,  
**815**  
*layout*, **819, 807**, used:  
*layout* (type), **818, 807**, used:  
**807, 808**  
*lcm*, **826**, used:  
*leaf*, **820, 808, 820, 805**, used:  
**46, 47**  
*Leaf*, **820, 808, 693**, used: **820**,  
**808, 810, 693, 693, 694**,  
**694, 695**

- leafs*, **808, 806**, used: **808, 812, 816, 123**  
*leafs\_and\_nodes*, **816**, used: **817**  
*leaf\_label*, **811, 811**, used: **811, 812**  
*leaf\_node*, **811**, used: **812, 812**  
*leaf\_or\_int\_node*, **812**, used: **812**  
*leaf\_to\_string*, **810**, used: **810**  
*left\_to\_right*, **818, 807**, used:  
*lepton*, **240, 454, ??, ??, 501, 532, 278, 300, 321, 336, 349, 367, 378, 388, 397, 414, 428, ??, ??**, used: **241, 454, ??, ??, 501, 532, 278, 300, 321, 336, 349, 367, 378, 388, 398, 407, 414, 428, ??, ??**  
*Lepton*, **397**, used: **397, 400, 403, 403, 404**  
*lep\_family*, **447**, used:  
*less*, **54, 58, 64, 51**, used: **694, 695**  
*less'*, **58**, used: **58, 58**  
*lesseq*, **54, 58, 63, 51**, used: **64, 694, 695, 74**  
*lesseq'*, **58**, used: **58, 58**  
*lhs*, **94, 100, 103, 121, 89**, used: **103, 121, 122, 124, 131, 132**  
*Light*, **397**, used: **398, 398, 398, 405, 405, 407**  
*Light2*, **397**, used: **398, 398, 402**  
*Light\_Heavy*, **397**, used: **398, 402**  
*Linalg* (module), **833, 833**, used: **818, 819**  
*line* (type), **81, 82**, used: **81, 82, 82**  
*Line* (sig), **81**, used: **82**  
*linear*, **828, 831, 825**, used: **831**  
*Linear* (sig), **828, 825**, used: **831, 825**  
*Lines*, **83, 86**, used: **83, 84**  
*list*, **796, 797, 798, 731, 777, 796, 730, 776**, used:  
*List* (module), **761, 755**, used: **??, ??, ??, ??, ??, ??, ??, ??, ??, ??, ??, ??, ??, ??, 765, 765, 765, 742, 742, 742, 743, 743, 743, 744, 744, 744, 744, 745, 745, 746, 746, 746, 746, 746, 746, 746, 747, 747, 749, 797, 797, 797, 800, 781, 784, 784, 784, 785, 785, 785, 785, 728, 735, 738, 836, 820, 820, 820, 826, 829, 829, 830, 830, 830, 830, 830, 831, 831, 832, 730, 731, 731, 777, 777, 777, 777, 777, 777, 777, 777, 777, 790, 790, 791, 791, 791, 792, 792, 792, 792, 792, 793, 793, 793, 793, 793, 793, 794, 794, 794, 794, 794, 794, 795, 795, 795, 795, 795, 795, 795, 795, 795, 796, 802, 803, 803, 808, 809, 809, 810, 810, 810, 811, 812, 812, 814, 814, 814, 815, 815, 815, 815, 816, 817, 817, 817, 818, 818, 819, 819, 10, 10, 11, 11, 12, 13, 15, 16, 16, 16, 16, 16, 16, 17, 17, 17, 21, 24, 24, 24, 24, 26, 26, 29, 29, 29, 31, 31, 32, 32, 32, 32, 32, 33, 33, 33, 33, 34, 34, 47, 47, 48, 55, 55, 56, 57, 60, 61, 62, 62, 692, 692, 694, 694, 695, 696, 696, 697, 697, 181, 181, 181, 182, 82, 82, 82, 83, 84, 84, 84, 84, 84, 84, 84, 84, 84, 85, 85, 86, 87, 220, 221, 221, 699, 699, 700, 700, 700, 700, 700, 700, 701, 701, 701, 701, 702, 702, 703, 703, 703, 704, 705, 565, 565, 565, 569, 569, 570, 570, 572, 574, 574, 575, 576, 69, 70, 74, 75, 75, 75, 75, 75, 76, 76, 77, 78, 78, 78, 78, 186, 189, 191, 203, 204, 204, 205, 205, 205, 206, 206, 207, 207, 211, 211, 211, 212, 213, 214, 214, 214, 214, 214, 214, 215, 215, 215, 216, 216, 216, 96, 101, 103, 103, 104, 108,**

110, 110, 110, 111, 111,  
111, 112, 112, 116, 116,  
117, 117, 118, 119, 119,  
119, 120, 120, 120, 121,  
122, 122, 122, 122, 122,  
123, 123, 123, 123, 124,  
124, 124, 124, 129, 129,  
129, 129, 130, 130, 131,  
131, 131, 132, 132, 133,  
133, 133, 133, 708, 709,  
709, 709, 710, 710, 710,  
710, 711, 711, 711, 712,  
712, 712, 712, 712, 712,  
712, 713, 714, 714, 715,  
715, 716, 716, 716, 716,  
716, 717, 237, 237, 237,  
237, 245, 245, 246, 246,  
246, 246, 246, 247, 248,  
249, 250, 256, 257, 257,  
258, 258, 269, 269, 269,  
269, 270, 271, 456, 456,  
459, 461, 461, 463, 465,  
466, 466, 466, 469, 470,  
470, 470, 471, 472, 473,  
473, 474, 474, 475, 475,  
476, 477, 478, 478, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, 496, 496, 497, 497,  
504, 505, 505, 506, 507,  
507, 507, 509, 510, 511,  
511, 511, 512, 512, 512,  
513, 513, 513, 527, 527,  
527, 527, 529, 536, 536,  
537, 538, 538, 538, 539,  
541, 541, 541, 541, 543,  
544, 545, 545, 545, 546,  
546, 547, 547, 547, 548,  
275, 275, 281, 281, 281,  
281, 281, 282, 282, 282,  
282, 283, 283, 283, 284,  
284, 285, 285, 285, 286,  
287, 287, 290, 290, 333,  
333, 338, 338, 338, 338,  
338, 338, 338, 338, 344,  
344, 350, 350, 350, 351,  
351, 351, 351, 351, 363,  
363, 368, 368, 368, 368,  
368, 369, 375, 375, 379,  
379, 379, 379, 380, 380,  
385, 385, 389, 389, 389,  
389, 390, 390, 398, 402,  
403, 404, 406, 407, 407,  
408, 411, 411, 416, 417,  
417, 417, 417, 419, 420,  
428, 435, 435, 436, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, 718, 718, 718, 719,  
720, 720, 720, 720, 721,  
721, 723  
*list2*, **777**, **776**, used: 11, 15, 123,  
131, 246, 456, 456, 459,  
461, 461, 463, 465, 466,  
466, 466, 469, 470, 470,  
470, 471, 472, 473, 473,  
474, 474, 474, 474, 475,  
475, 475, 475, 476, 477,  
478, 478, ??, ??, 504, 505,  
505, 507, 507, 507, 509,  
511, 511, 511, 512, 512,  
513, 513, 536, 536, 537,  
538, 538, 539, 541, 541,  
541, 543, 545, 545, 545,  
546, 547, 547, 548, 428  
*list3*, **777**, **776**, used: 12, 15,  
506, 507, 513, 537, 538,  
541, 547, 548  
*ListItem*, ??, ??, used: ??, ??, ??  
*lists*, **41**, **47**, **38**, used: 117, 120  
*Lists* (module), **55**, **53**, used: 66,  
53  
*ListSimpleMake* (module), ??,  
??, used:  
*ListsW* (module), **66**, **53**, used:  
*Littlest* (module), **274**, **272**,  
used: ??, ??  
*littlest\_gauge\_higgs4*, **287**, **308**,  
used:  
*Littlest\_Tpar* (module), **297**,  
**272**, used: ??  
*LMOM*, **137**, used:  
*load*, **576**, used: 576  
*Lodd*, **297**, used: 297  
*longest*, **769**, **771**, **772**, **774**,  
**767**, **769**, used:  
*longest'*, **771**, **774**, used: 771, 774  
*longest\_first*, **793**, used: 794  
*lookup\_ketset*, **119**, used: 120  
*loop\_cs*, **398**, used: 398, 407

*loop-gen*, **398**, used: 398, 402,  
403, 403, 403, 403, 404,  
404, 404, 404, 407  
*loop-iso*, **398**, used: 398, 402,  
403, 403, 403, 404, 404,  
404, 404, 407  
*loop-kk*, **398**, used: 398, 398,  
402, 403, 403, 404, 404,  
404, 404, 405, 405, 405,  
405  
*loop-kk2*, **398**, used: 398, 402,  
405, 405  
*Loop-Tags* (module), **97**, used:  
*lorentz*, **222, 571, 184, 207,**  
**225, 226, 228, 230, 238,**  
**266, 267, 448, ??, ??,**  
**499, 530, 275, 298, 319,**  
**334, 345, 364, 375, 385,**  
**399, 411, 428, ??, ??,**  
**719, 172**, used: 571, 184,  
207, 102, 126, 130, 131,  
266, 267  
*lorentz* (label), **223, 175**, used:  
575  
*lorentz* (type), **135**, used: 571,  
572, 135, 172, 175  
*lorentz-aux*, **237, ??, ??, 428,**  
used: 238, ??, ??, 428  
*lorentz-ordering*, **102**, used: 102  
*lower* (field), **813, 807**, used: 815  
*lower* (camllex regexpr), **70, 566,**  
used: 70, 566  
*LPAREN*, **??, ??, ??, ??**, used:  
??, ??, 70, 566  
*LPAREN* (camlyacc token), **71,**  
**567**, used: 71, 567  
*LQ*, **529**, used: 529, 531, 540,  
540, 540, 540, 540, 541,  
541, 541, 541, 541, 541,  
542, 542, 542, 542, 542,  
542, 549  
*LQino*, **529**, used: 529, 531, 539,  
539, 540, 540, 540, 540,  
540, 540, 541, 541, 541,  
541, 541, 542, 542, 542,  
549  
*lqino-lq-gg*, **541**, used: 548  
*lqino-lq-gg'*, **541**, used: 541  
*lqino-lq-neu*, **541**, used: 548  
*lqino-lq-neu'*, **541**, used: 541  
*lqino-lq-new2*, **541**, used: 548  
*lqino-lq-new2'*, **541**, used: 541  
*lq-gauge4*, **542**, used: 549  
*lq-gauge4'*, **542**, used: 542  
*lq-gg-gauge2*, **542**, used: 549  
*lq-gg-gauge2'*, **542**, used: 542  
*lq-neutr-Z*, **542**, used: 548  
*lq-phiggs*, **541**, used: 548  
*lq-phiggs'*, **541**, used: 541  
*lq-se-su*, **541**, used: 548  
*lq-se-su'*, **540**, used: 541  
*lq-shiggs*, **541**, used: 548  
*lq-shiggs'*, **541**, used: 541  
*lq-snu-sd*, **541**, used: 548  
*lq-snu-sd'*, **541**, used: 541  
*lu\_backsubstitute*, **836**, used: 836,  
836  
*lu\_decompose*, **836, 833**, used:  
*lu\_decompose-in-place*, **835**,  
used: 836, 836, 836  
*lu\_decompose-split*, **835**, used:  
836  
*L-CN*, **450**, used:  
*L-CNG*, **450**, used:  
*L-K1-L*, **344**, used: 344, 347,  
353  
*L-K1-R*, **344**, used: 344, 347,  
353  
*L-K2-L*, **344**, used: 344, 347,  
353  
*L-K2-R*, **344**, used: 344, 347,  
353  
*L-NC*, **450**, used:  
*L-NCH*, **450**, used:  
*M*, **236, 267, 450, ??, ??, 274,**  
**333, 344, 363, 374, 384,**  
**411, 428, ??, ??**, used:  
237, 239, 243, 245, 246,  
253, 254, 254, 254, 254,  
254, 254, 255, 255, 255,  
255, 256, 256, 256, 256,  
257, 257, 257, 257, 258,  
259, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, 274, 277, 281,  
290, 291, 333, 335, 337,  
340, 344, 347, 350, 353,

- 363, 365, 368, 369, 370,  
375, 376, 379, 379, 381,  
385, 386, 389, 390, 391,  
411, 412, 417, 417, 418,  
418, 418, 418, 418, 418,  
419, 422, 428, 432, 433,  
433, 433, 433, 433, 434,  
434, 434, 434, 435, 435,  
435, 435, 435, 436, 437,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??
- M* (module), **765, 828, 829**,  
**831, 816, 48, 571**, used:  
765, 765, 765, 828, 828,  
828, 828, 828, 828, 829,  
829, 829, 829, 829, 829,  
829, 830, 830, 830, 830,  
830, 830, 830, 830, 831,  
831, 831, 831, 831, 831,  
831, 832, 816, 816, 817,  
817, 48, 571, 575, 576
- M1*, **446, 497, 528**, used: 447,  
456, 456, 459, 461, 461,  
463, 465, 466, 466, 466,  
469, 469, 470, 470, 470,  
471, 471, 472, 472, 473,  
473, 474, 474, 474, 474,  
475, 475, 475, 475, 476,  
477, 478, 479, 498, 504,  
505, 506, 507, 507, 507,  
508, 511, 511, 511, 512,  
512, 512, 513, 513, 513,  
514, 529, 536, 536, 538,  
538, 538, 539, 539, 539,  
540, 540, 540, 540, 540,  
540, 540, 541, 541, 541,  
541, 541, 541, 541, 542,  
542, 542, 545, 545, 545,  
546, 546, 547, 547, 547,  
548, 549
- M1* (module), **44**, used: 44, 44,  
44, 44
- M2*, **446, 497, 528**, used: 447,  
456, 456, 459, 461, 461,  
463, 465, 466, 466, 466,  
469, 469, 470, 470, 470,  
471, 471, 472, 472, 473,  
473, 474, 474, 474, 474,  
475, 475, 475, 475, 476,  
477, 478, 479, 498, 504,
- 505, 507, 507, 507, 508,  
511, 511, 511, 512, 512,  
512, 513, 513, 513, 514,  
529, 536, 536, 538, 538,  
539, 539, 539, 540, 540,  
540, 540, 540, 540, 540,  
540, 540, 540, 540, 541,  
541, 541, 541, 541, 541,  
541, 542, 542, 542, 545,  
545, 545, 546, 546, 547,  
547, 547, 548, 549
- M2* (module), **44**, used: 44, 44,  
44
- main*, ??, **707, 713**, ??, **707**,  
used: 75, 718, ??, ??, ??,  
718, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, 723
- main* (camlyacc non-terminal),  
**71**, used: 71
- Majorana*, **125, 135**, used: 125,  
126, 448, 499, 530, 364,  
719
- Maj\_Ghost*, **135**, used:
- make*, **826, 826, 823**, used: ??,  
??, 749, 798, 798, 834,  
835, 826, 830, 830, 574,  
124, 709, 240, 453, ??, ??,  
500, 531, 277, 300, 321,  
335, 348, 366, 377, 387,  
400, 413, 428, ??, ??
- Make* (module), **765, 782, 784**,  
**737, 770, 49, 693, 699**,  
**74, 210, 125, 708, 765**,  
**780, 784, 736, 768, 39**,  
**691, 698, 73, 210, 707**,  
used: ??, ??, 765, 765,  
746, 781, 784, 784, 772,  
730, 28, 44, 44, 44, 45, 48,  
219, 220, 221, 699, 700,  
702, 78, 186, 214, 215,  
215, 215, 216, 95, 103,  
103, 104, 105, 111, 112,  
116, 118, 119, 119, 123,  
124, 125, 127, 127, 127,  
127, 128, 129, 129, 131,

- 131, 708, 708, 718, ??, ??,  
??, 718, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, 723, 91
- MakeMap* (module), 772, 768,  
used:
- MakePoly* (module), 773, 769,  
used:
- Maker* (sig), 95, 179, 91, used:  
699, 128, 128, 708, 179,  
698, 91, 91, 91, 91, 93,  
707, 578, 578, 578
- make\_external\_dag*, 111, used:  
111
- Make\_Linear* (module), 831,  
825, used:
- Make\_Ring* (module), 829, 825,  
used:
- map*, 755, 760, 763, 769, 769,  
771, 772, 774, 827, 828,  
829, 831, 810, 9, 11, 12,  
14, 16, 41, 46, 692, 695,  
754, 767, 768, 768, 824,  
825, 806, 6, 38, 691,  
used: ??, 765, 760, 763,  
744, 745, 746, 746, 747,  
747, 749, 797, 800, 784,  
784, 785, 728, 771, 774,  
836, 820, 820, 828, 829,  
830, 831, 731, 731, 777,  
777, 792, 793, 793, 793,  
793, 793, 794, 794, 794,  
794, 795, 795, 795, 795,  
803, 809, 809, 810, 810,  
810, 811, 812, 816, 817,  
818, 819, 10, 10, 16, 17,  
17, 21, 24, 24, 26, 26, 32,  
33, 33, 33, 34, 47, 55, 60,  
62, 695, 696, 697, 697,  
697, 83, 84, 84, 84, 84, 84,  
84, 84, 84, 86, 699, 700,  
700, 701, 701, 701, 701,  
703, 565, 570, 575, 576,  
69, 70, 74, 75, 75, 75, 75,  
75, 78, 78, 78, 186, 189,  
191, 203, 204, 206, 206,  
207, 211, 213, 214, 214,  
214, 215, 215, 216, 216,  
101, 103, 108, 108, 110,  
112, 112, 112, 116, 116,  
117, 119, 119, 119, 120,  
122, 122, 123, 123, 123,  
123, 124, 124, 129, 129,  
129, 130, 131, 131, 133,  
133, 708, 709, 709, 710,  
710, 710, 710, 711, 711,  
711, 712, 712, 712, 712,  
712, 713, 714, 714, 715,  
716, 717, 237, 237, 237,  
245, 245, 246, 246, 246,  
246, 246, 247, 248, 249,  
250, 256, 257, 257, 258,  
258, 269, 269, 269, 269,  
270, 271, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??,  
496, 497, 506, 509, 510,  
512, 527, 527, 529, 538,  
543, 544, 546, 275, 275,  
281, 281, 281, 281, 281,  
282, 282, 282, 282, 283,  
283, 283, 284, 284, 285,  
285, 285, 286, 287, 287,  
290, 290, 333, 333, 338,  
338, 338, 338, 338, 338,  
338, 338, 344, 344, 350,  
350, 350, 351, 351, 351,  
351, 351, 363, 363, 368,  
368, 368, 368, 368, 369,  
375, 375, 379, 379, 379,  
379, 380, 380, 385, 385,  
389, 389, 389, 389, 390,  
390, 398, 402, 406, 407,  
407, 408, 411, 411, 416,  
417, 417, 417, 417, 419,  
420, 428, 435, 435, 436,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, 718, 718, 718,  
719, 720, 720, 720, 720,  
721, 721, 723
- map2*, 9, 11, 12, 14, 16, 6, used:  
747, 777, 818, 16, 181,  
182, 700, 700, 214, 108
- map1*, ??, 755, 760, 764, 744,  
769, 769, 771, 772, 774,  
754, 741, 767, 768, 768,



- used: ??, 760, 764, 771, 774, 819, 131
- map<sup>i</sup>*, 771, 774, used: 771, 774
- mappable*, 702, used: 702
- Mappable* (module), 702, used: 702, 702
- map\_amplitude\_wfs*, 116, used:
- map\_decay*, 692, 693, 691, used: 693, 694, 695
- map\_nodes*, 41, 46, 37, used:
- Map-S* (sig), 769, 768, used: 770, 772, 768
- mask*, 61, used: 61, 62, 65, 66, 66
- mask2*, 61, used:
- mask21*, 61, used: 61
- mask5*, 61, used: 61
- maskb*, 61, used: 61
- maskd*, 61, used: 61
- maskr*, 61, used: 61
- mask\_in*, 64, used: 64, 64, 64, 64, 64
- mask\_in1*, 64, used: 64, 64, 64, 64
- mask\_in2*, 64, used: 64
- Mass*, 241, ??, ??, 278, 300, 321, 337, 349, 367, 378, 388, 414, 428, ??, ??, used: 243, 244, ??, ??, 428
- massive*, 177, 178, used:
- massive* (type), 177, 177, used: 177, 177, 177, 178
- Massive*, 177, 177, used:
- Massive\_Vector*, 135, used: 238, 448, ??, ??, 499, 530, 275, 298, 319, 334, 345, 364, 375, 385, 399, 411, 428, ??, ??
- massless*, 177, 178, used:
- massless* (type), 177, 177, used: 177, 177
- Massless*, 177, 177, used:
- mass\_symbol*, 222, 571, 188, 207, 226, 227, 229, 233, 263, 267, 267, 487, ??, ??, 522, 560, 294, 316, 331, 343, 362, 373, 383, 394, 409, 425, 441, ??, ??, 723, 175, used: 571, 188, 207, 267, 267
- mass\_symbol* (label), 223, 175, used: 575
- matching*, 55, used:
- matmul*, 833, 833, used:
- matmulv*, 834, 833, used: 818
- Matter*, 208, 237, 267, ??, ??, 274, 333, 344, 363, 375, 385, 411, 428, ??, ??, 177, used: 237, 267, ??, ??, 274, 333, 344, 363, 375, 385, 411, 428, ??, ??
- matter\_field*, 208, 237, 267, ??, ??, 274, 333, 344, 363, 375, 385, 411, 428, ??, ??, 177, used: 237, 267, 271, 271, ??, ??, 275, 275, 333, 344, 363, 375, 385, 411, 428, ??, ??
- matter\_field* (type), 208, 236, 267, ??, ??, 274, 333, 344, 363, 374, 384, 411, 428, ??, ??, 176, used: 208, 208, 236, 237, 267, ??, ??, 274, 274, 333, 333, 344, 344, 363, 363, 374, 375, 384, 385, 411, 411, 428, ??, ??, ??, ??, 177, 177
- maxabsval*, 834, used: 835
- max\_arity*, 9, 10, 12, 13, 15, 16, 17, 26, 32, 6, 8, used: 16, 16, 17, 17, 24, 33
- max\_degree*, 222, 571, 186, 204, 207, 225, 227, 229, 232, 259, 267, 268, 479, ??, ??, 514, 549, 291, 312, 327, 340, 353, 370, 381, 391, 402, 422, 437, ??, ??, 721, 174, used: 571, 186, 204, 207, 105, 117, 268
- max\_degree* (label), 223, 175, used:
- max\_generations*, 267, used: 267, 269
- max\_subtree*, 20, 24, 24, 26, 26, 33, 34, 18, used: 26, 26, 111
- maybe\_backtrace*, ??, used: ??, ??

- Maybe-Graded* (module), **45**,  
 used: **48, 49**
- maybe\_read*, **737, 739, 736**,  
 used: **105**
- mem*, **755, 758, 763, 769, 769**,  
**771, 772, 773, 43, 44**,  
**48, 754, 767, 768, 768**,  
 used: **??, 758, 763, 786**,  
**771, 773, 816, 44, 45, 45**,  
**46, 48, 220, 221, 702, 76**,  
**77, 78, 123, 132, 710, 710**
- merge*, **757, 730, 698, 701, 730**,  
**698**, used: **757, 758, 758**,  
**758, 758, 716**
- merge\_overlapping*, **214**, used:  
**214, 215**
- merge\_partitions*, **215**, used: **215**
- merge\_sets*, **700**, used: **700**
- mgm*, **245, ??, ??, 281, 337**,  
**350, 368, 379, 389, 417**,  
**428, ??, ??**, used: **245**,  
**245, 246, 246, 246, 246**,  
**??, ??, 281, 281, 281, 281**,  
**281, 282, 282, 338, 338**,  
**338, 338, 350, 350, 350**,  
**351, 368, 368, 368, 379**,  
**379, 379, 379, 389, 389**,  
**389, 389, 417, 417, 417**,  
**417, 428, ??, ??, ??, ??**,  
**??, ??, ??, ??, ??**
- mhm*, **281**, used: **282, 282, 283**
- min*, **28**, used: **743, 568**
- minimal\_fusion\_tower*, **111**,  
 used: **116**
- MINUS*, **??, ??**, used: **??, 566**
- MINUS* (camlyacc token), **567**,  
 used: **567, 567**
- minus\_gauge4*, **248, 463, ??, ??**,  
**508, 542, 284, 305, 326**,  
**338, 351, 369, 380, 390**,  
**405, 420, 428, ??, ??**,  
 used: **248, 463, ??, ??**,  
**508, 542, 284, 284, 305**,  
**305, 326, 338, 351, 369**,  
**380, 390, 405, 405, 405**,  
**420, 428, ??, ??**
- min\_max\_rank*, **43, 44, 45, 48**,  
**49, 40**, used: **45, 110**
- mismatch*, **55, 61**, used: **55, 56**,  
**56, 57, 57, 57, 58, 58, 60**,  
**62, 62, 62, 63, 63, 63, 64**
- Mismatch*, **84**, used: **738, 55, 61**,  
**85, 85**
- Mismatch* (exn), **737, 738, 54**,  
**55, 61, 127, 128, 736**,  
**51, 91**, used:
- Mismatched\_arity* (exn), **10, 11**,  
**12, 14, 16, 8**, used:
- Miss*, **737, 738, 736**, used: **739**
- Mixed23* (module), **13, 26, 127**,  
**8, 19, 91**, used: **26, 127**,  
**??, ??, 718, ??, ??, ??**,  
**??, ??, ??, ??, ??, ??, ??**,  
**??, ??, ??, ??, ??, ??, ??**,  
**??, ??, ??, ??, ??, ??, ??**,  
**??, ??, ??, ??, ??, ??, ??**,  
**??, ??, ??, ??, ??, ??, ??**,  
**??, 723, 19**
- Mixed23* (sig), **13, 8**, used: **8**
- Mixed23\_Majorana* (module),  
**127, 91**, used: **??, ??, ??**,  
**??, ??, ??, ??, ??, ??**
- mixed\_fold\_left*, **111**, used: **111**
- mk\_and*, **69, 68**, used: **??, 75, 71**
- mk\_any\_flavor*, **69, 68**, used: **??**,  
**71**
- mk\_false*, **69, 68**, used:
- mk\_gauss*, **69, 68**, used: **??, 71**
- mk\_gauss\_not*, **69, 68**, used: **??**,  
**71**
- mk\_off\_shell*, **69, 68**, used: **??**,  
**71**
- mk\_off\_shell\_not*, **69, 68**, used:  
**??, 71**
- mk\_on\_shell*, **69, 68**, used: **??**,  
**71**
- mk\_on\_shell\_not*, **69, 68**, used:  
**??, 71**
- mk\_or*, **69, 68**, used: **??, 71**
- mk\_true*, **69, 68**, used: **??, 71**
- Model* (module), **571, 172, 568**,  
 used: **699, 74, 183, 207**,  
**210, 95, 95, 95, 97, 98**,  
**101, 125, 128, 128, 708**,  
**267, 179, 217, 698, 568**,  
**73, 183, 183, 210, 91, 93**,  
**93, 707, 224, 224, 224**,  
**224, 444, ??, 495, 525**,  
**272, 272, 273, ??**
- Modellib\_BSM* (module), **273**,  
**272**, used: **??, ??, ??, ??**,

- ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??  
*Modellib\_MSSM* (module), **444**,  
**443**, used: ??, ??, ??, ??  
*Modellib\_NMSSM* (module),  
**495**, **495**, used: ??, ??,  
 ??  
*Modellib\_NoH* (module), ??, ??,  
 used: ??, ??  
*Modellib\_PSSSM* (module), **526**,  
**525**, used: ??  
*Modellib\_SM* (module), **224**,  
**224**, used: **718**, ??, ??,  
 ??, **718**, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??  
*Modellib\_Zprime* (module), ??,  
 ??, used: ??, ??  
*Modeltools* (module), **218**, **217**,  
 used: **571**, **575**, **225**, **226**,  
**228**, **231**, **245**, **266**, **269**,  
**455**, ??, ??, **503**, **534**, **280**,  
**302**, **323**, **337**, **350**, **368**,  
**379**, **389**, **406**, **416**, **428**,  
 ??, ??, **720**  
*modname*, **396**, used: **398**, **400**,  
**402**, **408**  
*mod\_float2*, **732**, used: **733**  
*mom*, **245**, ??, ??, **337**, **350**,  
**368**, **428**, ??, used: **256**,  
**257**, **257**, **258**, **258**, ??, ??,  
 ??, ??, ??, ??, ??, ??,  
**338**, **338**, **351**, **351**, **368**,  
**435**, **435**, **436**  
*MOM*, **137**, used:  
*MOM5*, **137**, used:  
*Momenta*, **178**, used: **713**  
*momentum*, **94**, **100**, **101**, **121**,  
**88**, used: **699**, **108**, **121**,  
**717**  
*momentum* (field), **100**, **101**,  
 used: **101**, **101**, **102**, **104**,  
**108**, **108**, **109**, **112**, **117**,  
**117**, **117**, **118**, **119**, **123**,  
**123**, **124**, **124**, **124**  
*momentum* (type), **692**, **693**,  
**691**, used: **692**, **693**, **694**,  
**695**, **691**, **691**, **691**  
*momentum* (camlyacc  
 non-terminal), **72**, used:  
**72**  
*Momentum*, **566**, used: **566**  
*Momentum* (module), **54**, **50**,  
 used: **693**, **699**, **74**, **95**, **97**,  
**98**, **101**, **128**, **128**, **707**,  
**707**, **717**, **179**, **691**, **698**,  
**73**, **91**, **93**, **93**, **707**  
*momentum\_list*, **94**, **100**, **101**,  
**121**, **88**, used: **121**, **709**,  
**709**  
*momentum\_list* (camlyacc  
 non-terminal), **72**, used:  
**71**, **72**  
*momentum\_to\_string*, **75**, used:  
**75**  
*momentum\_to\_TeX*, **712**, used:  
**712**, **712**, **712**, **712**  
*MOML*, **137**, used:  
*MOMR*, **137**, used:  
*Mono* (sig), **9**, **6**, used: **10**, **12**, **8**,  
**8**  
*MSSM* (module), **445**, **444**,  
 used: ??, ??, ??, ??  
*MSSM\_flags* (sig), **444**, **443**,  
 used: **444**, **444**, **445**, **445**,  
**445**, **445**, **445**, **444**  
*MSSM\_goldstone* (module), **444**,  
**444**, used:  
*MSSM\_Grav* (module), **445**,  
**444**, used: ??  
*MSSM\_Hgg* (module), **445**, **444**,  
 used: ??  
*MSSM\_no\_4* (module), **445**,  
**444**, used: ??  
*MSSM\_no\_4\_ckm* (module),  
**445**, **444**, used: ??  
*MSSM\_no\_goldstone* (module),  
**444**, **444**, used:  
*Mu*, **450**, **501**, used:  
*mul*, **826**, **826**, **827**, **828**,  
**830**, **823**, **824**, **824**,  
 used: **829**, **830**, **830**, **830**,  
**830**, **830**, **831**  
*mul1*, **828**, used: **828**, **829**, **829**  
*MULT*, ??, ??, used: ??, **566**  
*MULT* (camlyacc token), **567**,  
 used: **567**, **567**  
*Multi* (module), **128**, **93**, used:  
**708**, **179**  
*Multi* (sig), **127**, **91**, used: **128**,  
**93**

- multinomial*, **790, 787**, used:  
*multiplicity*, **29, 127, 129, 92**,  
     used: **29, 30, 30**  
*multiplicity* (field), **129**, used:  
     **129, 134**  
*multiply*, **746, 565, 741, 564**,  
     used: **565, ??, 567**  
*multi\_choose*, **794, 789**, used:  
*Multi\_Maker* (sig), **128, 93**,  
     used: **93**  
*multi\_split*, **793, 788**, used: **793**,  
     **794**  
*multi\_split'*, **792**, used: **792, 793**,  
     **793**  
*mult\_vertex*, **190**, used: **192, 193**,  
     **194, 196, 196, 197, 198**,  
     **199, 199, 200, 200, 202**  
*mult\_vertex3*, **188**, used: **190**  
*mult\_vertex4*, **189**, used: **190**  
*mult\_vertexn*, **190**, used: **190**  
*Muon*, **227**, used: **228, 228, 229**,  
     **229**  
*Mutable* (module), **222, 217**,  
     used: **571**  
*Mutable* (sig), **175**, used: **217**  
*M\_N*, **450**, used:  
*M\_SF*, **450**, used:  
*M\_U*, **450**, used:  
*M\_V*, **450**, used:  
*n* (field), **695**, used:  
*N*, **236, 447, ??, ??, 498, 529**,  
     **274, 297, 319, 333, 344**,  
     **363, 374, 384, 411, 428**,  
     **??, ??**, used: **237, 239**,  
     **243, 246, 246, 257, 257**,  
     **259, 447, 449, 453, 455**,  
     **456, 457, 457, 459, 461**,  
     **462, 476, 476, 479, ??, ??**,  
     **??, ??, ??, ??, ??, ??**,  
     **498, 500, 503, 504, 505**,  
     **506, 507, 514, 529, 531**,  
     **535, 535, 537, 538, 538**,  
     **540, 540, 540, 540, 549**,  
     **275, 277, 281, 281, 282**,  
     **282, 282, 291, 297, 299**,  
     **303, 303, 303, 304, 312**,  
     **319, 320, 323, 323, 324**,  
     **325, 327, 333, 335, 338**,  
     **338, 338, 340, 344, 347**,  
     **350, 350, 351, 353, 363**,  
     **365, 368, 368, 370, 375**,  
     **376, 379, 379, 381, 385**,  
     **386, 389, 389, 391, 411**,  
     **412, 417, 417, 422, 428**,  
     **435, 436, 437, ??, ??, ??**,  
     **??, ??, ??, ??, ??, ??, ??**,  
     **??**  
*N1*, **446, 497, 528**, used: **447**,  
     **459, 459, 459, 462, 463**,  
     **476, 477, 478, 479, 498**,  
     **506, 507, 513, 514, 529**,  
     **538, 538, 548, 549**  
*N10*, **528**, used: **529, 549**  
*N11*, **528**, used: **529, 549**  
*N2*, **446, 497, 528**, used: **447**,  
     **459, 459, 459, 462, 463**,  
     **476, 477, 478, 479, 498**,  
     **506, 507, 513, 514, 529**,  
     **538, 538, 548, 549**  
*N3*, **446, 497, 528**, used: **447**,  
     **459, 459, 459, 462, 463**,  
     **476, 477, 478, 479, 498**,  
     **506, 507, 513, 514, 529**,  
     **538, 538, 548, 549**  
*N4*, **446, 497, 528**, used: **447**,  
     **459, 459, 459, 462, 463**,  
     **476, 477, 478, 479, 498**,  
     **506, 507, 513, 514, 529**,  
     **538, 538, 548, 549**  
*N5*, **497, 528**, used: **498, 506**,  
     **507, 513, 514, 529, 538**,  
     **538, 548, 549**  
*N6*, **528**, used: **529, 549**  
*N7*, **528**, used: **529, 549**  
*N8*, **528**, used: **529, 549**  
*N9*, **528**, used: **529, 549**  
*name*, **727, 726**, used: **728, 105**,  
     **105, 267**  
*name* (field), **727**, used: **727**  
*Nary* (module), **15, 24, 127, 8**,  
     **19, 91**, used: **17, 24, 26**,  
     **32, 33, 127, 127, 19, 20**  
*Nary* (sig), **15, 8**, used: **8, 8**  
*Nary4* (module), **26**, used: **26, 26**  
*Nary\_Majorana* (module), **127**,  
     **91**, used:  
*nc*, **186, 207, 718, 178, 178**,  
     used: **192, 193, 196, 207**,  
     **719**

- nc\_coupling*, **245**, ??, ??, **280**,  
**302, 322, 337, 350, 367**,  
**378, 389, 416, 428**, ??,  
used: **245**, ??, ??, **280**,  
**302, 322, 337, 350, 368**,  
**379, 389, 416, 428**, ??
- nc\_value*, **186**, used: **186**
- neg*, **826, 826, 827, 830, 830**,  
**54, 56, 62, 565, 823**,  
**824, 51, 564**, used: **830**,  
**831, 832, 56, 57, 57, 59**,  
**62, 62, 63, 64, 696**, ??, **74**,  
**76, 77, 78, 123, 567**
- Neg*, **397, 166**, used: **244, 245**,  
**245, ??, ??, 280, 280, 302**,  
**302, 322, 322, 337, 337**,  
**350, 350, 367, 368, 378**,  
**379, 389, 389, 398, 400**,  
**403, 403, 403, 403, 404**,  
**404, 404, 404, 404, 405**,  
**405, 405, 405, 405, 407**,  
**408, 416, 416, 428**, ??, ??
- neg'*, **56**, used: **56, 56**
- negate*, **565**, used: **565, 565, 565**
- Negative* (exn), **54, 57, 62, 51**,  
used:
- Negative\_EW\_order* (exn), **98**,  
used:
- Negative\_QCD\_EW\_orders* (exn),  
**98**, used:
- Negative\_QCD\_order* (exn), **98**,  
used:
- neu* (type), **446, 497, 528**, used:  
**447, 450, 498, 501, 529**,  
**532**
- Neutralino*, **447, 498, 529**, used:  
**447, 449, 456, 457, 458**,  
**458, 459, 459, 459, 462**,  
**462, 476, 479, 498, 500**,  
**504, 505, 506, 506, 506**,  
**514, 529, 531, 535, 536**,  
**537, 537, 538, 541, 541**,  
**549**
- neutral\_currents*, **246, 455**, ??,  
??, **503, 535, 281, 303**,  
**323, 338, 350, 368, 379**,  
**389, 417, 428**, ??, ??,  
used: **258, 477**, ??, ??,  
**513, 548, 291, 312, 327**,  
**340, 353, 370, 380, 391**,  
**422, 436**, ??, ??
- neutral\_currents'*, ??, used: ??
- neutral\_heavy\_currents*, **281**,  
**303, 324**, ??, used: **291**,  
**312, 327**, ??
- neutral\_sfermion\_currents*, **456**,  
**505, 536**, used: **477, 513**,  
**548**
- neutral\_sfermion\_currents'*, **456**,  
**505, 536**, used: **456, 505**,  
**536**
- neutral\_up\_type\_currents*, ??,  
used: ??
- neutral\_Z*, **505, 536**, used: **513**,  
**548**
- neutral\_Z\_1*, **457**, used: **477**
- neutral\_Z\_2*, **457**, used: **477**
- neutr\_lqino\_current*, **542**, used:  
**548**
- NH*, **319**, used: **319, 320, 323**,  
**324, 327**
- nl*, **678**, used: **678**
- nlist*, **529**, used: **529, 548**
- NMSSM* (module), **495, 495**,  
used: ??
- NMSSM\_CKM* (module), **496**,  
**495**, used: ??
- NMSSM\_flags* (sig), **495, 495**,  
used: **495, 496, 496, 496**,  
**495**
- NMSSM\_func* (module), **496**,  
**495**, used: ??, ??, ??
- NMSSM\_Hgg* (module), **496**,  
**495**, used: ??
- Nodd*, **297**, used: **297**
- node*, **808, 806**, used:
- node* (field), **816**, used: **816**
- node* (type), ??, **41, 41, 42, 42**,  
**43, 45, 109**, ??, **36, 37**,  
**40**, used: ??, **41, 41, 42**,  
**42, 42, 45, 48, 100**, ??,  
??, **36, 36, 36, 37, 37, 37**,  
**37, 37, 37, 37, 38, 38, 38**,  
**38, 38, 39, 39, 39, 39, 40**,  
**40, 40, 40**
- Node*, **755, 820, 808**, used: **756**,  
**756, 756, 758, 759, 760**,  
**760, 761, 820, 808, 809**,  
**809, 809, 809, 810, 811**

*nodes*, **808, 806**, used: **808, 816**

*Nodes* (module), **41, 42, 42, 43,**  
**109, 36, 40**, used: **41, 42,**  
**42, 43, 45, 45, 45, 47,**  
**48, 109, 36, 40, 40, 40**

*node\_to\_string*, **810**, used: **810**

*node\_with\_tension* (type), **816**,  
used:

*NoH* (module), ??, ??, used: ??

*NoH\_flags* (sig), ??, ??, used:  
??, ??, ??, ??, ??

*NoH\_k\_matrix* (module), ??, ??,  
used: ??, ??

*NOT*, ??, ??, used: ??, **70**

*NOT* (camlyacc token), **71**, used:  
**71, 71**

*Not\_invertible* (exn), **816**, used:

*Not\_Square* (exn), **833, 833**,  
used:

*no\_cascades*, **73, 76, 72**, used:  
**79, 717**

*No\_Tags* (module), **97**, used:

*No\_termination* (exn), **10, 11,**  
**15, 17, 8**, used:

*null*, **826, 826, 827, 828, 829,**  
**831, 823, 824, 825**, used:  
**830, 830, 830, 830, 830,**  
**830, 831, 831, 831, 181**

*Null* (module), **181, 180**, used:  
**222, 225, 226, 720, 224**

*null\_coupling*, **97, 97, 97, 98,**  
**93**, used: **108, 112**

*null\_wf*, **97, 97, 97, 98, 93**,  
used: **101, 108, 108, 112**

*num* (field), **83, 84, 80**, used: **86**

*num\_ext*, **29**, used: **29**

*num\_prop*, **29**, used: **29**

*N\_K1*, **344**, used: **344, 347, 353**

*N\_K2*, **344**, used: **344, 347, 353**

*O*, **236, 267, ??, ??, 274, 333,**  
**344, 363, 374, 384, 411,**  
**428, ??, ??**, used: **237,**  
**239, 239, 245, 246, 251,**  
**251, 251, 251, 252, 253,**  
**253, 255, 255, 255, 256,**  
**256, 256, 256, 257, 257,**  
**257, 257, 258, 259, 267,**  
**269, ??, ??, ??, ??, ??,**  
**??, ??, ??, ??, ??, ??, ??,**  
**??, ??, ??, ??, ??, ??, ??**

[illegible]

??, ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, **723**  
*Omega\_2HDM* (module), ??, used:  
*Omega\_2HDM\_CKM* (module), ??, used:  
*Omega\_2HDM\_CKM\_VM* (module), ??, used:  
*Omega\_2HDM\_VM* (module), ??, used:  
*Omega\_AltH* (module), ??, used:  
*Omega\_GravTest* (module), ??, used:  
*Omega\_HSExt* (module), ??, used:  
*Omega\_HSExt\_VM* (module), ??, used:  
*Omega\_Littlest* (module), ??, used:  
*Omega\_Littlest\_Eta* (module), ??, used:  
*Omega\_Littlest\_Tpar* (module), ??, used:  
*Omega\_MSSM* (module), ??, used:  
*Omega\_MSSM\_CKM* (module), ??, used:  
*Omega\_MSSM\_Grav* (module), ??, used:  
*Omega\_MSSM\_Hgg* (module), ??, used:  
*Omega\_NMSSM* (module), ??, used:  
*Omega\_NMSSM\_CKM* (module), ??, used:  
*Omega\_NMSSM\_Hgg* (module), ??, used:  
*Omega\_NoH\_rx* (module), ??, used:  
*Omega\_PSSSM* (module), ??, used:  
*Omega\_QCD* (module), ??, used:  
*Omega\_QCD\_VM* (module), ??, used:

- Omega-QED* (module), **718**,  
 used:  
*Omega-QED\_VM* (module), **??**,  
 used:  
*Omega-Simplest* (module), **??**,  
 used:  
*Omega-Simplest-univ* (module),  
**??**, used:  
*Omega-SM* (module), **718**, used:  
  
*Omega-SM\_ac* (module), **??**,  
 used:  
*Omega-SM\_ac-CKM* (module),  
**??**, used:  
*Omega-SM-CKM* (module), **??**,  
 used:  
*Omega-SM-CKM\_VM* (module),  
**??**, used:  
*Omega-SM\_Higgs* (module), **??**,  
 used:  
*Omega-SM\_Higgs\_VM* (module),  
**??**, used:  
*Omega-SM\_rr* (module), **??**,  
 used:  
*Omega-SM\_top* (module), **??**,  
 used:  
*Omega-SM\_top\_anom* (module),  
**??**, used:  
*Omega-SM\_tt\_threshold* (module),  
**??**, used:  
*Omega-SM\_VM* (module), **??**,  
 used:  
*Omega-SSC* (module), **??**, used:  
*Omega-SYM* (module), **718**,  
 used:  
*Omega-Template* (module), **??**,  
 used:  
*Omega-Threesl* (module), **??**,  
 used:  
*Omega-Threesl\_nohf* (module),  
**??**, used:  
*Omega-UED* (module), **??**, used:  
  
*Omega-Xdim* (module), **??**, used:  
  
*Omega-Zprime* (module), **??**,  
 used:  
*Omega-Zprime\_VM* (module),  
**??**, used:  
  
*one*, **829, 27, 27, 19**, used: **829**,  
**830, 29, 30, 32, 32**  
*one\_compatible*, **74**, used: **74, 76**  
*Only\_Insertion*, **137**, used: **238**,  
**448, ??, ??, 276, 298, 320**,  
**334, 346, 364, 376, 386**,  
**412, 428, ??, ??**  
*ONHELL*, **??, ??**, used: **??, 70**  
*ONHELL* (camlyacc token), **71**,  
 used: **71**  
*on\_shell*, **73, 76, 94, 101, 103**,  
**122, 73, 90**, used: **117**,  
**122**  
*on\_shell* (field), **76, 100, 103**,  
 used: **76, 76, 79, 103, 116**,  
**117, 121**  
*On\_shell*, **69, 74, 68**, used: **69**,  
**75**  
*On\_shell\_not*, **69, 74, 68**, used:  
**69, 75**  
*openmp*, **729, 729**, used:  
*open\_file*, **733, 732**, used:  
*Open\_File*, **732**, used: **733**  
*open\_in\_bin\_first*, **738**, used:  
**738**  
*Open\_line* (exn), **82, 82**, used:  
*open\_out\_bin\_last*, **738**, used:  
**738**  
*options*, **222, 576, 184, 207, 94**,  
**98, 127, 128, 225, 226**,  
**227, 230, 236, 266, 267**,  
**445, ??, ??, 496, 526**,  
**274, 297, 319, 333, 344**,  
**363, 374, 384, 396, 410**,  
**428, ??, ??, 718, 175**,  
**178, 88, 91**, used: **184**,  
**207, 128, 713, 266, 267**  
*Options* (module), **730, 730**,  
 used: **222, 576, 94, 98**,  
**127, 128, 713, 225, 226**,  
**227, 230, 236, 445, ??, ??**,  
**496, 526, 274, 297, 319**,  
**333, 344, 363, 374, 384**,  
**396, 410, 428, ??, ??, 718**,  
**175, 178, 88, 91**  
*opt\_array\_to\_list*, **708**, used: **708**  
*Or*, **69, 68**, used: **69**  
*OR*, **??, ??**, used: **??, 70**  
*OR* (camlyacc token), **71**, used:  
**71, 71**



- Ord* (sig), **40, 35**, used: **41, 42, 42, 42, 43, 43, 43, 36, 36, 39, 39**
- ordered\_multi\_choose*, **794, 789**, used:
- ordered\_multi\_split*, **793, 788**, used: **794**
- ordered\_partitions*, **793, 788**, used:
- ordered\_partitions'*, **793**, used: **793, 793**
- ordered\_split*, **791, 788**, used: **792, 793**
- ordered\_split\_unsafe*, **791**, used: **791, 792**
- Ordered\_Type* (sig), **784, 783**, used: **784, 784**
- orders*, **225, 226, 228, 230, 242, 453, ??, ??, 503, 534, 280, 302, 322, 337, 350, 367, 378, 388, 402, 416, 428, ??, ??, 719**, used:
- orders* (type), **225, 226, 228, 230, 242, 453, ??, ??, 502, 534, 280, 302, 322, 337, 349, 367, 378, 388, 402, 416, 428, ??, ??, 719**, used:
- order\_flavor*, **102**, used: **102**
- order\_spin\_table*, **130**, used: **130**
- order\_spin\_table1*, **130**, used: **130, 130**
- Order\_Tags* (module), **98**, used: **125**
- order\_wf*, **100, 102**, used: **103, 103, 109, 111, 119, 123**
- other*, **208, 237, 267, ??, ??, 274, 333, 344, 363, 375, 385, 411, 428, ??, ??, 177**, used: **237, 237, 267, ??, ??, 275, 333, 344, 363, 375, 385, 411, 428, ??, ??**
- other* (type), **208, 236, 267, ??, ??, 274, 333, 344, 363, 374, 384, 411, 428, ??, ??, 177**, used: **208, 208, 236, 237, 267, ??, ??, 274, 274, 333, 333, 344, 344, 363, 363, 374, 375, 384, 385, 411, 411, 428, ??, ??, ??, ??, 177, 177**
- Other*, **208, 237, 267, ??, ??, 274, 333, 344, 363, 375, 385, 411, 428, ??, ??, 177**, used: **237, 267, ??, ??, 274, 333, 344, 363, 375, 385, 411, 428, ??, ??**
- OUnit* (module), **??, ??**, used: **??, 765, 765, 799, 799, 765, 796**
- OUnitDiff* (module), **??, ??**, used:
- out* (field), **699**, used:
- outer*, **778, 776**, used:
- outer* (field), **813, 807**, used: **814, 711, 711, 712**
- outer\_self*, **778, 776**, used:
- outgoing*, **54, 58, 59, 64, 64, 210, 210, 94, 101, 103, 122, 52, 53, 209, 90**, used: **122, 129, 129**
- outgoing* (field), **100, 103**, used: **103, 116, 117, 121, 121**
- out\_ghost\_flags*, **83, 84, 80**, used:
- Out\_of\_bounds* (exn), **746, 741**, used:
- out\_to\_lists*, **83, 84, 80**, used:
- overlapping*, **214**, used: **214**
- overlapping\_flavor\_sums*, **215**, used: **215**
- Overlapping\_indices* (exn), **746, 741**, used:
- p* (field), **55**, used: **55, 56, 56, 57, 57, 57, 58, 58**
- p* (type), **73, 74, 94, 100, 101, 121, 128, 72, 88**, used: **73, 74, 76, 94, 95, 97, 100, 100, 101, 101, 121, 128, 73, 73, 73, 73, 88, 91, 93**
- P*, **137**, used: **457, 457, 458, 458, 459, 459, 505, 536, 282, 283, 304, 304, 325**
- P* (module), **765, 707**, used: **765, 708**
- P1*, **498, 528**, used: **498, 505, 506, 506, 509, 510, 512, 513, 514, 529, 537, 537,**

- 538, 543, 544, 546, 547,  
548, 549
- P123*, 190, used: 201
- P132*, 190, used: 201
- P2*, 498, 528, 137, used: 498,  
505, 506, 506, 509, 510,  
512, 513, 514, 529, 537,  
537, 538, 543, 544, 546,  
547, 548, 549
- P213*, 190, used: 201
- P231*, 190, used: 201
- p2s*, 124, 709, used: 124, 709,  
712
- P3*, 26, 528, used: 26, 529, 548,  
549
- P312*, 190, used: 201
- P321*, 190, used: 201
- P4*, 26, 528, used: 26, 529, 548,  
549
- P5*, 528, used: 529, 548, 549
- P6*, 528, used: 529, 548, 549
- P7*, 528, used: 529, 548, 549
- pack\_map*, 700, used: 701
- pack\_tree*, 700, used: 700
- pair*, 130, used: 131
- pairs*, 802, 496, 527, 802, used:  
11, 15, 21, 33, 497, 497,  
510, 513, 527, 527, 544,  
548
- pairs'*, 802, used: 802, 802
- pair\_or\_triple* (type), 13, 8,  
used: 13
- parameters*, 222, 571, 186, 207,  
225, 227, 229, 232, 245,  
267, 268, 455, ??, ??,  
503, 534, 280, 302, 323,  
337, 350, 368, 379, 389,  
407, 416, 428, ??, ??,  
721, 175, used: 571, 186,  
207, 267, 268
- parameters* (label), 223, 175,  
used: 575
- parameters* (type), 171, used:  
175, 175
- parameters\_to\_channel*, 178,  
used: 715
- Parents* (module), 45, used: 45,  
45, 45, 45, 45, 46, 46,  
46, 46, 46, 46, 46, 46, 46,  
47, 47, 47, 47, 47, 48
- parse*, 728, 730, 726, 730, used:  
??, 802, 9, 20, 40, 54, 218,  
698, 568, 183, 93, 713,  
224, 444, ??, 495, 526,  
273, ??, 678, ??, 718
- parse1*, 727, used: 728
- parse\_color*, 574, used: 574
- parse\_decay*, 210, 212, 209,  
used: 714
- parse\_error*, ??, 71, used: ??,  
??, ??, ??
- parse\_expr*, 573, used: 573, 573,  
574
- parse\_function\_row*, 573, used:  
574
- parse\_lagrangian\_row*, 573, used:  
574
- parse\_particle\_row*, 574, used:  
574
- parse\_process*, 210, 211, 209,  
used: 212, 212
- parse\_scattering*, 210, 212, 209,  
used: 714
- parse\_source*, 727, used: 728
- parse\_spin*, 574, used: 574
- parse\_symbol*, 573, used: 574
- parse\_table*, 574, used: 574
- parse\_variable\_row*, 574, used:  
574
- partial*, 828, 831, 825, used:
- Partial* (module), 765, 764,  
used:
- particle* (type), 571, used:
- particles\_file*, 576, used: 576, 576
- particle\_flavor* (type), 572, used:
- partition*, 24, 33, 73, 76, 73,  
used: 786, 24, 33, 133
- partition* (field), 76, used: 76, 76
- partition* (type), 20, 21, 24, 26,  
26, 33, 33, 18, used: 20,  
18, 19
- Partition* (module), 802, 802,  
used: 11, 13, 15, 17, 21,  
24, 33, 33
- partitioned\_sort*, 746, 741, used:  
215
- partitions*, 793, 20, 22, 24, 26,  
26, 33, 33, 788, 18,

- used: 793, 24, 24, 26, 26,  
32, 33, 34
- partitions'*, 793, 21, 24, 33,  
used: 793, 793, 794, 21,  
22, 24, 24, 33, 33
- partition\_to\_string*, 78, used: 79
- part\_to\_string*, 78, used: 78
- path* (type), ??, ??, used: ??, ??,  
??, ??, ??, ??
- PBP*, 138, used: 188, 461, 461,  
507, 507, 538, 539, 540,  
540
- pdg*, 222, 571, 184, 207, 226,  
227, 229, 233, 263, 267,  
267, 484, ??, ??, 519,  
555, 294, 315, 330, 342,  
361, 373, 383, 394, 399,  
424, 441, ??, ??, 723,  
172, used: 571, 184, 207,  
229, 229, 233, 233, 263,  
264, 267, 267, ??, ??, ??,  
??, 294, 294, 316, 316,  
343, 343, 362, 362, 373,  
373, 383, 384, 394, 394,  
425, 425, 441, 441, ??, ??,  
??, ??
- pdg* (label), 223, 175, used: 575
- pdg\_heuristic*, 570, used: 573,  
573
- pdg\_mw*, 487, 522, 559, 331,  
used: 487, 487, 522, 522,  
560, 560, 331, 331
- perform\_test*, ??, ??, used: ??
- permutation*, 96, 127, used: 96,  
127
- Permutation* (module), 796, 796,  
used:
- permutation4* (type), 190, used:
- permutation\_symmetry*, 32, used:  
32
- permute*, 795, 789, used: 795,  
204
- permute3*, 220, used: 220
- permute4*, 221, used: 221
- permute\_contract4*, 190, used:  
191
- permute\_contract4\_list*, 191,  
used: 191
- permute\_even*, 795, 789, used:
- permute\_odd*, 795, 789, used:
- permute\_signed*, 795, 789, used:  
795, 795, 795
- permute\_signed'*, 795, used: 795,  
795
- permute\_tensor*, 795, 789, used:
- permute\_tensor\_even*, 795, 789,  
used:
- permute\_tensor\_odd*, 795, 789,  
used:
- permute\_tensor\_signed*, 795,  
789, used: 795, 795
- permute\_vertex4*, 191, used: 201
- permute\_vertex4'*, 191, used: 191
- Phasespace* (module), 692, 691,  
used:
- Phi*, 225, 226, 718, used: 225,  
225, 226, 226, 227, 227,  
227, 719, 720, 721
- Phi0*, 236, 447, ??, ??, 274,  
297, 319, 333, 344, 363,  
374, 384, 411, 428, ??,  
??, used: 237, 239, 239,  
253, 447, 449, 449, 457,  
458, 459, 464, 465, 467,  
468, 468, 470, 472, 473,  
473, 479, ??, ??, ??, ??,  
275, 276, 277, 290, 298,  
299, 299, 312, 319, 320,  
320, 327, 333, 335, 335,  
340, 344, 346, 347, 353,  
363, 365, 365, 370, 375,  
376, 376, 380, 385, 386,  
386, 391, 411, 412, 412,  
422, 428, 431, ??, ??, ??,  
??, ??, ??, ??, ??
- Phi3* (module), 225, 224, used:
- Phi4* (module), 226, 224, used:
- phiggs* (type), 498, 528, used:  
498, 501, 529, 532
- PHiggs*, 498, 529, used: 498,  
500, 505, 506, 506, 508,  
508, 509, 509, 510, 510,  
512, 513, 514, 529, 531,  
536, 537, 537, 541, 541,  
543, 543, 544, 544, 544,  
546, 547, 549
- phiggs\_neutr*, 506, 537, used:  
506, 538
- Phim*, 236, 447, ??, ??, 274,  
297, 319, 333, 344, 363,

- 374, 384, 411, 428, ??**,  
**??**, used: **237, 239, 239**,  
**253, 447, 449, 449, 457**,  
**458, 458, 464, 465, 467**,  
**468, 468, 470, 470, 472**,  
**473, 473, 479, ??, ??, ??**,  
**??, 275, 276, 277, 290**,  
**298, 299, 299, 312, 319**,  
**320, 320, 327, 333, 335**,  
**335, 340, 344, 346, 347**,  
**353, 363, 365, 365, 370**,  
**375, 376, 376, 380, 385**,  
**386, 386, 391, 411, 412**,  
**412, 422, 428, 431, ??, ??**,  
**??, ??, ??, ??, ??, ??**
- Phino*, **363**, used: **363, 365, 369**,  
**370**
- Phip*, **236, 447, ??, ??, 274**,  
**297, 319, 333, 344, 363**,  
**374, 384, 411, 428, ??**,  
**??**, used: **237, 239, 239**,  
**253, 447, 449, 449, 457**,  
**458, 458, 464, 465, 467**,  
**468, 468, 470, 470, 472**,  
**473, 473, 479, ??, ??, ??**,  
**??, 275, 276, 277, 290**,  
**298, 299, 299, 312, 319**,  
**320, 320, 327, 333, 335**,  
**335, 340, 344, 346, 347**,  
**353, 363, 365, 365, 370**,  
**375, 376, 376, 380, 385**,  
**386, 386, 391, 411, 412**,  
**412, 422, 428, 431, ??, ??**,  
**??, ??, ??, ??, ??, ??**
- Photon*, **227**, used: **228, 228, 229**,  
**229**
- pi*, **781, 781, 782, 216, 118**,  
**779, 780**, used: **782, 782**,  
**782**
- Pi*, **241, 450, ??, ??, 278, 300**,  
**321, 337, 349, 367, 378**,  
**388, 414, 428, ??, ??**,  
used: **244, ??, ??, 428**
- pivot\_column*, **835**, used: **835**
- plist*, **529**, used: **529**
- PLUS*, **??, ??, ??, ??**, used: **??**,  
**??, 70, 566**
- PLUS* (camlyacc token), **71, 567**,  
used: **71, 72, 567, 567**
- PM* (module), **826**, used: **828**,  
**829, 829, 830, 831, 832**
- Pmap* (module), **755, 754**, used:  
**749, 773, 826, 816, 769**
- PMap* (module), **749**, used: **749**
- poles*, **94, 123, 91**, used: **700, 123**
- Poles* (module), **699**, used: **699**,  
**699, 700, 701**
- poles'*, **124**, used: **124**
- poles\_beneath*, **123**, used: **123**
- poles\_to\_whizard*, **699**, used: **700**
- Pole\_Map* (module), **700**, used:  
**700, 700, 700**
- Poly* (sig), **772, 10, 768, 8**, used:  
**773, 10, 13, 15, 42, 97, 97**,  
**97, 98, 98, 101, 769, 8, 8**,  
**8, 36, 93**
- Pos*, **397**, used: **398, 400, 403**,  
**403, 403, 403, 404, 404**,  
**404, 404, 404, 405, 405**,  
**405, 405, 405, 407, 408**
- Positron*, **227**, used: **228, 228**,  
**229, 229**
- POT*, **137**, used: **369**
- Pow*, **166**, used:
- power*, **827, 828, 829, 777, 9**,  
**11, 12, 15, 17, 565, 824**,  
**776, 7, 564**, used: **829**,  
**830, 830, 830, ??, 718**,  
**718, 718, 567**
- power* (field), **83, 84, 80**, used:
- power* (type), **83, 84, 80**, used:  
**83, 84, 80**
- POWER*, **??, ??**, used: **??, 566**
- POWER* (camlyacc token), **567**,  
used: **567, 567**
- power\_fold*, **9, 11, 12, 15, 17, 7**,  
used: **15, 104**
- PowSet* (module), **784, 783**,  
used: **78, 215**
- pp\_comma\_separator*, **??, ??**,  
used:
- pp\_diff*, **??, ??, ??, ??**, used: **??**,  
**??**
- pp\_printer*, **??, ??, ??, ??, ??**,  
**??**, used: **??, ??, ??, ??**,  
**??, ??**
- pp\_print\_gen*, **??**, used: **??, ??**,  
**??**
- pp\_print\_sep*, **??, ??**, used: **??**,  
**??, ??**

- pred*, **27, 27, 19**, used: **742, 742, 742, 742, 743, 745, 746, 746, 749, 798, 798, 833, 834, 835, 835, 836, 829, 789, 790, 790, 791, 792, 792, 794, 802, 803, 818, 819, 11, 12, 16, 17, 17, 24, 27, 29, 30, 31, 32, 33, 33, 34, 61, 62, 65, 66, 86, 568, 569, 569, 215, 215, 134, 708, 497, 527**
- prepend\_tofst\_unsorted*, **792**, used: **793**
- Pre\_Bundle* (module), **213**, used: **213**
- print*, **678, 678**, used:
- print\_time*, **799**, used: **800**
- Proc* (module), **131, 708**, used: **133, 133, 714**
- process* (type), **210, 211, 127, 128, 209, 91**, used: **210, 127, 129, 129, 209, 92, 92, 92**
- Process* (module), **210, 209**, used: **131, 708**
- processes*, **127, 129, 92**, used:
- processes* (field), **129**, used: **129, 134**
- Process\_Bundle* (module), **213**, used: **215**
- process\_sans\_color*, **129**, used: **133, 133**
- process\_table*, **127, 129, 92**, used: **708**
- process\_table* (field), **129**, used: **129, 134, 134**
- process\_to\_string*, **129**, used: **133**
- Prod*, **166**, used: **244, 245, 245, ??, ??, 280, 280, 302, 302, 322, 322, 337, 337, 350, 350, 367, 367, 378, 378, 389, 389, 416, 416, 428, ??, ??**
- product*, **785, 827, 827, 829, 830, 9, 11, 12, 15, 16, 824, 825, 6**, used: **786, 11, 12, 119, 119**
- Product*, **564, 564**, used: **565, 565, 565**
- Product* (module), **777, 776**, used: **795, 795, 810, 11, 11, 12, 12, 15, 16, 17, 17, 47, 701, 212, 213, 108, 108, 119, 123, 123, 123, 131, 246, 456, 456, 459, 461, 461, 463, 465, 466, 466, 466, 469, 470, 470, 470, 471, 472, 473, 473, 474, 474, 474, 474, 475, 475, 475, 475, 476, 477, 478, 478, ??, ??, 504, 505, 505, 506, 507, 507, 507, 509, 511, 511, 511, 512, 512, 513, 513, 513, 536, 536, 537, 537, 538, 538, 539, 541, 541, 541, 541, 543, 545, 545, 545, 546, 547, 547, 547, 548, 428, 718, 718, 718**
- product\_fold*, **9, 11, 12, 15, 16, 6**, used: **11, 12, 15, 16**
- Progress* (module), **732, 732**, used: **133, 133, 133**
- progress\_mode* (type), **128**, used:
- progress\_option*, **128**, used: **128, 133**
- project*, **267**, used: **267, 268, 268, 268, 268, 269, 271, 271**
- Projection* (sig), **781, 779**, used: **782, 780**
- prop* (field), **28**, used: **29, 29, 30, 30, 30**
- propagator*, **222, 571, 185, 207, 225, 226, 228, 230, 238, 266, 267, 448, ??, ??, 499, 530, 276, 298, 320, 334, 346, 364, 376, 386, 400, 412, 428, ??, ??, 719, 174**, used: **571, 185, 207, 104, 710, 710, 266, 267**
- propagator* (label), **223, 175**, used: **575**
- propagator* (type), **137**, used: **572, 174, 175**
- propagator\_of\_lorentz*, **572**, used: **573, 573**

- prop-aux*, **238**, ??, ??, **428**,  
 used: **238**, ??, ??, **428**  
*Prop-Col-Feynman*, **137**, used:  
 184  
*Prop-Col-Majorana*, **137**, used:  
 184  
*Prop-Col-Scalar*, **137**, used: 184  
*Prop-Col-Unitarity*, **137**, used:  
 184  
*Prop-ConjSpinor*, **137**, used:  
 572, 228, 230, 238, 448,  
 ??, ??, 499, 530, 276, 276,  
 298, 298, 320, 334, 346,  
 364, 376, 386, 400, 412,  
 428, ??, ??, 719  
*Prop-Feynman*, **137**, used: 572,  
 228, 230, 238, 448, ??, ??,  
 499, 530, 276, 298, 320,  
 334, 346, 364, 376, 386,  
 400, 412, 428, ??, ??, 719  
*Prop-Gauge*, **137**, used: 266  
*Prop-Ghost*, **137**, used:  
*Prop-Majorana*, **137**, used: 572,  
 448, 499, 530, 364, 719  
*Prop-Rxi*, **137**, used: 266  
*Prop-Scalar*, **137**, used: 572,  
 572, 225, 226, 238, 266,  
 448, ??, 499, 530, 276,  
 298, 320, 334, 346, 364,  
 376, 386, 412, 428, ??, ??,  
 719  
*prop-spinor*, **238**, **448**, ??, ??,  
**499**, **530**, **276**, **298**, **320**,  
**334**, **346**, **364**, **376**, **386**,  
**412**, **428**, ??, ??, used:  
 238, 448, ??, ??, 499, 530,  
 276, 298, 320, 334, 346,  
 364, 376, 386, 412, 428,  
 ??, ??  
*Prop-Spinor*, **137**, used: 572,  
 228, 230, 238, 448, ??, ??,  
 499, 530, 276, 276, 298,  
 298, 320, 334, 346, 364,  
 376, 386, 400, 412, 428,  
 ??, ??, 719  
*Prop-Tensor\_2*, **137**, used: ??,  
 334, 346, 428  
*Prop-Unitarity*, **137**, used: 572,  
 238, 448, ??, ??, 499, 530,  
 276, 298, 320, 334, 346,  
 364, 376, 386, 400, 412,  
 428, ??, ??  
*Prop-Vectorspinor*, **137**, used:  
 364  
*PSet* (module), **215**, used: 216,  
 216  
*Psi*, **137**, used: 229, 231, 245,  
 245, 246, 246, 246, 246,  
 246, 253, 254, 254, 254,  
 254, 254, 254, 255, 255,  
 255, 255, 256, 256, 256,  
 256, 256, 257, 257, 257,  
 257, 257, 257, 258, 258,  
 258, 455, 455, 455, 456,  
 456, 456, 457, 457, 457,  
 457, 458, 458, 458, 458,  
 458, 459, 461, 461, 462,  
 462, 462, 462, 462, 476,  
 476, 476, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, 503, 503, 503,  
 504, 504, 504, 505, 505,  
 505, 506, 506, 506, 506,  
 507, 507, 507, 508, 534,  
 535, 535, 535, 535, 535,  
 536, 536, 537, 537, 537,  
 537, 537, 538, 538, 538,  
 539, 539, 539, 539, 540,  
 540, 540, 540, 540, 540,  
 540, 540, 541, 541, 541,  
 541, 542, 542, 542, 281,  
 281, 281, 281, 281, 282,  
 282, 282, 282, 283, 290,  
 302, 303, 303, 303, 303,  
 303, 304, 304, 304, 304,  
 312, 323, 323, 323, 323,  
 324, 325, 325, 325, 325,  
 327, 338, 338, 338, 338,  
 338, 350, 350, 350, 351,  
 351, 368, 368, 368, 368,  
 369, 379, 379, 379, 379,  
 379, 389, 389, 389, 389,  
 390, 403, 403, 403, 403,  
 404, 404, 404, 404, 417,  
 417, 417, 417, 417, 418,  
 418, 418, 418, 418, 418,

- 419, 428, 432, 433, 433,  
 433, 433, 433, 434, 434,  
 434, 434, 435, 435, 435,  
 435, 435, 435, 435, 436,  
 436, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, 720  
*Psi0*, **274, 297**, used: 275, 277,  
 282, 285, 286, 287, 291,  
 298, 299, 304, 307, 307,  
 308, 312  
*Psi1*, **274, 297**, used: 275, 277,  
 282, 286, 287, 291, 298,  
 299, 304, 307, 308, 312  
*Psibar*, **137**, used: 229, 231, 245,  
 245, 246, 246, 246, 246,  
 246, 253, 254, 254, 254,  
 254, 254, 254, 255, 255,  
 255, 255, 256, 256, 256,  
 256, 256, 257, 257, 257,  
 257, 257, 257, 258, 258,  
 258, 455, 455, 455, 456,  
 456, 456, 457, 457, 457,  
 457, 458, 458, 458, 458,  
 458, 459, 461, 461, 462,  
 462, 462, 462, 462, 476,  
 476, 476, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, 503, 503, 503,  
 504, 504, 504, 505, 505,  
 505, 506, 506, 506, 506,  
 507, 507, 507, 508, 534,  
 535, 535, 535, 535, 535,  
 536, 536, 537, 537, 537,  
 537, 537, 538, 538, 538,  
 539, 539, 539, 539, 540,  
 540, 540, 540, 540, 540,  
 540, 540, 541, 541, 541,  
 542, 542, 542, 281, 281,  
 281, 281, 281, 282, 282,  
 282, 282, 283, 290, 302,  
 303, 303, 303, 303, 303,  
 304, 304, 304, 304, 312,  
 323, 323, 323, 323, 324,  
 325, 325, 325, 325, 327,  
 338, 338, 338, 338, 338,  
 350, 350, 350, 351, 351,  
 368, 368, 368, 368, 369,  
 379, 379, 379, 379, 379,  
 389, 389, 389, 389, 390,  
 403, 403, 403, 403, 404,  
 404, 404, 404, 417, 417,  
 417, 417, 417, 418, 418,  
 418, 418, 418, 418, 419,  
 428, 432, 433, 433, 433,  
 433, 433, 434, 434, 434,  
 434, 435, 435, 435, 435,  
 435, 435, 435, 436, 436,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, 720  
*Psim*, **274, 297**, used: 275, 277,  
 282, 285, 286, 287, 291,  
 298, 299, 304, 307, 307,  
 308, 312  
*Psimm*, **274, 297**, used: 275,  
 277, 285, 286, 287, 291,  
 298, 299, 307, 307, 308,  
 312  
*Psip*, **274, 297**, used: 275, 277,  
 282, 285, 286, 287, 291,  
 298, 299, 304, 307, 307,  
 308, 312  
*Psipp*, **274, 297**, used: 275, 277,  
 285, 286, 287, 291, 298,  
 299, 307, 307, 308, 312  
*PSSSM* (module), **526, 525**,  
 used: ??  
*PSSSM\_QCD* (module), **526**,  
**525**, used:  
*pullback*, **184**, used: 184, 184,  
 185, 186, 188  
*pure\_adjoint*s, **205**, used: 205  
*PV*, **137**, used:  
*p\_aux* (field), **571**, used: 573,  
 573, 574  
*p\_color* (field), **571**, used: 573,  
 573, 574  
*p\_mass* (field), **571**, used: 573,  
 573, 574  
*p\_name* (field), **571**, used: 573,  
 573, 574  
*P\_NNA*, **450**, used:  
*P\_NNG*, **450**, used:  
*P\_NNH1*, **450**, used:  
*P\_NNH2*, **450**, used:  
*p\_spin* (field), **571**, used: 573,  
 573, 574

- p\_symbol* (field), **571**, used: **572**, **574**, **574**
- p\_to\_string*, **697**, used: **697**, **697**
- P\_Whizard* (module), **707**, used: **708**
- p\_width* (field), **571**, used: **573**, **573**, **574**
- Q*, **228**, **718**, used: **229**, **229**, **719**, **720**, **720**, **721**
- Q* (module), **181**, **181**, used:
- QBUB*, **236**, **??**, **??**, **428**, used: **237**, **257**, **257**, **259**, **??**, **??**, **??**, **??**, **??**, **??**, **428**, **435**, **435**, **437**
- QCD* (module), **230**, **224**, used: **??**, **??**
- qcd\_ew\_check*, **107**, used:
- qcd\_order*, **98**, used: **98**, **98**
- qcd\_order* (type), **98**, used:
- QCD\_order*, **98**, used: **98**, **98**
- QED* (module), **227**, **224**, used: **718**, **??**
- qgc*, **248**, **??**, **??**, **281**, **338**, **351**, **369**, **380**, **390**, **420**, **428**, **??**, **??**, used: **248**, **249**, **250**, **??**, **??**, **284**, **284**, **338**, **351**, **369**, **380**, **390**, **420**, **428**, **??**, **??**
- QGUG*, **236**, **??**, **??**, **428**, used: **237**, **256**, **256**, **259**, **??**, **??**, **??**, **??**, **??**, **??**, **428**, **435**, **435**, **437**
- QH*, **319**, used: **319**, **320**, **323**, **323**, **324**, **325**, **325**, **327**, **327**
- qn\_baryon*, **401**, used: **401**
- qn\_charge*, **401**, used: **401**
- qn\_generation*, **401**, used: **401**
- qn\_lepton*, **401**, used: **401**
- QQ* (module), **182**, **181**, used: **240**, **266**, **453**, **??**, **??**, **500**, **531**, **277**, **300**, **321**, **335**, **348**, **366**, **377**, **387**, **400**, **413**, **428**, **??**, **??**, **224**, **224**, **224**, **444**, **??**, **495**, **525**, **272**, **272**, **273**, **??**
- quark*, **397**, used: **398**, **407**
- Quark*, **397**, used: **397**, **400**, **403**, **403**, **404**, **404**, **404**
- quark\_current*, **720**, used: **721**
- quark\_currents*, **304**, used: **312**
- quartic\_anom*, **234**, **234**, **234**, **234**, **235**, **235**, **235**, **235**, **235**, **236**, **??**, **??**, **427**, **428**, **224**, **??**, **273**, used: **249**, **??**, **??**, **428**
- quartic\_gauge*, **251**, **463**, **??**, **??**, **508**, **542**, **285**, **306**, **326**, **339**, **352**, **369**, **380**, **390**, **420**, **428**, **??**, **??**, used: **259**, **478**, **??**, **??**, **514**, **549**, **291**, **312**, **327**, **340**, **353**, **370**, **381**, **391**, **422**, **437**, **??**, **??**
- quartic\_gravitino*, **476**, used: **478**
- quartic\_grav\_char*, **476**, used: **476**
- quartic\_grav\_gauge*, **476**, used: **476**
- quartic\_grav\_neu*, **476**, used: **476**
- quartic\_grav\_sneutrino*, **476**, used: **476**
- Quiet*, **128**, used: **128**
- Quot*, **166**, used: **244**, **245**, **245**, **245**, **??**, **??**, **280**, **280**, **280**, **302**, **302**, **302**, **322**, **322**, **322**, **337**, **337**, **337**, **350**, **350**, **350**, **367**, **368**, **368**, **378**, **379**, **379**, **389**, **389**, **389**, **416**, **416**, **416**, **428**, **??**, **??**, **??**
- quote*, **753**, **751**, used: **714**
- QUQD1L*, **236**, **??**, used: **237**, **257**, **258**, **259**, **??**, **??**, **??**, **??**
- QUQD1R*, **236**, **??**, used: **237**, **257**, **258**, **259**, **??**, **??**, **??**, **??**
- QUQD8L*, **236**, **??**, used: **237**, **258**, **258**, **259**, **??**, **??**, **??**, **??**
- QUQD8R*, **236**, **??**, used: **237**, **258**, **258**, **259**, **??**, **??**, **??**, **??**
- QW*, **236**, **??**, **??**, **428**, used: **237**, **257**, **257**, **259**, **??**, **??**, **??**, **??**, **??**, **??**, **428**, **435**, **436**, **437**
- Q\_charg*, **450**, **501**, **532**, used: **455**, **503**, **535**



- Q<sub>down</sub>*, **241, 450, ??, ??, 501, 532, 278, 300, 321, 337, 349, 367, 378, 388, 414, 428, ??, ??**, used: **244, 245, 455, 455, ??, ??, 503, 503, 534, 534, 542, 542, 281, 302, 323, 325, 338, 350, 368, 379, 389, 417, 428, ??, ??**
- Q<sub>lepton</sub>*, **241, 450, ??, ??, 501, 532, 278, 300, 321, 337, 349, 367, 378, 388, 414, 428, ??, ??**, used: **244, 245, 455, 455, ??, ??, 503, 503, 534, 534, 281, 286, 302, 307, 323, 338, 350, 368, 379, 389, 417, 428, ??, ??**
- Q<sub>top</sub>*, **??**, used: **??**
- Q<sub>up</sub>*, **241, 450, ??, ??, 501, 532, 278, 300, 321, 337, 349, 367, 378, 388, 414, 428, ??, ??**, used: **244, 245, 455, 455, ??, ??, 503, 503, 534, 534, 281, 281, 302, 303, 323, 325, 338, 350, 368, 379, 389, 417, 428, ??, ??**
- Q<sub>Z-up</sub>*, **278, 300, 321**, used: **281, 303**
- r* (field), **55**, used: **55, 55, 55, 56, 56, 56, 56, 57, 57, 57, 58, 58, 59, 59, 60, 60**
- raises*, **??**, used: **??**
- range*, **743, 740**, used: **746, 797, 797, 799, 800, 800, 800, 800, 16, 17, 60, 86, 575, 74, 204, 116, 117, 120, 269, 718**
- Range* (exn), **54, 55, 61, 51**, used: **??**
- rank*, **42, 43, 43, 43, 45, 48, 54, 55, 61, 83, 83, 87, 109, 39, 40, 51, 80**, used: **44, 45, 62, 62, 62, 64, 64, 64, 64, 64, 64, 64, 65, 104, 109, 124**
- rank* (type), **43, 44, 45, 48, 49, 40**, used: **43, 44, 44, 48, 48, 40, 40**
- rank0*, **61**, used: **61, 62, 62, 62, 63, 63, 63**
- ranked*, **43, 44, 45, 48, 49, 40**, used: **45, 110**
- ranks*, **43, 44, 45, 48, 49, 40**, used: **45**
- rank-default*, **87**, used: **87**
- rank-set*, **44**, used: **44**
- Rat* (module), **181**, used: **181, 182**
- Rational* (sig), **826, 823**, used: **826, 827, 829, 823, 824, 825**
- raw* (field), **730**, used: **730, 730, 730, 731, 731**
- raw* (type), **727, 564, 726, 564**, used: **564, ??, 571, 726, 564, 564, 564, ??, 567**
- r<sub>cs</sub>*, **802, 9, 10, 12, 13, 15, 20, 21, 24, 26, 26, 28, 33, 33, 41, 45, 54, 55, 61, 224, 698, 571, 183, 207, 95, 95, 98, 125, 225, 226, 227, 230, 236, 266, 267, 445, ??, ??, 496, 526, 274, 297, 319, 332, 343, 363, 374, 384, 396, 410, 428, ??, ??, 718, 175, 802, 7, 19, 39, 53**, used: **105, 105, 125, 712, 267**
- RCS* (module), **727, 726**, used: **802, 9, 9, 10, 12, 13, 15, 20, 20, 21, 24, 26, 26, 33, 33, 40, 41, 45, 54, 54, 55, 61, 218, 224, 698, 568, 183, 183, 207, 93, 94, 95, 95, 98, 105, 105, 105, 125, 712, 224, 225, 226, 227, 230, 236, 266, 267, 444, 445, ??, ??, ??, 495, 496, 526, 526, 273, 332, 343, 363, 374, 384, 396, 428, ??, 678, ??, 718, 175, 178, 802, 7, 19, 39, 53, 91**
- r<sub>cs-author</sub>* (field), **727**, used: **727, 728**
- r<sub>cs-date</sub>* (field), **727**, used: **727, 728**

- racs\_file*, **9**, **20**, **40**, **54**, **218**, **568**,  
**183**, **93**, **224**, **444**, **??**,  
**495**, **526**, **273**, **??**, **678**,  
**??**, **718**, used: **10**, **12**, **13**,  
**15**, **21**, **24**, **26**, **26**, **28**, **33**,  
**33**, **45**, **55**, **61**, **224**, **571**,  
**183**, **207**, **95**, **98**, **125**, **225**,  
**226**, **227**, **230**, **236**, **266**,  
**445**, **??**, **??**, **496**, **526**, **274**,  
**297**, **319**, **332**, **343**, **363**,  
**374**, **384**, **396**, **410**, **428**,  
**??**, **??**, **718**  
*racs\_list*, **94**, **125**, **178**, **91**, used:  
**712**  
*racs\_revision* (field), **727**, used:  
**727**, **728**  
*racs\_source* (field), **727**, used:  
**727**, **728**  
*read*, **737**, **738**, **736**, used: **739**  
*read\_generation*, **268**, used: **268**  
*read\_lines*, **712**, used:  
*read\_lines\_rev*, **712**, used: **712**,  
**713**  
*Real*, **171**, used: **575**, **244**, **??**, **??**,  
**428**  
*Real\_Array*, **171**, used: **245**, **??**,  
**??**, **280**, **302**, **322**, **337**,  
**350**, **367**, **378**, **389**, **416**,  
**428**, **??**  
*real\_variable*, **572**, used: **572**,  
**573**, **573**, **575**  
*Rec*, **166**, used:  
*remove*, **755**, **758**, **763**, **769**,  
**769**, **770**, **772**, **773**, **29**,  
**754**, **767**, **768**, **768**,  
used: **??**, **758**, **763**, **770**,  
**770**, **773**, **773**, **828**, **829**,  
**830**, **831**, **29**, **30**, **30**, **215**  
*remove\_duplicate\_final\_states*,  
**210**, **215**, **210**, used: **133**  
*rename*, **728**, **726**, used: **10**, **12**,  
**13**, **15**, **21**, **24**, **26**, **26**, **33**,  
**33**, **45**, **55**, **61**, **224**, **183**,  
**207**, **95**, **98**, **125**, **225**, **226**,  
**227**, **230**, **236**, **266**, **267**,  
**445**, **??**, **??**, **496**, **526**, **332**,  
**343**, **363**, **374**, **384**, **396**,  
**428**  
*repeat*, **800**, used: **801**  
*RError*, **??**, **??**, used: **??**  
*reset*, **734**, **732**, used:  
*result* (type), **737**, **738**, **736**,  
used: **737**, **736**  
*result\_flavour*, **??**, used: **??**  
*result\_msg*, **??**, used: **??**  
*result\_path*, **??**, used: **??**  
*rev* (field), **811**, **806**, used: **811**,  
**812**, **812**, **813**, **813**, **709**,  
**710**, **710**  
*revision*, **727**, **726**, used: **728**  
*revision* (field), **727**, **726**, used:  
**728**, **802**, **9**, **20**, **40**, **54**,  
**218**, **698**, **568**, **183**, **93**,  
**224**, **444**, **??**, **495**, **526**,  
**273**, **??**, **678**, **??**, **718**  
*revmap*, **398**, used: **398**, **398**  
*revmap2*, **398**, used: **398**  
*rev\_flatmap*, **743**, **741**, used:  
**795**, **206**  
*rev\_multiply*, **746**, used: **746**, **746**  
*Rf*, **??**, **428**, used: **??**, **??**, **??**,  
**??**, **428**, **432**, **432**, **437**  
*rf3*, **??**, **432**, used: **??**, **436**  
*rf3t*, **??**, **432**, used: **??**, **436**  
*RFailure*, **??**, **??**, used: **??**  
*rhs*, **94**, **100**, **103**, **121**, **89**, used:  
**121**  
*rhs* (type), **94**, **100**, **103**, **121**,  
**89**, used: **94**, **100**, **100**,  
**100**, **103**, **103**, **108**, **119**,  
**121**, **89**, **89**, **89**, **89**, **89**  
*Ring* (sig), **827**, **824**, used: **828**,  
**829**, **831**, **825**, **825**  
*RMOM*, **137**, used:  
*RPAREN*, **??**, **??**, **??**, **??**, used:  
**??**, **??**, **70**, **566**  
*RPAREN* (camlyacc token), **71**,  
**567**, used: **71**, **567**  
*rphi3*, **??**, **432**, used: **??**, **436**  
*Rphim*, **??**, **428**, used: **??**, **??**,  
**??**, **428**, **432**, **437**  
*Rphimm*, **??**, **428**, used: **??**, **??**,  
**??**, **428**, **432**, **437**  
*Rphin*, **??**, **428**, used: **??**, **??**, **??**,  
**428**, **432**, **437**  
*Rphip*, **??**, **428**, used: **??**, **??**, **??**,  
**428**, **432**, **437**  
*Rphipp*, **??**, **428**, used: **??**, **??**,  
**428**, **432**

- Rsigma*, ??, **428**, used: ??, ??, ??, ??, ??, **428**, **431**, **431**, **432**, **437**  
*rsigma3*, ??, **431**, used: ??, **436**  
*rsigma3t*, ??, **431**, used: ??, **436**  
*rsigma4*, ??, **432**, used: ??, **437**  
*RSkip*, ??, ??, used: ??  
*RSuccess*, ??, ??, used: ??  
*rt3*, ??, **432**, used: ??, **436**  
*Rtm*, ??, **428**, used: ??, ??, ??, **428**, **432**, **437**  
*Rtmm*, ??, **428**, used: ??, ??, ??, **428**, **432**, **437**  
*Rtn*, ??, **428**, used: ??, ??, ??, **428**, **432**, **437**  
*RTodo*, ??, ??, used: ??  
*Rtp*, ??, **428**, used: ??, ??, ??, **428**, **432**, **437**  
*Rtpp*, ??, **428**, used: ??, ??, **428**, **432**  
*Running*, **137**, used:  
*run\_test\_tt*, ??, ??, used: ??  
*run\_test\_tt\_main*, ??, ??, used:  
*R\_CN*, **450**, used:  
*R\_CNG*, **450**, used:  
*R\_NC*, **450**, used:  
*R\_NCH*, **450**, used:  
*S*, **230**, **384**, **137**, used: **230**, **230**, **231**, **232**, **246**, **457**, **458**, **459**, **505**, **536**, **282**, **282**, **304**, **304**, **325**, **338**, **351**, **368**, **379**, **385**, **386**, **390**, **390**, **390**, **390**, **390**, **391**, **391**, **428**, ??, ??  
*S* (module), ??, **99**, **567**, used: ??, **99**, **99**, **567**  
*S* (sig), ??, ??, used: ??, ??, ??, ??  
*S1*, **497**, **528**, used: **498**, **505**, **506**, **506**, **509**, **510**, **512**, **512**, **513**, **514**, **529**, **537**, **537**, **538**, **543**, **544**, **546**, **547**, **547**, **548**, **549**  
*S1* (module), **44**, used: **44**  
*S2*, **497**, **528**, **137**, used: **498**, **505**, **506**, **506**, **509**, **510**, **512**, **512**, **513**, **514**, **529**, **537**, **537**, **538**, **543**, **544**, **546**, **547**, **547**, **548**, **549**, **290**, **312**, **327**  
*S2* (module), **44**, used: **44**  
*S2L*, **137**, used:  
*S2LR*, **137**, used: **290**, **312**  
*S2P*, **137**, used:  
*S2R*, **137**, used:  
*S3*, **497**, **528**, used: **498**, **505**, **506**, **506**, **509**, **510**, **512**, **512**, **513**, **514**, **529**, **537**, **537**, **538**, **543**, **544**, **546**, **547**, **547**, **548**, **549**  
*S4*, **528**, used: **529**, **548**, **549**  
*S5*, **528**, used: **529**, **548**, **549**  
*S6*, **528**, used: **529**, **548**, **549**  
*S7*, **528**, used: **529**, **548**, **549**  
*S8*, **528**, used: **529**, **548**, **549**  
*S9*, **528**, used: **529**, **548**, **549**  
*sanitize\_symbol*, **570**, used: **573**  
*sans\_colors*, **129**, used: **129**  
*Sbar*, **230**, used: **230**, **230**, **231**, **232**  
*Scalar*, **135**, used: **572**, **574**, **225**, **226**, **237**, **238**, **448**, ??, ??, **499**, **530**, **275**, **298**, **319**, **334**, **345**, **364**, **375**, **385**, **411**, **428**, ??, ??, **719**  
*Scalar2\_Vector2*, **139**, used: **189**, **251**, **464**, **465**, **465**, **466**, **466**, **466**, **467**, ??, **509**, **509**, **509**, **509**, **509**, **509**, **509**, **510**, **510**, **510**, **511**, **511**, **511**, **511**, **512**, **542**, **542**, **542**, **543**, **543**, **543**, **543**, **543**, **544**, **544**, **544**, **544**, **544**, **544**, **544**, **544**, **545**, **545**, **545**, **546**, **546**, **287**, **287**, **308**, **308**, **326**, **326**, **339**, **352**, **369**, **380**, **390**, **420**, **429**, **432**, ??, ??, **721**  
*Scalar4*, **139**, used: **575**, **189**, **191**, **227**, **227**, **251**, **467**, **468**, **468**, **471**, **471**, **472**, **472**, **473**, **473**, **474**, **474**, **474**, **474**, **474**, **475**, **475**, **475**, **290**, **311**, **326**, **339**, **352**, **369**, **380**, **390**, **421**, **429**, ??, ??  
*Scalar\_Scalar\_Scalar*, **138**, used: **575**, **188**, **225**, **227**, **227**,

- 251, 467, 467, 469, 469,  
470, 470, 470, 512, 512,  
513, 513, 513, 540, 541,  
541, 541, 546, 547, 547,  
547, 547, 290, 311, 326,  
339, 352, 369, 380, 390,  
421, 429, ??, ??
- Scalar\_Vector\_Vector*, **138**, used:  
188, 251, 253, 463, 464,  
??, ??, ??, ??, 508, 543,  
285, 285, 285, 290, 306,  
306, 307, 312, 326, 326,  
327, 339, 340, 352, 353,  
369, 370, 380, 380, 390,  
391, 420, 422, 428, 431,  
431, 432, ??, ??, ??, ??
- Scalar\_Vector\_Vector\_t*, **138**,  
used: 188, ??, 431
- scale*, **827, 828, 830, 831, 565**,  
**824, 825**, used: 830, 831,  
565, 565
- scattering* (type), **210, 211, 209**,  
used: 210, 211, 209, 209
- Scattering*, **210, 211, 209**, used:  
211, 212, 212
- Scattering* (module), **54, 58, 64**,  
**52**, used: 696, 696, 699,  
699, 699, 702, 107, 116,  
123, 124
- Sccs*, **278, 300, 321**, used:
- SD*, **446, 497, 527**, used: 456,  
459, 461, 465, 466, 469,  
470, 471, 473, 474, 474,  
505, 506, 507, 507, 510,  
510, 511, 513, 513, 536,  
538, 538, 539, 544, 545,  
546, 547, 547
- Sdown*, **447, 498, 529**, used:  
447, 449, 455, 456, 456,  
459, 461, 462, 462, 465,  
466, 466, 466, 467, 469,  
470, 470, 470, 471, 472,  
473, 473, 474, 474, 475,  
475, 475, 476, 479, 498,  
500, 503, 504, 505, 506,  
507, 507, 508, 510, 510,  
511, 511, 511, 512, 513,  
513, 513, 514, 529, 531,  
534, 536, 536, 538, 538,  
539, 540, 540, 541, 542,  
544, 545, 545, 545, 546,  
546, 547, 547, 547, 549
- sdown4\_1gen*, **475**, used: 478
- sdown4\_1gen'*, **475**, used: 475
- sdown4\_2gen*, **475**, used: 478
- sdown4\_2gen'*, **475**, used: 475
- search\_path*, **737**, used: 738, 738,  
738
- selectors* (type), **73, 76, 94, 112**,  
**127, 128, 72, 89, 91**,  
used: 73, 73, 73, 94, 95,  
112, 127, 128, 128, 72, 72,  
73, 73, 73, 73, 73, 89,  
91, 92, 93
- select\_p*, **73, 76, 73**, used: 116
- select\_p* (field), **76**, used: 76, 76,  
79
- select\_wf*, **73, 76, 73**, used: 116
- select\_wf* (field), **76**, used: 76,  
76, 79
- Selfconjugate*, **571**, used: 573
- seq* (type), **789, 787**, used: 788,  
788, 788, 788, 788, 788,  
788, 789, 789, 789, 789,  
789
- set*, **216**, used: ??, 746, 749, 749,  
798, 798, 798, 833, 834,  
834, 835, 835, 836, 817,  
817, 818, 570, 574, 216,  
133, 134
- set* (type), **784, 778, 776**, used:
- Set* (module), ??, used: ??, ??,  
??, ??, ??, ??, ??, 746,  
781, 784, 784, 44, 44, 45,  
220, 221, 700, 702, 186,  
214, 215, 215, 103, 119,  
123, 131
- SetMake* (module), ??, ??, used:
- SetTestPath* (module), ??, used:  
??
- setup*, **223, 175**, used: 575
- set\_cache\_name*, **94, 105, 127**,  
**134, 90, 92**, used: 134
- set\_color*, **222**, used: 223
- set\_conjugate*, **222**, used: 223
- set\_constant\_symbol*, **222**, used:  
223
- set\_external\_flavors*, **222**, used:  
223
- set\_fermion*, **222**, used: 223

- set\_flavors*, **222**, used: **223**  
*set\_flavor\_of\_string*, **222**, used: **223**  
*set\_flavor\_symbol*, **222**, used: **223**  
*set\_flavor\_to\_string*, **222**, used: **223**  
*set\_flavor\_to\_TeX*, **222**, used: **223**  
*set\_fuse*, **222**, used: **223**  
*set\_fuse2*, **222**, used: **223**  
*set\_fuse3*, **222**, used: **223**  
*set\_gauge\_symbol*, **222**, used: **223**  
*set\_goldstone*, **222**, used: **223**  
*set\_lorentz*, **222**, used: **223**  
*set\_mass\_symbol*, **222**, used: **223**  
*set\_max\_degree*, **222**, used: **223**  
*set\_of\_flavors*, **700**, used: **700**  
*set\_of\_list*, **785**, used: **785**  
*set\_parameters*, **222**, used: **223**  
*set\_pdg*, **222**, used: **223**  
*set\_propagator*, **222**, used: **223**  
*set\_to\_string*, **784**, used: **784**  
*set\_vertices*, **222**, used: **223**  
*set\_width*, **222**, used: **223**  
*set\_width\_symbol*, **222**, used: **223**  
*sff* (type), **446**, **497**, **527**, used: **450**, **450**, **501**, **532**  
*sfm* (type), **446**, **497**, **528**, used: **447**, **450**, **498**, **501**, **529**, **532**  
*SG*, **718**, used: **719**, **721**  
*shift\_left\_pred*, **214**, used: **215**  
*shift\_left\_pred'*, **214**, used: **214**  
*shiggs* (type), **497**, **528**, used: **498**, **501**, **529**, **532**  
*SHiggs*, **498**, **529**, used: **498**, **500**, **505**, **506**, **506**, **508**, **508**, **509**, **509**, **509**, **510**, **512**, **512**, **513**, **514**, **529**, **531**, **536**, **537**, **537**, **541**, **541**, **543**, **543**, **544**, **544**, **544**, **546**, **547**, **547**, **549**  
*shiggs\_neutr*, **506**, **537**, used: **506**, **538**  
*shortest*, **769**, **771**, **772**, **774**, **767**, **769**, used: **767**, **769**  
*shortest'*, **771**, **774**, used: **771**, **774**  
*shuffle*, **798**, used: **800**, **800**, **800**, **800**  
*sign*, **94**, **99**, **99**, **100**, **103**, **121**, **89**, used: **103**, **121**  
*sign* (field), **99**, **99**, used: **99**, **108**, **112**  
*sign* (type), **99**, **99**, used: **99**, **99**  
*Simplest* (module), **319**, **272**, used: **??**, **??**  
*Sin*, **450**, **166**, used: **450**  
*Sin2al*, **450**, used: **450**  
*Sin2am2b*, **450**, used: **450**  
*Sin2be*, **450**, used: **450**  
*Sin2thw*, **241**, **450**, **??**, **??**, **278**, **300**, **321**, **337**, **349**, **367**, **378**, **388**, **414**, **428**, **??**, **??**, used: **243**, **244**, **245**, **??**, **??**, **280**, **302**, **322**, **337**, **350**, **367**, **378**, **389**, **416**, **428**, **??**  
*Sin4al*, **450**, used: **450**  
*Sin4be*, **450**, used: **450**  
*Sinamb*, **450**, used: **450**  
*Sinapb*, **450**, used: **450**  
*Singlet*, **81**, **80**, used: **81**, **572**, **574**, **225**, **226**, **228**, **238**, **448**, **??**, **??**, **499**, **530**, **275**, **298**, **320**, **334**, **345**, **364**, **375**, **385**, **399**, **412**, **428**, **??**, **??**, **719**  
*singleton*, **755**, **756**, **761**, **828**, **831**, **54**, **55**, **62**, **754**, **825**, **51**, used: **828**, **829**, **831**, **214**, **101**, **112**  
*Singular* (exn), **833**, **833**, used: **833**  
*Sinpsi*, **278**, **300**, **321**, used: **278**, **300**, **321**  
*Sinthw*, **241**, **??**, **??**, **278**, **300**, **321**, **337**, **349**, **367**, **378**, **388**, **414**, **428**, **??**, **??**, used: **244**, **??**, **??**, **428**  
*size*, **41**, **47**, **38**, used: **41**, **47**, **38**  
*Skip* (exn), **??**, used: **??**  
*skip\_if*, **??**, **??**, used: **??**  
*SL*, **446**, **497**, **527**, **363**, **137**, used: **257**, **257**, **258**, **258**, **258**, **456**, **457**, **457**, **459**, **461**, **461**, **462**, **465**, **469**, **470**, **471**, **473**, **??**, **??**, **??**, **??**, **??**, **505**, **505**, **506**, **507**, **510**, **510**, **513**, **513**

- 536, 537, 538, 538, 544,  
545, 547, 547, 282, 304,  
325, 363, 365, 369, 370,  
436
- Slepton*, **447, 498, 529**, used:  
447, 449, 455, 456, 456,  
459, 461, 462, 465, 469,  
469, 470, 471, 471, 472,  
473, 474, 474, 474, 475,  
476, 479, 498, 500, 503,  
504, 505, 506, 507, 510,  
510, 512, 513, 513, 514,  
529, 531, 534, 535, 536,  
538, 538, 539, 539, 540,  
544, 545, 547, 547, 547,  
549
- slepton2\_squark2*, **474**, used: 478
- slepton2\_squark2'*, **474**, used:  
474
- slepton2\_squark2''*, **474**, used:  
474
- slepton4\_1gen*, **474**, used: 478
- slepton4\_1gen'*, **474**, used: 474
- slepton4\_2gen*, **474**, used: 478
- slepton4\_2gen'*, **474**, used: 474
- slep\_sneu\_squark2*, **475**, used:  
478
- slep\_sneu\_squark2'*, **475**, used:  
475
- slep\_sneu\_squark2''*, **475**, used:  
475
- slist*, **529**, used: 529
- slow\_binomial*, **790**, used: 790
- SLR*, **137**, used: 257, 457, 458,  
458, 458, 458, 458, 459,  
461, 461, 462, 462, 462,  
??, ??, 505, 506, 506, 506,  
506, 506, 507, 507, 507,  
537, 537, 537, 537, 538,  
538, 538, 539, 539, 539,  
540, 540, 540, 540, 540,  
540, 540, 540, 540, 540,  
541, 541, 541, 541, 541,  
282, 283, 304, 304, 436
- SLRV*, **137**, used: 476, 476, 476
- SLV*, **137**, used: 476, 476
- SM* (module), **236, 266, 224**,  
used: 266, 266, 266, 266,  
266, 267, 272, 718, ??, ??,
- ??, ??, ??, ??, ??, ??, ??,  
??
- Small\_Rational* (module), **826**,  
**823**, used: 181, 240, 453,  
??, ??, 500, 531, 277, 300,  
321, 335, 348, 366, 377,  
387, 400, 413, 428, ??, ??,  
181, 181
- SM\_anomalous* (module), **234**,  
**224**, used: ??
- SM\_anomalous\_ckm* (module),  
**235, 224**, used: ??
- SM\_anomalous\_top* (module),  
**235, 224**, used: ??
- SM\_clones* (module), **272, 224**,  
used:
- SM\_flags* (sig), **234**, ??, ??, **224**,  
??, used: 234, 234, 234,  
235, 235, 235, 235, 236,  
236, ??, ??, ??, ??, ??,  
224, 224, ??, ??
- SM\_gluons* (module), ??, used:
- SM\_Higgs* (module), **235, 224**,  
used: ??, ??
- SM\_k\_matrix* (module), **235**,  
**224**, used: ??
- SM\_no\_anomalous* (module),  
**234**, ??, ??, **224**, ??,  
used: 266, 272, 718, ??,  
??, ??, ??
- SM\_no\_anomalous\_ckm* (module),  
**234, 224**, used: ??, ??
- SM\_Rxi* (module), **266, 224**,  
used:
- SM\_tt\_threshold* (module), **236**,  
**224**, used: ??
- SN*, **446, 497, 527**, used: 456,  
459, 461, 465, 469, 471,  
472, 505, 506, 507, 511,  
512, 536, 538, 538, 545,  
547
- sneu2\_slep2\_1*, **474**, used: 478
- sneu2\_slep2\_1'*, **474**, used: 474
- sneu2\_slep2\_2*, **474**, used: 478
- sneu2\_slep2\_2'*, **474**, used: 474
- sneu2\_squark2*, **474**, used: 478
- sneu2\_squark2'*, **474**, used: 474
- Sneutrino*, **447, 498, 529**, used:  
447, 449, 456, 456, 459,  
461, 462, 465, 469, 470,

- 471, 472, 474, 474, 474,  
475, 476, 479, 498, 500,  
504, 505, 506, 507, 510,  
511, 512, 514, 529, 531,  
535, 536, 538, 538, 540,  
540, 541, 545, 545, 547,  
549  
*sneutrino4*, **474**, used: 478  
*sneutrino4'*, **474**, used: 474  
*solve*, **837**, **833**, used:  
*solve\_destructive*, **836**, used: 837  
*solve\_many*, **837**, **833**, used: 819  
*solve\_many\_destructive*, **836**,  
used: 837  
*sort*, **809**, **692**, **695**, **806**, **691**,  
used: 746, 747, 747, 797,  
797, 797, 820, 820, 830,  
832, 793, 793, 809, 55,  
694, 696, 700, 701, 110,  
130, 133, 709, 714  
*sort'*, **809**, used: 809, 809  
*sort3*, **696**, used: 696  
*sorted\_keys*, **44**, used:  
*sort\_2i*, **811**, used: 812, 816  
*sort\_2i'*, **811**, used: 811, 811  
*sort\_children*, **820**, used: 820  
*sort\_decay*, **692**, **693**, **691**, used:  
693, 695  
*sort\_momenta*, **694**, used: 694,  
696  
*sort\_section*, **746**, used: 746  
*sort\_signed*, **796**, **789**, used: 96,  
127  
*sort\_spin\_table*, **130**, used: 131  
*source*, **727**, **726**, used:  
*source* (field), **727**, **726**, used:  
728, 802, 9, 20, 40, 54,  
218, 698, 568, 183, 93,  
224, 444, ??, 495, 526,  
273, ??, 678, ??, 718  
*SP*, **137**, used: 459, 459, 537,  
417, 418, 418, 418, 418,  
418, 418, 419  
*spacelike*, **54**, **59**, **60**, **64**, **64**, **52**,  
**53**, used: 696, 699  
*species*, **811**, used: 811, 812, 812  
*spinor*, **237**, **448**, ??, ??, **498**,  
**530**, **275**, **298**, **319**, **333**,  
**345**, **364**, **375**, **385**, **411**,  
**428**, ??, ??, used: 238,  
448, ??, ??, 499, 530, 275,  
298, 319, 334, 345, 364,  
375, 385, 411, 428, ??, ??  
*Spinor*, **135**, used: 570, 574, 228,  
230, 237, 448, ??, ??, 498,  
530, 275, 275, 298, 298,  
319, 333, 345, 364, 375,  
385, 399, 411, 428, ??, ??,  
719  
*split*, **757**, **735**, **792**, **9**, **11**, **12**,  
**15**, **16**, **54**, **60**, **65**, **735**,  
**788**, **6**, **52**, used: 757,  
759, 760, 735, 832, 793,  
795, 818, 16, 34, 700, 96,  
108  
*split'*, **735**, **791**, used: 735, 735,  
791, 791, 792  
*splitn*, **742**, **740**, used: 206  
*splitn'*, **742**, used: 742, 742  
*split\_color\_string*, **186**, used: 186  
*SPM*, **137**, used: 255, 434  
*SQ*, **718**, used: 719, 720, 720,  
721, 721  
*Sqrt*, **166**, used: 244, ??, ??, 428  
*square*, **85**, used: 86  
*square* (type), **84**, used:  
*Square*, **84**, used: 85, 85  
*square2*, **85**, used: 86  
*squark\_current*, **720**, used: 721  
*squark\_seagull*, **721**, used: 721  
*SR*, **137**, used: 257, 257, 258,  
258, 258, 457, 457, 459,  
461, 461, ??, ??, ??, ??,  
??, ??, 505, 537, 282, 304,  
325, 436  
*SRV*, **137**, used:  
*SSC* (module), **428**, **273**, used:  
??  
*SSC\_flags* (sig), **427**, **273**, used:  
428, 428, 273, 273  
*SSC\_kmatrix* (module), **428**,  
**273**, used: ??  
*Stale*, **737**, **738**, **736**, used: 739  
*standard\_gauge\_higgs*, **251**, **287**,  
**308**, **326**, **339**, **352**, **369**,  
**428**, used: 253, 290, 311,  
327, 339, 352, 369, 430  
*standard\_gauge\_higgs'*, **285**, **306**,  
**326**, used: 287, 308, 326

- standard\_gauge\_higgs4*, **251**,  
**287, 308, 326, 339, 352**,  
**369, 429**, used: **253, 290**,  
**311, 327, 339, 352, 370**,  
**430**
- standard\_higgs*, **251, 290, 311**,  
**326, 339, 352, 369, 429**,  
used: **253, 290, 312, 327**,  
**339, 352, 370, 431**
- standard\_higgs4*, **251, 290, 311**,  
**326, 339, 352, 369, 429**,  
used: **253, 290, 312, 327**,  
**340, 352, 370, 431**
- standard\_quartic\_gauge*, **248, ??**,  
**??, 284, 305, 326, 338**,  
**351, 369, 428**, used: **251**,  
**??, ??, 285, 306, 326, 339**,  
**352, 369, 428**
- standard\_triple\_gauge*, **246, ??**,  
**??, 283, 305, 325, 338**,  
**351, 368, 428**, used: **248**,  
**??, ??, 284, 305, 326, 338**,  
**351, 369, 428**
- stat*, **95, 95, 99, 125**, used: **99**,  
**112**
- stat* (type), **95, 95, 99, 125**,  
used: **95, 99, 108, 110**,  
**111, 111, 111**
- Stat* (sig), **95**, used: **95, 95, 125**
- state* (type), **732**, used: **732**
- Stat\_Dirac* (module), **95**, used:  
**125, 127, 127, 127**
- stat\_fuse*, **95, 96, 99, 126**, used:  
**99, 108, 112**
- stat\_keystone*, **112**, used: **112**
- Stat\_Majorana* (module), **125**,  
used: **127, 127, 127, 127**
- Stat\_Maker* (sig), **95**, used: **98**
- Stat\_Map* (module), **111**, used:  
**111**
- stat\_sign*, **95, 96, 99, 127**, used:  
**99, 108, 112**
- step* (field), **732**, used: **733, 734**,  
**734, 734**
- steps* (field), **732**, used: **734, 734**
- string\_of\_angle*, **450**, used: **487**
- string\_of\_char*, **446, 497, 528**,  
used: **481, 487, 518, 522**,  
**554, 560, 561**
- string\_of\_fermion\_gen*, **498**,  
**529**, used: **522, 560**
- string\_of\_fermion\_type*, **498**,  
**529**, used: **522, 560**
- string\_of\_gen*, **446, 497, 527**,  
used: **446, 497, 527**
- string\_of\_higgs*, **447**, used: **447**,  
**487**
- string\_of\_int\_list*, **723**, used:  
**723**
- string\_of\_neu*, **446, 497, 528**,  
used: **481, 487, 518, 522**,  
**551, 554, 560, 561**
- string\_of\_node*, **??, ??**, used: **??**
- string\_of\_path*, **??, ??**, used: **??**,  
**??, ??**
- string\_of\_phiggs*, **498, 528**, used:  
**518, 522, 554, 560, 561**
- string\_of\_sff*, **446, 497, 527**,  
used: **450, 487, 522, 560**,  
**561**
- string\_of\_sfm*, **446, 497, 528**,  
used: **487, 522, 560, 561**
- string\_of\_shiggs*, **498, 528**, used:  
**518, 522, 554, 560, 561**
- strip\_before\_a\_keyword*, **727**,  
used: **728**
- strip\_before\_keyword*, **727**, used:  
**727**
- strip\_dollars*, **727**, used: **727, 727**
- strip\_from\_first*, **752, 751**, used:  
**727**
- strip\_from\_last*, **752, 751**, used:  
**727**
- strip\_keyword*, **727**, used: **727**,  
**727**
- strip\_prefix*, **751, 751**, used: **727**,  
**727**
- strip\_prefix\_star*, **752, 751**, used:  
**727**
- strip\_required\_prefix*, **752, 751**,  
used: **727**
- strip\_svn\_repos*, **728**, used: **728**
- sty*, **813, 806**, used:  
**811**
- style*, **811**, used: **811**
- style* (field), **811, 806**, used: **811**,  
**813, 813, 709**
- SU*, **446, 497, 527**, used: **456**,  
**459, 461, 465, 466, 469**,  
**470, 471, 473, 474, 474**,  
**505, 506, 507, 507, 510**,



- 510, 511, 513, 513, 536,  
538, 538, 539, 544, 545,  
546, 547, 547
- sub0*, **184**, used: 204, 205
- sub*, **826, 826, 827, 828, 830,**  
**831, 54, 57, 62, 823,**  
**824, 825, 51**, used: ??,  
??, 751, 752, 752, 752,  
752, 753, 727, 727, 830,  
830, 831, 818, 57, 62, 694,  
696, 568, ??, 186, 211,  
268, 721, 70
- sub'*, **57**, used: 57, 57
- substitute\_char*, **570**, used: 570
- substring*, **568**, used: 569, 569,  
569
- subtract*, **565, 564**, used: ??, 567
- succ*, **27, 27, 19**, used: 743, 744,  
744, 745, 749, 751, 752,  
752, 753, 798, 732, 734,  
772, 774, 835, 835, 835,  
836, 802, 803, 812, 814,  
815, 816, 817, 16, 21, 24,  
27, 30, 31, 32, 33, 47, 56,  
59, 62, 66, 82, 84, 699,  
568, 569, 569, 74, 186,  
204, 211, 211, 212, 214,  
110, 131, 133, 268, 496,  
527
- suite*, **765, 766, 799, 800, 765,**  
**796**, used:
- suite\_apply*, **766, 800**, used: 766,  
800
- suite\_compose*, **800**, used: 800
- suite\_inverse*, **800**, used: 800
- suite\_of\_list*, **799**, used: 800
- sum*, **827, 828, 830, 831, 818,**  
**181, 181, 181, 181, 181,**  
**182, 825, 825, 180,**  
used: 818, 211, 122
- Sum*, **564, 166, 564**, used: 565,  
565, 565
- summary*, **728, 734, 726, 732,**  
used: 133, 712
- SUM-1*, **450**, used:
- SUN*, **81, 80**, used: 81, 574, 230,  
238, 448, ??, ??, 499, 530,  
275, 298, 320, 334, 345,  
364, 375, 385, 399, 412,  
428, ??, ??, 719
- sup* (field), **809, 810**, used: 809,  
810, 811
- Sup*, **810, 447, 498, 529**, used:  
811, 447, 449, 455, 456,  
456, 459, 461, 462, 462,  
465, 466, 466, 466, 467,  
469, 470, 470, 470, 471,  
472, 473, 473, 474, 474,  
475, 475, 475, 476, 479,  
498, 500, 503, 504, 505,  
506, 507, 507, 508, 510,  
510, 511, 511, 511, 512,  
513, 513, 513, 514, 529,  
531, 534, 536, 536, 538,  
538, 539, 540, 540, 540,  
542, 544, 545, 545, 545,  
546, 546, 547, 547, 547,  
549
- sup2\_sdown2*, **475**, used: 478
- sup2\_sdown2\_1*, **475**, used: 475
- sup2\_sdown2\_2*, **475**, used: 475
- sup2\_sdown2\_3*, **475**, used: 475
- sup4\_1gen*, **475**, used: 478
- sup4\_1gen'*, **475**, used: 475
- sup4\_2gen*, **475**, used: 478
- sup4\_2gen'*, **475**, used: 475
- Supp*, **278, 300, 321**, used:
- Supp2*, **278, 300, 321**, used:
- supremum\_or\_infinity* (type),  
**810**, used: 810
- SV*, **137**, used:
- swap*, **834**, used: 835, 835
- SYM* (module), **718**, used: 723
- symbol*, **564, 564**, used: ??, 567
- symbol* (type), **571**, used: 571
- symbol* (camllex regexpr), **566**,  
used: 566
- Symbol*, **564, 564**, used: 564
- SYMBOL*, ??, ??, used: ??, 566
- SYMBOL* (camlyacc token), **567**,  
used: 567
- symmetry*, **790, 32, 94, 101,**  
**103, 122, 787, 90**, used:  
32, 117, 122
- symmetry* (field), **100, 103**, used:  
103, 116, 121
- Syntax\_Error* (exn), **70, 68**,  
used:
- system\_cache\_dir*, **729, 729**,  
used: 737

*s\_channel*, 54, 59, 64, 94, 123,  
124, 53, 91, used: 699,  
702  
*s\_channel\_in*, 54, 59, 64, 52,  
used: 59, 59, 64, 64  
*s\_channel\_out*, 54, 59, 64, 52,  
used: 59, 64  
*s\_channel\_out'*, 59, used: 59, 59  
*S\_NNA*, 450, used:  
*S\_NNG*, 450, used:  
*S\_NNH1*, 450, used:  
*S\_NNH2*, 450, used:  
*t* (type), ??, ??, ??, ??, 765,  
765, 765, 755, 755, 761,  
746, 796, 797, 797, 780,  
781, 781, 781, 782, 784,  
784, 784, 727, 737, 737,  
732, 769, 769, 770, 772,  
773, 820, 826, 826, 827,  
827, 828, 828, 829, 831,  
730, 730, 808, 9, 10, 12,  
13, 16, 27, 27, 28, 40,  
41, 41, 42, 42, 43, 43,  
43, 43, 44, 45, 48, 54,  
55, 61, 66, 66, 66, 692,  
695, 181, 181, 181, 181,  
181, 182, 81, 81, 81, 82,  
83, 83, 84, 85, 87, 218,  
218, 219, 219, 219, 698,  
699, 699, 700, 702, 69,  
73, 74, 78, 186, 210,  
210, 214, 215, 215, 215,  
99, 99, 103, 103, 104,  
105, 109, 111, 116, 119,  
119, 123, 124, 129, 129,  
131, 140, ??, ??, 764,  
754, 796, 779, 780, 783,  
783, 726, 736, 736, 732,  
767, 768, 768, 820, 823,  
824, 824, 825, 730, 805,  
6, 19, 35, 36, 37, 40, 50,  
53, 691, 180, 80, 80,  
217, 698, 68, 72, 209,  
71, 71, 567, 567, used:  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, 765, 765,  
765, 755, 755, 796, 780,  
781, 781, 782, 784, 784,  
784, 784, 784, 737, 769,  
769, 770, 772, 773, 820,  
826, 826, 827, 827, 828,  
828, 829, 831, 730, 808,  
9, 10, 12, 13, 15, 20,  
22, 24, 26, 26, 27, 28, 28,  
33, 33, 40, 41, 41, 42, 42,  
42, 42, 42, 43, 43, 44, 44,  
44, 44, 45, 45, 48, 48, 49,  
54, 55, 61, 66, 66, 66, 692,  
693, 181, 181, 181, 181,  
181, 182, 81, 81, 82, 82,  
82, 82, 83, 218, 219, 698,  
699, 699, 699, 700, 571,  
572, 69, ??, 73, 73, 74, 74,  
74, 210, 213, 215, 216, 94,  
95, 95, 97, 97, 97, 97, 98,  
98, 99, 99, 100, 100, 101,  
101, 101, 103, 103, 104,  
105, 109, 110, 111, 111,  
111, 118, 127, 129, 129,  
129, 131, 707, 717, 172,  
172, 174, 175, 175, 175,  
178, 178, 178, 178, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, 764, 765, 754, 796,  
779, 780, 780, 780, 780,  
780, 783, 783, 783, 783,  
783, 784, 784, 784, 726,  
726, 726, 726, 726, 736,  
732, 767, 767, 767, 767,  
767, 767, 768, 768, 768,  
768, 768, 769, 769, 769,  
820, 820, 823, 823, 824,  
824, 824, 824, 824, 825,  
825, 825, 825, 825, 825,  
825, 825, 825, 825, 730,  
802, 805, 805, 806, 806,  
806, 806, 806, 806, 806,  
807, 807, 6, 6, 6, 6, 6, 6,  
6, 6, 7, 7, 7, 7, 8, 8, 8,  
8, 19, 19, 19, 20, 20, 20,  
35, 36, 36, 36, 36, 36, 37,  
37, 37, 37, 37, 37, 37, 37,  
38, 38, 38, 38, 38, 38, 39,  
39, 39, 39, 39, 39, 40, 40,  
40, 40, 50, 51, 51, 51, 51,  
51, 51, 51, 51, 51, 52, 52,  
52, 52, 52, 52, 52, 52, 52,  
53, 53, 53, 53, 53, 53, 53,  
53, 53, 691, 691, 691, 691,  
691, 180, 180, 180, 180,

- 180, 181, 181, 80, 80, 80,  
81, 217, 698, 698, 68, 68,  
68, ??, 72, 72, 73, 209,  
209, 209, 210, 210, 210,  
88, 89, 89, 91, 91, 91, 91,  
92, 93, 93, 707, 71
- $T$ , **230**, used: 230, 230, 231, 232
- $T$  (module), **708**, used: 712, 713,  
715, 716
- $T$  (sig), **765, 755, 796, 781**,  
**784, 737, 769, 20, 41**,  
**54, 692, 181, 698, 73**,  
**210, 94, 707, 172, 178**,  
**764, 754, 796, 779, 783**,  
**736, 767, 18, 37, 50**,  
**691, 180, 698, 72, 209**,  
**88, 707**, used: 765, 797,  
797, 799, 770, 773, 48,  
693, 181, 181, 181, 181,  
182, 699, 74, 183, 210, 95,  
95, 95, 97, 98, 125, 128,  
128, 708, 172, 175, 176,  
178, 179, 765, 755, 755,  
796, 796, 796, 780, 784,  
736, 768, 769, 19, 20, 20,  
39, 40, 53, 691, 180, 180,  
180, 181, 181, 698, 568,  
73, 183, 210, 91, 93, 93,  
707, 224, 224, 444, 495,  
525, 272, 272
- $t'$  (type), **215**, used: 215
- $T2$ , **13, 8**, used: 13, 14, 14, 15,  
15, 15
- $T3$ , **13, 8**, used: 13, 14, 14, 15,  
15, 15
- table*, **225, 229, 232, 259, 267**,  
**270, 479, ??, ??, 514**,  
**549, 291, 312, 327, 340**,  
**353, 370, 381, 391, 406**,  
**422, 437, ??, ??, 721**,  
used: 225, 229, 232, 259,  
267, 270, 479, ??, ??, 514,  
549, 291, 312, 327, 340,  
353, 370, 381, 391, 406,  
422, 437, ??, ??, 721
- tag* (field), **737**, used: 738, 738
- tagged* (type), **737**, used:
- Tagged* (module), **98**, used: 125,  
125
- Tagged\_Binary* (module), **125**,  
**93**, used:
- Tagged\_Coupling* (module), **99**,  
used: 100, 103, 108, 112,  
119
- Tagged\_Coupling* (sig), **99**, used:  
99
- Tagged\_Maker* (sig), **97, 93**,  
used: 93
- Tagger* (sig), **97, 93**, used: 97,  
98, 125, 93
- Tags* (module), **99, 100, 101**,  
used: 99, 99, 100, 100,  
101, 101, 101, 101, 101,  
108, 108, 112, 112
- Tags* (sig), **97, 93**, used: 97, 100,  
93
- tail\_opt*, **205**, used: 205
- Tan*, **166**, used:
- Tana*, **450**, used:
- Tanb*, **450**, used:
- Target* (module), **178**, used: 708,  
707, 578, 578, 578
- Targets* (module), **578, 578**,  
used: 718, ??, ??, ??, ??,  
718, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, 723
- Targets\_Kmatrix* (module), **678**,  
**678**, used:
- Tau*, **227**, used: 228, 228, 229,  
229
- Tbar*, **230**, used: 230, 230, 231,  
232
- TBWA*, **236, ??, ??, 428**, used:  
237, 255, 259, ??, ??, ??,  
??, ??, ??, 428, 434, 437
- TBWZ*, **236, ??, ??, 428**, used:  
237, 256, 259, ??, ??, ??,  
??, ??, ??, 428, 434, 437
- Template* (module), **374, 272**,  
used: ??
- tension* (field), **811, 816, 806**,  
used: 813, 816, 709
- tension\_to\_equation*, **818**, used:  
819

- Tensor\_1*, **135**, used: **237**, **??**,  
**??**, **428**  
*Tensor\_2*, **135**, used: **??**, **334**,  
**345**, **428**  
*Tensor\_2\_Vector\_Vector*, **138**,  
used: **188**  
*Tensor\_2\_Vector\_Vector\_1*,  
**138**, used: **188**, **??**, **??**,  
**432**, **432**  
*Tensor\_2\_Vector\_Vector\_t*, **138**,  
used: **188**, **??**, **432**  
*Term* (module), **828**, **825**, used:  
*Term* (sig), **827**, **824**, used: **828**,  
**829**, **825**, **825**  
*Ternary* (module), **12**, **26**, **8**, **19**,  
used: **15**, **26**, **19**  
*Ternary* (sig), **12**, **8**, used: **8**  
*test* (type), **??**, **??**, used: **??**, **765**,  
**799**, **??**, **??**, **??**, **??**, **??**,  
**??**, **??**, **??**, **??**, **??**, **??**,  
**765**, **796**  
*Test* (module), **765**, **799**, **765**,  
**796**, used:  
*TestCase*, **??**, **??**, used: **??**, **??**,  
**??**  
*TestLabel*, **??**, **??**, used: **??**, **??**,  
**??**  
*TestList*, **??**, **??**, used: **??**, **??**, **??**  
*test\_case\_count*, **??**, **??**, used:  
**??**, **??**, **??**  
*test\_case\_paths*, **??**, **??**, used: **??**  
*test\_decorate*, **??**, **??**, used: **??**  
*test\_event* (type), **??**, **??**, used:  
**??**  
*test\_filter*, **??**, **??**, used: **??**  
*test\_fun* (type), **??**, **??**, used: **??**,  
**??**, **??**, **??**  
*test\_result* (type), **??**, **??**, used:  
**??**, **??**, **??**, **??**, **??**  
*test\_rhs*, **112**, used: **112**  
*test\_sum*, **60**, **64**, used: **60**, **65**  
*tex\_lbl*, **811**, used: **811**, **812**, **812**  
*tgc*, **246**, **??**, **??**, **281**, **338**, **351**,  
**368**, **380**, **390**, **419**, **428**,  
**??**, **??**, used: **246**, **247**,  
**??**, **??**, **283**, **283**, **338**, **351**,  
**368**, **380**, **390**, **419**, **428**,  
**??**, **??**  
*THDM* (module), **410**, **272**,  
used: **??**, **??**  
*THDM\_CKM* (module), **410**,  
**272**, used: **??**, **??**  
*THDM\_flags* (sig), **410**, **272**,  
used: **410**, **410**, **410**, **272**  
*this* (field), **813**, **807**, used: **815**  
*ThoArray* (module), **748**, **748**,  
used:  
*ThoFilename* (module), **735**,  
**735**, used: **737**  
*ThoList* (module), **742**, **740**,  
used: **797**, **797**, **797**, **799**,  
**800**, **800**, **800**, **800**, **830**,  
**832**, **777**, **790**, **793**, **793**,  
**793**, **794**, **795**, **795**, **808**,  
**808**, **816**, **816**, **816**, **816**,  
**16**, **16**, **17**, **17**, **17**, **24**, **24**,  
**33**, **34**, **60**, **86**, **219**, **223**,  
**701**, **575**, **74**, **204**, **204**,  
**204**, **204**, **206**, **206**, **212**,  
**213**, **213**, **215**, **216**, **216**,  
**216**, **108**, **116**, **117**, **119**,  
**120**, **120**, **120**, **123**, **123**,  
**123**, **131**, **131**, **131**, **133**,  
**133**, **133**, **709**, **709**, **712**,  
**713**, **714**, **225**, **226**, **228**,  
**230**, **237**, **237**, **246**, **246**,  
**256**, **257**, **257**, **258**, **258**,  
**258**, **269**, **269**, **269**, **270**,  
**447**, **448**, **458**, **458**, **459**,  
**459**, **459**, **461**, **461**, **463**,  
**465**, **466**, **466**, **466**, **469**,  
**470**, **470**, **470**, **471**, **472**,  
**474**, **474**, **475**, **475**, **476**,  
**477**, **478**, **??**, **??**, **??**, **??**,  
**??**, **??**, **??**, **??**, **??**, **??**, **??**,  
**??**, **498**, **498**, **507**, **509**,  
**510**, **511**, **511**, **511**, **512**,  
**512**, **513**, **513**, **514**, **529**,  
**529**, **538**, **539**, **540**, **540**,  
**540**, **540**, **540**, **541**, **541**,  
**541**, **542**, **542**, **542**, **543**,  
**544**, **545**, **545**, **545**, **546**,  
**546**, **547**, **548**, **549**, **275**,  
**275**, **291**, **298**, **298**, **312**,  
**319**, **319**, **323**, **325**, **327**,  
**333**, **333**, **340**, **344**, **345**,  
**353**, **363**, **364**, **370**, **375**,  
**375**, **380**, **385**, **385**, **391**,  
**398**, **411**, **411**, **422**, **428**,  
**435**, **435**, **436**, **436**, **??**, **??**,

- ??, ??, ??, ??, ??, ??, ??, ??,  
718, 719
- ThoString* (module), 751, 751,  
used: 727, 714
- thread*, 777, 776, used:
- thread\_unfinished\_decays*, 696,  
used: 697
- thread\_unfinished\_decays'*, 696,  
used: 696, 696, 697
- three*, 28, used: 29, 29, 30, 30, 31
- Threshl* (module), 396, 272,  
used: ??, ??
- Threshl\_ckm* (module), 395,  
272, used:
- Threshl\_ckm\_no\_hf* (module),  
395, 272, used:
- Threshl\_diet* (module), 396,  
272, used:
- Threshl\_diet\_no\_hf* (module),  
396, 272, used:
- Threshl\_no\_ckm* (module), 395,  
272, used: ??
- Threshl\_no\_ckm\_no\_hf* (module),  
395, 272, used: ??
- Threshl\_options* (sig), 395, 272,  
used: 395, 395, 395, 395,  
396, 396, 396, 272
- three\_gluon*, 231, 720, used: 232,  
721
- Thw*, 450, used:
- Th\_SF*, 450, used:
- time*, 766, 799, 799, 801, 796,  
used: 799, 799, 733, 734,  
734, 734, 734
- timelike*, 54, 59, 59, 64, 64, 52,  
53, used: 59, 60, 64, 64,  
699, 702, 107, 116, 123,  
124
- Timelike*, 137, used: 225, 226,  
228, 230, 236, 445, ??, ??,  
496, 526, 274, 297, 319,  
333, 344, 363, 374, 384,  
396, 410, 428, ??, ??, 720
- timelike\_map*, 699, used: 699,  
700
- time\_fun*, ??, used: ??
- time\_to\_string*, 733, used: 734,  
734
- tlm*, 742, 740, used: 742
- TLR*, 137, used: 255, 256, ??,  
??, ??, ??, 434, 434
- TLRM*, 137, used: 255, ??, ??,  
433
- todo*, ??, ??, used:
- Todo* (exn), ??, used:
- token*, ??, ??, ??, ??, used: ??,  
573, ??, ??, 75, 70, 566
- token* (type), ??, ??, ??, ??,  
used: ??, ??, ??, ??
- token* (camllex parsing rule), 70,  
566, used:
- TopH*, 274, used: 275, 277, 281,  
282, 283, 290, 291
- TopHb*, 274, used: 275, 277, 281,  
282, 283, 290, 291
- Topology* (module), 20, 18, used:  
98, 125, 127, 127, 127, 127
- Topp*, 297, used: 298, 299, 303,  
304, 304, 312, 312
- Toppb*, 297, used: 298, 299, 303,  
304, 304, 312, 312
- top\_anom*, 234, 234, 234, 234,  
235, 235, 235, 235, 236,  
??, ??, 427, 428, 224,  
??, 273, used: 253, 254,  
254, 254, 254, 255, 255,  
255, 255, 256, 256, 256,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, 432, 433, 433, 433,  
433, 433, 434, 434, 434,  
434, 435, 435
- top\_anom\_4f*, 234, 234, 234,  
234, 235, 235, 235, 235,  
236, ??, ??, 427, 428,  
224, ??, 273, used: 256,  
257, 257, 257, 258, 258,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, 435, 435, 436,  
436
- top\_quartic*, 290, 312, 327, used:  
291, 312
- tower\_of\_dag*, 110, used:
- tower\_to\_dot*, 94, 125, 91, used:  
716
- to\_feynmf\_channel*, 812, used:  
814, 815
- to\_float*, 826, 826, 823, used:

- to\_gauss*, **78**, used: **79**
- to\_int*, **27, 27, 19**, used: **32**
- to\_ints*, **54, 55, 62, 51**, used: **62, 66, 697, 701, 75, 78, 101, 124**
- to\_ints'*, **62**, used: **62, 62**
- to\_list*, **9, 11, 13, 15, 17, 84, 7**, used: **746, 797, 797, 797, 798, 798, 818, 819, 84, 84, 84, 103, 104, 107, 108, 108, 108, 119, 123, 123, 708, 714**
- to\_lists*, **784, 785, 83, 84, 783, 80**, used: **78, 215**
- to\_momentum*, **66, 66, 66, 53**, used: **66**
- to\_on\_shell*, **77**, used: **79**
- to\_ratio*, **826, 826, 823**, used:
- to\_selectors*, **73, 79, 72**, used: **715**
- to\_select\_p*, **76**, used: **79**
- to\_select\_wf*, **76**, used: **79**
- to\_string*, **784, 784, 784, 820, 826, 826, 827, 827, 828, 829, 831, 832, 810, 27, 27, 54, 55, 62, 697, 81, 82, 83, 84, 85, 69, 73, 75, 78, 213, 215, 783, 784, 820, 823, 824, 825, 825, 806, 19, 52, 68, 72**, used: **??, ??, 784, 737, 820, 831, 832, 83, 75, 79, 214, 715, 716**
- to\_string1*, **697**, used: **697, 697**
- translate\_constant*, **575**, used: **575**
- translate\_tensor3*, **575**, used: **575**
- translate\_tensor4*, **575**, used: **575**
- transpose*, **744, 749, 741**, used: **749, 750**
- tree* (type), **699**, used: **699**
- Tree* (module), **755, 808, 755, 805**, used: **749, 816, 41, 47, 94, 123, 707, 709, 709, 710, 710, 711, 711, 711, 711, 711, 712, 712, 712, 712, 716, 717, 39, 91, 707**
- Tree2* (module), **820, 820**, used: **41, 46, 94, 100, 101, 103, 131, 38, 89**
- trees*, **698, 700, 698**, used: **716**
- trees* (field), **699**, used: **700, 701**
- Trie*, **770, 773**, used: **770, 770, 770, 771, 771, 773, 773, 773, 774, 774**
- Trie* (module), **769, 767**, used:
- triples*, **803, 496, 527, 802**, used: **13, 15, 512, 546**
- triplet\_gauge2\_higgs*, **286, 307**, used: **287, 308**
- triplet\_gauge\_higgs*, **285, 307**, used: **287, 308**
- triple\_anom*, **234, 234, 234, 234, 235, 235, 235, 235, 235, 236, ??, ??, 427, 428, 224, ??, 273**, used: **248, ??, ??, 428**
- triple\_gauge*, **248, 463, ??, ??, 508, 542, 284, 305, 326, 338, 351, 369, 380, 390, 419, 428, ??, ??**, used: **258, 477, ??, ??, 513, 548, 291, 312, 327, 340, 353, 370, 380, 391, 422, 436, ??, ??**
- triple\_gravitino*, **463**, used: **478**
- triple\_gravitino'*, **462**, used: **463**
- triple\_gravitino''*, **462**, used: **463**
- TRL*, **137**, used: **255, 256, ??, ??, ??, ??, 434, 434**
- TRLM*, **137**, used: **255, ??, ??, 433**
- True*, **69, 74, 68**, used: **69, 69, 75, 75**
- try\_add*, **54, 57, 63, 51**, used: **60, 64**
- try\_add'*, **56**, used: **56, 57**
- try\_first*, **738**, used: **738**
- try\_fusion*, **54, 60, 65, 52**, used: **696**
- try\_of\_momenta*, **697**, used:
- try\_sub*, **54, 57, 63, 51**, used: **60, 63, 64, 696**
- try\_sub'*, **57**, used: **57, 57**
- try\_thread\_unfinished\_decays*, **697**, used: **697**
- TS* (module), **727**, used: **727, 727, 727, 727**
- TTGG*, **236, ??, ??, 428**, used: **237, 255, 259, ??, ??, ??**

- ??, ??, ??, 428, 434, 437  
*TTWW*, 236, ??, ??, 428, used:  
 237, 256, 259, ??, ??, ??,  
 ??, ??, ??, 428, 435, 437  
*tt\_threshold*, 234, 234, 234, 234,  
 235, 235, 235, 235, 236,  
 224, used: 254, 254, 263  
*tt\_threshold\_ttA*, 254, used: 258  
*tt\_threshold\_ttZ*, 254, used: 258  
*Tuple* (module), 9, 24, 33, 6,  
 used: 22, 23, 24, 24, 24,  
 26, 26, 33, 33, 33, 33, 34,  
 42, 97, 97, 97, 98, 98, 101,  
 125, 127, 127, 127, 127,  
 19, 20, 20, 36, 91, 91, 93  
*tuples*, 803, 802, used: 803, 803,  
 17, 24, 33  
*tuples'*, 803, used: 803, 803  
*tuple\_of\_list2*, 23, used: 24  
*TVA*, 137, used: 255, 256, 256,  
 ??, ??, ??, ??, ??, ??,  
 434, 435, 435  
*TVAM*, 137, used: 253, 254, 254,  
 254, 254, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??,  
 432, 433, 433, 433, 433  
*two*, 28, used: 29, 29, 30, 30, 31,  
 31, 31, 32  
*TwoHiggsDoublet* (module), 410,  
 272, used: ??, ??, ??, ??  
*two\_adjoints\_couple\_to\_singlets*,  
 205, used: 205  
*two\_and\_one*, 497, 527, used:  
 506, 512, 538, 546  
*two\_and\_one'*, 497, 527, used:  
 497, 497, 527, 527  
*t\_channel* (field), 695, used: 696,  
 696, 696, 697  
*U*, 230, 236, 447, ??, ??, 498,  
 529, 274, 297, 319, 333,  
 344, 363, 374, 384, 411,  
 428, ??, ??, used: 230,  
 230, 231, 232, 237, 239,  
 243, 245, 245, 246, 246,  
 246, 246, 253, 254, 254,  
 254, 254, 255, 255, 255,  
 255, 256, 256, 256, 256,  
 257, 257, 257, 257, 257,  
 257, 258, 258, 258, 259,  
 447, 449, 453, 455, 455,  
 456, 457, 457, 457, 458,  
 459, 461, 462, 462, 476,  
 479, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, 498,  
 500, 503, 503, 504, 505,  
 505, 506, 507, 507, 508,  
 514, 529, 531, 534, 535,  
 535, 537, 537, 538, 538,  
 539, 539, 539, 539, 540,  
 540, 549, 275, 277, 281,  
 281, 281, 281, 281, 282,  
 282, 282, 282, 283, 290,  
 291, 297, 299, 302, 303,  
 303, 303, 303, 303, 304,  
 304, 304, 304, 312, 312,  
 319, 320, 323, 323, 323,  
 323, 324, 325, 325, 325,  
 327, 333, 335, 338, 338,  
 338, 338, 338, 338, 340,  
 344, 347, 350, 350, 350,  
 351, 351, 351, 353, 363,  
 365, 368, 368, 368, 368,  
 370, 375, 376, 379, 379,  
 379, 379, 379, 381, 385,  
 386, 389, 389, 389, 389,  
 390, 391, 411, 412, 417,  
 417, 417, 417, 417, 418,  
 418, 418, 422, 428, 432,  
 433, 433, 433, 434, 434,  
 434, 434, 435, 435, 435,  
 435, 435, 435, 436, 436,  
 437, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??  
*u1\_gauged*, 273, 273, 273, 274,  
 272, used: 275, 281, 281,  
 282, 283, 283, 284, 285,  
 285, 286, 287, 291, 298,  
 303, 303, 304, 304, 305,  
 305, 306, 307, 307, 308,  
 312  
*Ubar*, 230, used: 230, 230, 231,  
 232  
*UED* (module), 343, 272, used:  
 ??  
*Unbounded\_Nary* (module), 17,

- 8**, used:
- unbounded\_power*, **17**, used: **17**
- unbounded\_power\_fold*, **17**, used: **17**
- uncolored\_colored*, **711**, used: **712**
- uncolored\_only*, **711**, used: **712**
- uncolorize\_wf*, **117**, used: **121**
- uncompress*, **749, 748**, used: **750**
- uncompress2*, **750, 748**, used:
- uncons*, **755, 758, 763, 754**, used:
- uncons\_opt*, **755, 758, 763, 754**, used:
- uncross\_colored*, **206**, used: **207**
- unfinished\_decays* (type), **695**, used:
- unfinished\_decays\_of\_momenta*, **696**, used: **697, 697**
- unfold*, **701**, used: **701**
- unfold1*, **700**, used: **701**
- unfold\_tree*, **701**, used: **701**
- Uninitialized* (exn), **222**, used:
- union*, **755, 760, 764, 784, 784, 754, 783**, used: **760, 764, 746, 784, 786, 786, 78, 214, 215**
- uniq*, **744, 748, 709, 740, 748**, used: **830, 832, 133, 709, 709, 714**
- uniq* (field), **748**, used: **748, 749, 749, 750**
- uniq'*, **744**, used: **744, 744**
- uniq2*, **749, 748**, used:
- uniq2* (field), **748**, used: **749, 749, 750**
- unique\_final\_state*, **211**, used:
- unique\_flavors*, **211**, used: **211**
- unit*, **826, 826, 827, 827, 828, 829, 823, 824, 824**, used:
- Unit*, **241, 450, ??, ??, 278, 300, 321, 337, 349, 367, 378, 388, 414, 428, ??, ??**, used: **??, 576, 98, 128, 712, 713, 236, 256, 445, ??, ??, ??, ??, 496, 526, 274, 297, 319, 333, 344, 363, 374, 384, 396, 410, 428, 435, ??, ??**
- Unitarity\_Gauge* (sig), **177**, used:
- unitialized*, **222**, used: **222**
- unit\_tension*, **816**, used:
- Unordered* (exn), **692, 693, 691**, used:
- unpack\_map*, **700**, used: **701**
- unphysical\_of\_flavor*, **131**, used: **131**
- unphysical\_of\_flavors*, **131**, used: **131**
- unphysical\_of\_flavors1*, **131**, used: **131**
- unphysical\_of\_lorentz*, **130**, used: **131**
- unphysical\_polarization*, **713**, used: **713, 715**
- unquote*, **??, 70**, used: **??, 70**
- Uodd*, **297**, used: **297, 298**
- update*, **755, 759, 762, 754**, used: **759, 759, 760, 762, 762**
- upper* (camlllex regexpr), **70, 566**, used: **70, 566**
- user\_cache\_dir*, **729, 729**, used: **737**
- use\_channel*, **733**, used: **734, 734, 734**
- use\_fudged\_width*, **236, 445, ??, ??, 496, 526, 274, 297, 319, 333, 344, 363, 374, 384, 410, 428, ??, ??**, used: **236, 239, 445, 449, ??, ??, ??, ??, 496, 499, 526, 531, 274, 276, 297, 299, 319, 320, 333, 334, 344, 346, 363, 365, 374, 376, 384, 386, 410, 412, 428, 428, ??, ??, ??, ??**
- Using\_Arrays* (module), **797, 796**, used: **798**
- Using\_Lists* (module), **797, 796**, used:
- U\_K1\_L*, **344**, used: **344, 347, 353**
- U\_K1\_R*, **344**, used: **344, 347, 353**
- U\_K2\_L*, **344**, used: **344, 347, 353**



- U\_K2\_R*, **344**, used: **344**, **347**, **353**
- v* (field), **28**, used: **29**, **29**, **30**, **30**
- V*, **137**, used: **229**, **231**, **245**, **245**, **256**, **455**, **455**, **457**, **462**, **462**, **??**, **??**, **??**, **??**, **503**, **503**, **505**, **508**, **534**, **535**, **536**, **539**, **542**, **542**, **542**, **281**, **281**, **281**, **302**, **303**, **303**, **323**, **323**, **325**, **338**, **338**, **350**, **351**, **368**, **369**, **379**, **379**, **389**, **389**, **403**, **403**, **404**, **417**, **417**, **428**, **435**, **??**, **??**, **??**, **??**, **720**
- V2*, **137**, used: **476**
- V2LR*, **137**, used: **476**, **476**
- v3* (field), **219**, used: **219**, **220**, **221**
- V3*, **140**, used: **220**, **190**, **191**, **227**
- v4* (field), **219**, used: **219**, **220**, **221**
- V4*, **140**, used: **221**, **190**, **191**, **227**
- VA*, **137**, used: **246**, **455**, **457**, **457**, **??**, **??**, **503**, **505**, **535**, **536**, **536**, **281**, **281**, **281**, **282**, **303**, **303**, **303**, **304**, **323**, **338**, **350**, **368**, **379**, **389**, **417**, **428**, **??**, **??**, **??**
- VA2*, **137**, used: **403**, **403**, **404**, **404**, **404**
- VA3*, **137**, used:
- VA3M*, **137**, used:
- value* (field), **737**, used:
- value* (type), **737**, **737**, **736**, used: **737**, **737**, **736**, **736**
- Value* (sig), **737**, **736**, used: **737**, **736**
- VAM*, **137**, used: **254**, **254**
- vanilla*, **813**, **806**, used: **813**
- Vanishing*, **137**, used: **236**, **445**, **??**, **??**, **496**, **526**, **274**, **297**, **319**, **333**, **344**, **363**, **374**, **384**, **396**, **410**, **428**, **??**, **??**
- Vanishing-couplings* (exn), **98**, used:
- vanishing-flavors*, **127**, **129**, **92**, used:
- vanishing-flavors* (field), **129**, used: **129**, **134**
- variable*, **124**, **709**, used: **124**, **716**
- variable* (type), **171**, used: **171**
- variable'*, **709**, used: **712**, **712**, **712**
- variables*, **94**, **101**, **103**, **122**, **90**, used:
- variables\_file*, **576**, used: **576**, **576**
- variable\_array* (type), **171**, used: **171**
- VA\_ILC\_ttA*, **241**, used: **254**
- VA\_ILC\_ttZ*, **241**, used: **254**
- vc* (type), **450**, **501**, **532**, used: **450**, **501**, **532**
- VCache* (module), **105**, used: **105**, **105**, **105**
- vector* (type), **566**, used:
- Vector*, **135**, used: **574**, **228**, **230**, **237**, **238**, **448**, **??**, **??**, **499**, **530**, **275**, **298**, **319**, **334**, **345**, **364**, **375**, **385**, **399**, **411**, **428**, **??**, **??**, **719**
- Vector4*, **139**, used: **189**, **191**, **232**, **248**, **249**, **463**, **??**, **??**, **508**, **542**, **284**, **305**, **326**, **338**, **351**, **369**, **380**, **390**, **405**, **420**, **428**, **??**, **??**, **721**
- Vector4\_K\_Matrix\_jr*, **139**, used: **189**, **191**, **250**, **??**, **??**, **428**
- Vector4\_K\_Matrix\_tho*, **139**, used: **189**
- Vectorspinor*, **135**, used: **448**, **364**
- vector\_keyword*, **566**, used:
- Vector\_Scalar\_Scalar*, **138**, used: **188**, **455**, **456**, **456**, **456**, **462**, **463**, **464**, **503**, **504**, **504**, **505**, **508**, **508**, **534**, **535**, **536**, **536**, **542**, **542**, **542**, **543**, **286**, **307**, **327**, **420**, **720**
- version*, **712**, used: **713**
- vertex3* (type), **138**, used: **218**, **105**, **140**, **174**, **175**, **217**
- vertex4* (type), **139**, used: **218**, **105**, **140**, **174**, **175**, **217**
- vertexn* (type), **140**, used: **218**, **105**, **140**, **174**, **175**, **217**

- vertex\_table* (type), **105**, used: **105**
- vertices*, **222, 571, 191, 207, 105, 225, 227, 229, 232, 259, 266, 270, 479, ??, ??, 514, 549, 291, 312, 327, 340, 353, 370, 381, 391, 406, 422, 437, ??, ??, 721, 174**, used: **571, 205, 207, 105, 117, 122, 225, 229, 232, 259, 266, 267, 270, 270, 479, ??, ??, 514, 549, 291, 312, 327, 340, 353, 370, 381, 391, 406, 422, 437, ??, ??, 721**
- vertices* (label), **223, 175**, used:
- vertices* (type), **104**, used: **104, 105, 105**
- vertices3*, **232, 258, 478, ??, ??, 513, 548, 291, 312, 327, 340, 353, 370, 380, 391, 422, 436, ??, ??, 721**, used: **232, 259, 479, ??, ??, 514, 549, 291, 312, 327, 340, 353, 370, 381, 391, 422, 437, ??, ??, 721**
- vertices3'*, **478**, used: **478**
- vertices3''*, **477**, used: **478**
- vertices4*, **232, 259, 478, ??, ??, 514, 549, 291, 312, 327, 340, 353, 370, 381, 391, 422, 437, ??, ??, 721**, used: **232, 259, 479, ??, ??, 514, 549, 291, 312, 327, 340, 353, 370, 381, 391, 422, 437, ??, ??, 721**
- vertices4'*, **478**, used: **478**
- vertices4''*, **478**, used: **478**
- vertices4'''*, **478**, used: **478**
- vertices\_aaww*, **405**, used: **406**
- vertices\_all*, **403**, used: **406**
- vertices\_aqq*, **403**, used: **406**
- vertices\_aww*, **404**, used: **406**
- vertices\_cache*, **105**, used: **105**
- vertices\_ggg*, **405**, used: **406**
- vertices\_gggg*, **406**, used: **406**
- vertices\_gqq*, **404**, used: **406**
- vertices\_nocache*, **104**, used: **105, 105**
- vertices\_wll*, **403**, used: **403, 406**
- vertices\_wll\_diet*, **403**, used: **406**
- vertices\_wqq*, **404**, used: **406**
- vertices\_wqq-no-ckm*, **403**, used: **404, 406**
- vertices\_wqq-no-ckm-diet*, **404**, used: **406**
- vertices\_www*, **405**, used: **406**
- vertices\_wwza*, **405**, used: **406**
- vertices\_wwzz*, **405**, used: **406**
- vertices\_zll*, **404**, used: **406**
- vertices\_zqq*, **404**, used: **406**
- vertices\_zww*, **405**, used: **406**
- Vev*, **241, 450, ??, ??, 278, 300, 321, 337, 349, 367, 378, 388, 414, 428, ??, ??**, used: **244, ??, ??, 428**
- VHeavy*, **278, 300, 321**, used:
- VL*, **137**, used: **246, 246, 246, 257, 257, 257, 456, 456, ??, ??, ??, ??, ??, ??, ??, ??, 504, 504, 535, 535, 281, 281, 282, 282, 303, 303, 303, 304, 323, 325, 338, 350, 368, 379, 389, 417, 428, 435, 435, 436, ??, ??**
- VLR*, **137**, used: **256, 257, 257, 456, 462, ??, ??, ??, ??, ??, ??, 504, 505, 535, 324, 435, 435, 435**
- VLRM*, **137**, used: **254, 255, ??, ??, ??, ??, 433, 433**
- VM* (module), **578**, used: **??, ??, ??, ??, ??, ??, ??, ??, ??, ??**
- VMOM*, **137**, used:
- vn* (field), **219**, used: **219, 220, 221**
- Vn*, **140**, used: **190, 191**
- VR*, **137**, used: **281, 303**
- VSet* (module), **104**, used: **104, 104**
- V-0*, **450**, used:
- V-CKM*, **450**, used:
- V-P*, **450**, used:
- w*, **397**, used: **398**
- W*, **450, 397**, used: **397, 400, 403, 403, 404, 404, 405, 405, 405, 405, 405, 407**
- W* (module), **708**, used: **716**

- was\_successful*, **??**, used: **??, ??, ??**
- wavefunctions*, **100, 103**, used: **117, 120**
- wf* (type), **94, 97, 97, 97, 98, 100, 101, 121, 127, 128, 88, 91, 93**, used: **94, 97, 100, 100, 100, 100, 100, 100, 100, 100, 101, 101, 103, 103, 103, 103, 103, 103, 108, 109, 110, 111, 111, 111, 111, 116, 118, 119, 121, 123, 127, 128, 128, 129, 131, 88, 88, 88, 88, 89, 89, 89, 89, 90, 90, 90, 91, 92, 92, 93, 93**
- wf1*, **709**, used: **709**
- WfMap* (module), **116, 131**, used: **116, 117, 117, 131**
- WfMap2* (module), **131**, used: **131**
- WFSet* (module), **103, 123**, used: **103, 123, 124**
- WFSet2* (module), **131**, used: **132, 132**
- WFTSet* (module), **131**, used: **131**
- wf\_tag*, **94, 100, 101, 121, 88**, used: **121**
- wf\_tag* (field), **100, 101**, used: **101, 101, 102, 108, 108, 112, 117, 117, 118, 123**
- wf\_tag\_raw*, **100, 101**, used: **108**
- wf\_to\_string*, **97, 97, 97, 98, 93**, used: **101**
- wf\_to\_TeX*, **712**, used: **712, 712, 712**
- white* (camllex regexpr), **70**, used: **70**
- White*, **184**, used: **185, 186, 186, 192, 192, 192, 192, 195, 195, 195, 196, 196, 196, 203, 205**
- Whizard* (module), **698, 698**, used: **708**
- Whizard* (sig), **66, 53**, used: **699, 53, 698**
- whizard\_tree*, **701**, used: **701**
- whizard\_tree\_debug*, **701**, used: **701**
- WHm*, **274, 297**, used: **275, 277, 281, 282, 283, 284, 285, 285, 286, 287, 291, 298, 299, 303, 303, 305, 305, 306, 307, 307, 308, 312**
- WHp*, **274, 297**, used: **275, 277, 281, 282, 283, 284, 285, 285, 286, 287, 291, 298, 299, 303, 303, 305, 305, 306, 307, 307, 308, 312**
- width*, **222, 571, 185, 207, 225, 226, 228, 230, 239, 266, 267, 449, ??, ??, 499, 531, 276, 299, 320, 334, 346, 365, 376, 386, 400, 412, 428, ??, ??, 720, 174**, used: **571, 185, 207, 266, 267**
- width* (label), **223, 175**, used: **575**
- width* (type), **137**, used: **174, 175**
- Width*, **241, ??, ??, 278, 300, 321, 337, 349, 367, 378, 388, 414, 428, ??, ??**, used: **174, 175**
- width\_symbol*, **222, 571, 188, 207, 226, 227, 229, 233, 264, 267, 267, 487, ??, ??, 522, 560, 294, 316, 331, 343, 362, 373, 384, 394, 409, 425, 441, ??, ??, 723, 175**, used: **571, 188, 207, 267, 267**
- width\_symbol* (label), **223, 175**, used: **575**
- with\_infinity*, **810**, used: **811**
- with\_supremum* (type), **809**, used: **809**
- with\_supremum\_or\_infinity* (type), **810**, used: **810**
- Wm*, **236, 447, ??, ??, 498, 529, 274, 297, 319, 333, 344, 363, 374, 384, 411, 428, ??, ??**, used: **237, 239, 246, 246, 246, 246, 247, 248, 249, 250, 251, 251, 252, 253, 255, 255, 256, 256, 256, 259, 447, 449, 456, 456, 456, 456, 456, 462, 463, 463, 463, 464**

- 464, 465, 465, 466, 466,  
 476, 476, 476, 476, 479,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, 498, 500, 504, 504,  
 504, 504, 504, 508, 508,  
 508, 509, 509, 509, 509,  
 510, 510, 510, 510, 510,  
 511, 511, 511, 514, 529,  
 531, 535, 535, 535, 535,  
 536, 542, 542, 543, 544,  
 544, 544, 544, 544, 544,  
 544, 544, 545, 545, 545,  
 545, 549, 275, 277, 281,  
 282, 283, 283, 284, 284,  
 285, 285, 285, 286, 287,  
 287, 290, 291, 298, 299,  
 303, 303, 304, 305, 305,  
 305, 305, 306, 306, 307,  
 307, 308, 308, 312, 312,  
 319, 320, 323, 325, 325,  
 325, 326, 326, 326, 326,  
 327, 327, 333, 335, 338,  
 338, 338, 339, 339, 339,  
 340, 340, 344, 347, 350,  
 351, 351, 352, 352, 352,  
 353, 353, 363, 365, 368,  
 368, 369, 369, 369, 370,  
 370, 375, 376, 379, 380,  
 380, 380, 380, 380, 381,  
 385, 386, 389, 390, 390,  
 390, 390, 391, 391, 411,  
 412, 417, 419, 420, 420,  
 420, 422, 422, 428, 428,  
 429, 430, 431, 431, 431,  
 432, 432, 432, 432, 432,  
 433, 434, 434, 435, 435,  
 437, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??  
*Wm1*, 344, used: 344, 347, 351,  
 353  
*Wm2*, 344, used: 344, 347, 353  
*Wp*, 236, 447, ??, ??, 498, 529,  
 274, 297, 319, 333, 344,  
 363, 374, 384, 411, 428,  
 ??, ??, used: 237, 239,  
 244, 246, 246, 246, 246,  
 247, 248, 249, 250, 251,  
 251, 252, 253, 255, 255,  
 256, 256, 256, 259, 447,  
 449, 456, 456, 456, 456,  
 456, 462, 463, 463, 463,  
 464, 464, 465, 465, 466,  
 466, 476, 476, 476, 476,  
 479, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, 498, 500,  
 504, 504, 504, 504, 504,  
 508, 508, 508, 509, 509,  
 509, 509, 510, 510, 510,  
 510, 510, 511, 511, 511,  
 514, 529, 531, 535, 535,  
 535, 535, 536, 542, 542,  
 543, 544, 544, 544, 544,  
 544, 544, 544, 544, 545,  
 545, 545, 545, 549, 275,  
 277, 281, 282, 283, 283,  
 284, 284, 285, 285, 285,  
 286, 287, 287, 290, 291,  
 298, 299, 303, 303, 304,  
 305, 305, 305, 305, 306,  
 306, 307, 307, 308, 308,  
 312, 312, 319, 320, 323,  
 325, 325, 325, 326, 326,  
 326, 326, 327, 327, 333,  
 335, 338, 338, 338, 339,  
 339, 339, 340, 340, 344,  
 347, 350, 351, 351, 352,  
 352, 352, 353, 353, 363,  
 365, 368, 368, 369, 369,  
 369, 370, 370, 375, 376,  
 379, 380, 380, 380, 380,  
 380, 381, 385, 386, 389,  
 390, 390, 390, 390, 391,  
 391, 411, 412, 417, 419,  
 420, 420, 420, 422, 422,  
 428, 428, 429, 430, 431,  
 431, 431, 432, 432, 432,  
 432, 432, 433, 434, 434,  
 435, 435, 437, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??, ??, ??, ??, ??, ??, ??,  
 ??  
*Wp1*, 344, used: 344, 347, 351,  
 353  
*Wp2*, 344, used: 344, 347, 351,  
 353

- write*, **737, 738, 698, 702, 736, 698**, used: ??, 105  
*write\_dir*, **737, 738, 736**, used: 105  
*write\_interface*, **704, 698**, used:  
*write\_interface\_function*, **703**, used: 704  
*write\_interface\_subroutine*, **703**, used: 704  
*write\_makefile*, **705, 698**, used:  
*write\_makefile\_processes*, **705, 698**, used:  
*write\_other\_declarations*, **704**, used: 704  
*write\_other\_interface\_functions*, **704**, used: 704  
*X0*, **319**, used: 319, 320, 323, 325, 326, 327, 327  
*Xdim* (module), **332, 272**, used: ??  
*XiA*, **266**, used: 266  
*XiW*, **266**, used: 266  
*XiZ*, **266**, used: 266  
*Xm*, **319**, used: 319, 320, 323, 325, 326, 326, 327  
*Xp*, **319**, used: 319, 320, 323, 325, 326, 326, 327  
*xy\_currents*, **323**, used: 327  
*Y0*, **319**, used: 319, 320, 323, 325, 327  
*yukawa*, **246, 282, 304, 325, 338, 351, 368, 379, 390, 417, 428, ??, ??**, used: 258, 291, 312, 327, 340, 353, 370, 380, 391, 422, 436, ??, ??  
*yukawa\_add*, **283, 304, 325**, used: 291, 312, 327  
*yukawa\_add'*, **282, 304**, used: 283, 304  
*yukawa\_c*, **461, 507, 538**, used: 477, 513, 548  
*yukawa\_cq*, **461, 507, 539**, used: 477, 513, 548  
*yukawa\_cq'*, **461, 507, 539**, used: 461, 507, 539  
*yukawa\_cq''*, **461**, used: 461  
*yukawa\_c\_1*, **461**, used: 461  
*yukawa\_c\_2*, **461, 507, 538**, used: 461, 507, 538  
*yukawa\_c\_3*, **461, 507, 538**, used: 461, 507, 538  
*yukawa\_goldstone*, **457**, used: 478  
*yukawa\_goldstone\_2*, **458**, used: 478  
*yukawa\_goldstone\_2'*, **458**, used: 458  
*yukawa\_goldstone\_2''*, **458**, used: 458  
*yukawa\_goldstone\_quark*, **458**, used: 478  
*yukawa\_higgs*, **457, 505, 537**, used: 477, 513, 548  
*yukawa\_higgs\_2*, **458, 506, 537**, used: 477, 513, 548  
*yukawa\_higgs\_2'*, **458**, used: 458  
*yukawa\_higgs\_2''*, **458**, used: 458  
*yukawa\_higgs\_FFP*, **505, 536**, used: 505, 537  
*yukawa\_higgs\_FFS*, **505, 536**, used: 505, 537  
*yukawa\_higgs\_NLC*, **505, 537**, used: 505, 537  
*yukawa\_higgs\_quark*, **457, 505, 537**, used: 477, 513, 548  
*yukawa\_n*, **459, 507, 538**, used: 477, 513, 548  
*yukawa\_n\_1*, **459**, used: 459  
*yukawa\_n\_2*, **459, 506, 538**, used: 459, 507, 538  
*yukawa\_n\_3*, **459, 506, 538**, used: 459, 507, 538  
*yukawa\_n\_4*, **459**, used: 459  
*yukawa\_n\_5*, **459, 507, 538**, used: 459, 507, 538  
*yukawa\_phiggs\_2*, **506, 537**, used: 506, 537  
*yukawa\_shiggs\_2*, **506, 537**, used: 506, 537  
*yukawa\_v*, **457, 505, 536**, used: 477, 513, 548  
*yuk\_lqino\_ec\_su1*, **540**, used: 548  
*yuk\_lqino\_ec\_su1'*, **540**, used: 540  
*yuk\_lqino\_ec\_su2*, **540**, used: 548  
*yuk\_lqino\_ec\_su2'*, **540**, used: 540

*yuk\_lqino\_nc\_sd1*, **540**, used:  
548  
*yuk\_lqino\_nc\_sd2*, **540**, used:  
548  
*yuk\_lqino\_phiggs*, **541**, used: 548  
*yuk\_lqino\_se\_uc1*, **539**, used:  
548  
*yuk\_lqino\_se\_uc1'*, **539**, used:  
539  
*yuk\_lqino\_se\_uc2*, **540**, used:  
548  
*yuk\_lqino\_se\_uc2'*, **539**, used:  
540  
*yuk\_lqino\_shiggs*, **541**, used: 548  
*yuk\_lqino\_sn\_dc1*, **540**, used:  
548  
*yuk\_lqino\_sn\_dc2*, **540**, used:  
548  
*yuk\_lq\_ec\_uc*, **540**, used: 548  
*yuk\_lq\_ec\_uc'*, **540**, used: 540  
*yuk\_lq\_ec\_uc2*, **540**, used: 548  
*yuk\_lq\_ec\_uc2'*, **540**, used: 540  
*yuk\_lq\_nc\_dc*, **540**, used: 548  
*yuk\_lq\_nc\_dc2*, **540**, used: 548  
*yyact*, ??, ??, used: ??, ??  
*yycheck*, ??, ??, used: ??, ??  
*yydefred*, ??, ??, used: ??, ??  
*yydgoto*, ??, ??, used: ??, ??  
*yygindex*, ??, ??, used: ??, ??  
*yylen*, ??, ??, used: ??, ??  
*yylhs*, ??, ??, used: ??, ??  
*yynames\_block*, ??, ??, used: ??,  
??  
*yynames\_const*, ??, ??, used: ??,  
??  
*yyrindex*, ??, ??, used: ??, ??  
*yyindex*, ??, ??, used: ??, ??  
*yytable*, ??, ??, used: ??, ??  
*yytables*, ??, ??, used: ??, ??  
*yytablesize*, ??, ??, used: ??, ??  
*yytransl\_block*, ??, ??, used: ??,  
??  
*yytransl\_const*, ??, ??, used: ??,  
??  
*z*, **397**, used:  
*Z*, **236, 447, ??, ??, 498, 529,**  
**274, 297, 319, 333, 344,**  
**363, 374, 384, 397, 411,**  
**428, ??, ??, used: 237,**  
**239, 243, 244, 246, 246,**  
247, 248, 249, 250, 251,  
251, 252, 253, 253, 254,  
254, 254, 256, 259, 447,  
449, 455, 456, 457, 457,  
462, 463, 463, 463, 464,  
464, 465, 465, 466, 466,  
476, 476, 476, 476, 479,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, 498,  
500, 503, 505, 505, 505,  
508, 508, 508, 509, 509,  
509, 509, 509, 510, 510,  
510, 511, 511, 511, 514,  
529, 531, 535, 536, 536,  
536, 542, 542, 542, 542,  
542, 542, 543, 543, 543,  
543, 543, 544, 544, 544,  
545, 545, 545, 546, 549,  
275, 277, 281, 281, 283,  
283, 284, 284, 285, 285,  
285, 286, 287, 287, 290,  
290, 291, 298, 299, 303,  
303, 305, 305, 305, 305,  
306, 306, 307, 307, 308,  
308, 311, 312, 312, 319,  
320, 323, 323, 325, 325,  
326, 326, 326, 326, 326,  
326, 327, 327, 327, 333,  
335, 338, 338, 338, 339,  
339, 339, 339, 340, 340,  
344, 347, 350, 351, 351,  
352, 352, 352, 352, 353,  
353, 363, 365, 368, 368,  
369, 369, 369, 369, 370,  
370, 375, 376, 379, 380,  
380, 380, 380, 380, 381,  
385, 386, 389, 390, 390,  
390, 390, 391, 391, 391,  
397, 398, 404, 404, 405,  
405, 405, 407, 411, 412,  
417, 419, 420, 420, 420,  
422, 422, 428, 428, 429,  
430, 430, 431, 431, 431,  
432, 432, 432, 432, 432,  
433, 433, 434, 437, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??, ??, ??, ??, ??, ??,  
??, ??  
*Z* (module), **181, 180**, used:

*Z1*, **344**, used: **344, 347, 351, 353**  
*Z2*, **344**, used: **344, 347, 351, 353**  
*zero*, **27, 27, 54, 55, 62, 83, 84**,  
**19, 51, 81**, used: **29, 29**,  
**29, 29, 30, 30, 30, 31, 31**,  
**32, 32, 32, 74, 134, 134**  
*Zero* (exn), **29**, used:  
*ZH*, **274, 297, 319, ??**, used:  
**275, 277, 281, 281, 283**,  
**284, 285, 285, 286, 287**,  
**291, 298, 299, 303, 303**,  
**305, 305, 306, 307, 307**,  
**308, 312, 319, 320, 324**,  
**325, 326, 326, 327, 327**,  
**??, ??, ??, ??**  
*Zprime* (module), **??, ??**, used:  
**??, ??**  
*ZZ* (module), **181, 180**, used:  
**228, 231, 224**  
*--ocaml\_lex\_tables*, **??, ??**, used:  
**??, ??**  
*--ocaml\_lex\_token\_rec*, **??, ??**,  
used: **??, ??, ??, ??**