Tool for High Energy Physics

Lecture 1
From Lagrangians to tree-level calculations

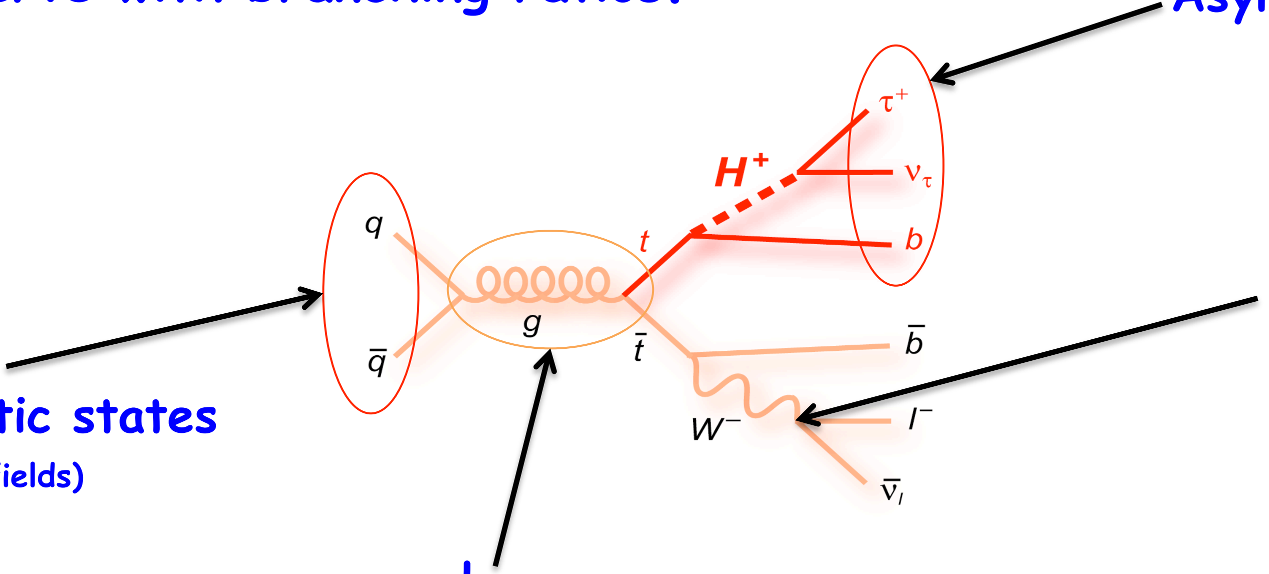
Rui Santos

ISEL & CFTC

6 September 2011

How do we calculate?

1. Write the Lagrangian;
2. Calculate the Feynman rules;
3. Calculate the relevant cross sections;
4. Serve with branching ratios.



Asymptotic states

(free fields)

Feynman rule

Asymptotic states

(free fields)

L_{int}

Is it a good model?

1. Does it survive the experimental test?
2. Does it survive the theoretical constraints?

Rules for building the Lagrangian

⊙ Conserved quantities (symmetries) ⇒ $L = abc$

$$\begin{cases} Q(a) = -1 \\ Q(b) = 1 \\ Q(c) = 0 \end{cases}$$

⊙ Natural units and dimensions

$\hbar = c = 1$ ⇒ $[L] = M^4; \quad [x,t] = M^{-1}; \quad [\partial] = M$

$$\begin{cases} s = 0,1 & M \\ s = 1/2 & M^{3/2} \end{cases}$$

⊙ Multiple spaces ⇒ $\psi_{i,j,k,\ldots}$

$$\begin{cases} i \Rightarrow isospin(2 \times 2) \\ j \Rightarrow flavour(3 \times 3) \end{cases}$$

<u>One space at a time</u>

$$\begin{bmatrix} a_i & b \end{bmatrix} \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} c_j \\ d \end{bmatrix} M_{ij} \qquad a = \begin{bmatrix} \bar{u} & \bar{c} & \bar{t} \end{bmatrix}$$

⊙ If you are stuck ⇒ <u>Use additional symmetries</u>

$$\begin{cases} \Phi \to -\Phi \\ \Phi \to e^{i\theta}\Phi \end{cases}$$

Rules for building the Lagrangian

$$f(x) = \int_{1}^{+\infty} \frac{1}{x+y}\,dy$$

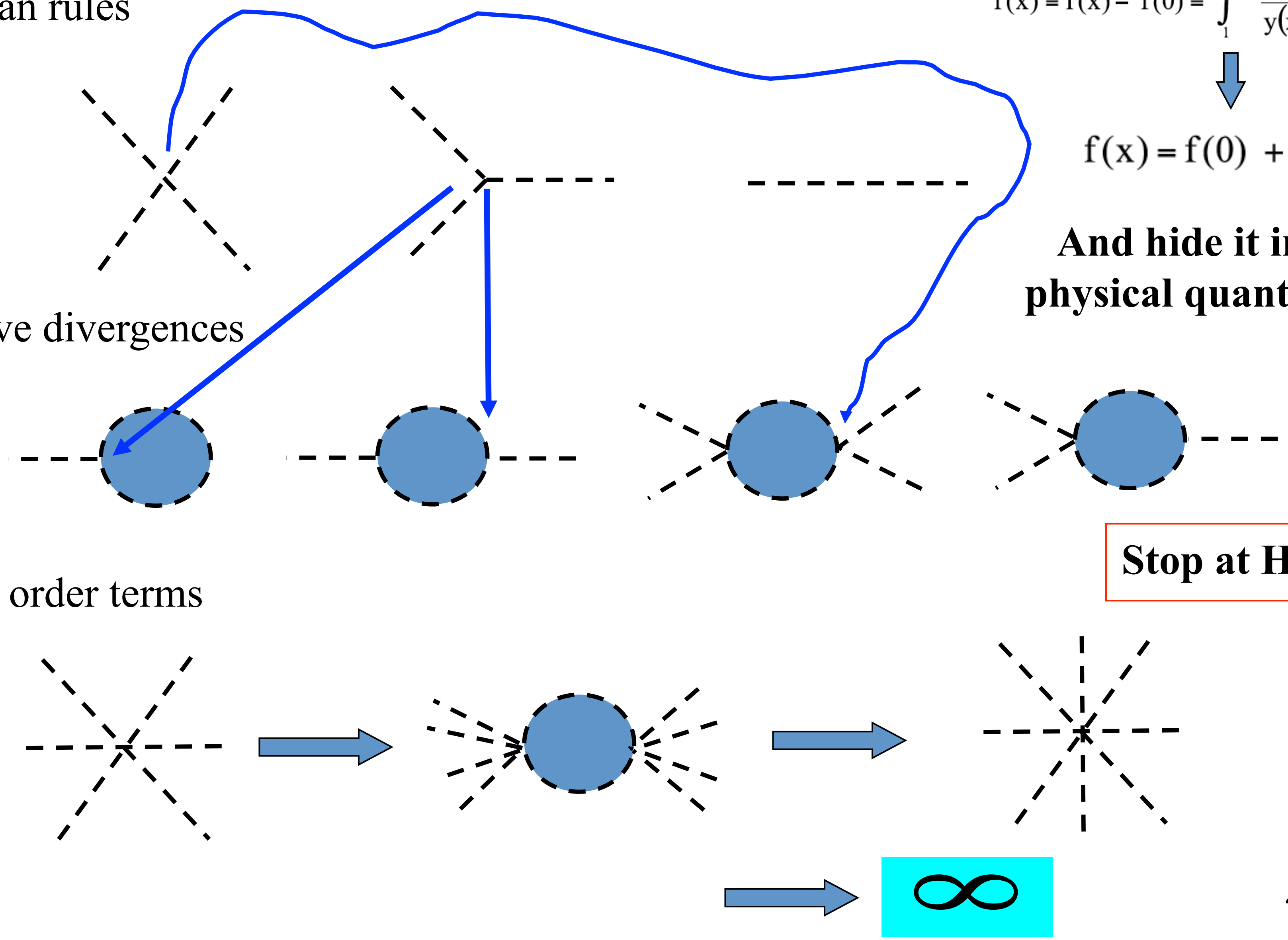
$$\Downarrow$$

$$\bar{f}(x) = f(x) - f(0) = \int_{1}^{+\infty} \frac{-x}{y(x+y)}\,dy$$

$$\Downarrow$$

$$f(x) = f(0) + \bar{f}(x)$$

Feynman rules



Primitive divergences

And hide it in physical quantity

Stop at H^4

Higher order terms

4

Rules for building the Lagrangian

THE BUILDING BLOCKS (particle content)

The doublet

$$\Phi \quad \Rightarrow \quad Y = 1 \qquad I_3 \to \begin{bmatrix} 1/2 \\ -1/2 \end{bmatrix} \qquad Q \to \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad \begin{bmatrix} a \\ b \end{bmatrix}$$

$$\Phi^* \quad \Rightarrow \quad Y = -1 \qquad I_3 \to \begin{bmatrix} -1/2 \\ 1/2 \end{bmatrix} \qquad Q \to \begin{bmatrix} -1 \\ 0 \end{bmatrix} \qquad \begin{bmatrix} a^* \\ b^* \end{bmatrix}$$

$$i\sigma_2\Phi \quad \Rightarrow \quad Y = 1 \qquad I_3 \to \begin{bmatrix} -1/2 \\ 1/2 \end{bmatrix} \qquad Q \to \begin{bmatrix} 0 \\ 1 \end{bmatrix} \qquad \begin{bmatrix} b \\ -a \end{bmatrix}$$

$$\tilde{\Phi} = i\sigma_2\Phi^* \quad \Rightarrow \quad Y = -1 \qquad I_3 \to \begin{bmatrix} 1/2 \\ -1/2 \end{bmatrix} \qquad Q \to \begin{bmatrix} 0 \\ -1 \end{bmatrix} \qquad \begin{bmatrix} b^* \\ -a^* \end{bmatrix}$$

$$Q = I_3 + \frac{Y}{2} \quad \Leftarrow$$

Remember

Rules for building the Lagrangian

THE BUILDING BLOCKS (particle content)

…and its invariants

	T	T_3	$Y/2$	Q
ν_{eL}	1/2	1/2	-1/2	0
e_L	1/2	-1/2	-1/2	-1
u_L	1/2	1/2	1/6	2/3
d_L	1/2	-1/2	1/6	-1/3
e_R	0	0	-1	-1
u_R	0	0	2/3	2/3
d_R	0	0	-1/3	-1/3

$$x = (\Phi^*)^T \Phi = \Phi^+\Phi$$

$$L_Y = \left(\bar{\nu}_e \quad \bar{e}\right)_L \begin{pmatrix} a \\ b \end{pmatrix} e_R$$

$$\mathrm{Y} = 1 + 1 - 2$$

$$(I_3)_{up} = -1/2 + 1/2 + 0$$

$$L_Y = \left(\bar{u} \quad \bar{d}\right)_L \begin{pmatrix} a \\ b \end{pmatrix} \mathrm{d}_R$$

$$\mathrm{Y} = -1/3 + 1 - 2/3$$

$$(I_3)_{up} = -1/2 + 1/2 + 0$$

$$L_Y = \left(\bar{u} \quad \bar{d}\right)_L \begin{pmatrix} b^* \\ -a^* \end{pmatrix} u_R$$

$$\mathrm{Y} = -1/3 - 1 + 4/3$$

$$(I_3)_{up} = -1/2 + 1/2 + 0$$

$$\tilde{\Phi} = i\sigma_2 \Phi^*$$

Rules for building the Lagrangian

THE BUILDING BLOCKS

Is the symmetry local?

$$D_\mu\Phi = \partial_\mu\Phi - \frac{i}{2}\begin{bmatrix} gW_\mu^3 + g'B_\mu & \sqrt{2}gW_\mu^+ \\ \sqrt{2}gW_\mu^- & -gW_\mu^3 + g'B_\mu \end{bmatrix}\Phi$$

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp W_\mu^2)$$

$$D_\mu = \partial_\mu + ig\vec{W}_\mu\cdot\vec{\mathrm{T}} + ig'\left(B_\mu/2\right)Y$$

or is it global?

$$D_\mu = \partial_\mu$$

No couplings between scalars and gauge bosons

That is it for the scalar doublet interaction with the known fields. The rest of the story you already know.

Mass, gauge group and rotation angles

Mass term in the lagrangian with two scalar fields (mixed)

$$L^{mass} = a\left(\varphi_1^g\right)^2 + 2b\varphi_1^g\varphi_2^g + c\left(\varphi_2^g\right)^2 = \left(\Phi^g\right)^T C_g \Phi^g = \begin{bmatrix}\varphi_1^g & \varphi_2^g\end{bmatrix}\begin{bmatrix} a & b \\ b & c \end{bmatrix}\begin{bmatrix}\varphi_1^g \\ \varphi_2^g\end{bmatrix}$$

Rotate the group eigenstates to the mass eigenstates

$$\Phi^m = R_\alpha \Phi^g \qquad \begin{bmatrix}\varphi_1^m \\ \varphi_2^m\end{bmatrix} = \begin{bmatrix}\cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha\end{bmatrix}\begin{bmatrix}\varphi_1^g \\ \varphi_2^g\end{bmatrix}$$

and we can write

$$L = \left(\Phi^g\right)^T C_g \Phi^g = \left(\Phi^m\right)^T R_\alpha^T C_g R_\alpha \Phi^m \equiv \left(\Phi^m\right)^T M \Phi^m$$

Finally the masses and the angles can be written in terms of the original parameters as

$$\tan(2\alpha) = \frac{2b}{a-c}$$

$$\begin{cases} m_1^2 = \dfrac{a+c+\sqrt{(a-c)^2-4b^2}}{2} \\[2ex] m_2^2 = \dfrac{a+c-\sqrt{(a-c)^2-4b^2}}{2} \end{cases} \Rightarrow \quad b = 0 \qquad \begin{cases} m_1^2 = a \\ m_2^2 = c \end{cases}$$

The Tools I

Tools already installed but…
it is a known fact that everyone can do it

Tools **(Model Generation)** →
- LanHEP → http://theory.sinp.msu.ru/~semenov/lanhep.html
- FeynRules → http://feynrules.irmp.ucl.ac.be/

Tools **(xsection and event generation)** →
- CompHEP → http://comphep.sinp.msu.ru/
- CalcHEP → http://theory.sinp.msu.ru/~pukhov/calchep.html
- MadGraph → http://madgraph.hep.uiuc.edu/

And many others…

But these are the ones where very easily one goes from the Lagrangian to the actual analysis (but not always)

The Tools I

We will be using CompHEP/CalcHEP – what are the features/limitations

Any processes within any model, but

a) Tree-level processes: decay and scattering

b) Squared Matrix Element calculation:
no spin information for outgoing particles – spin averaged amplitude

c) Limit on number of external legs – 6

d) Limit on the number of diagrams ~ *100-200*

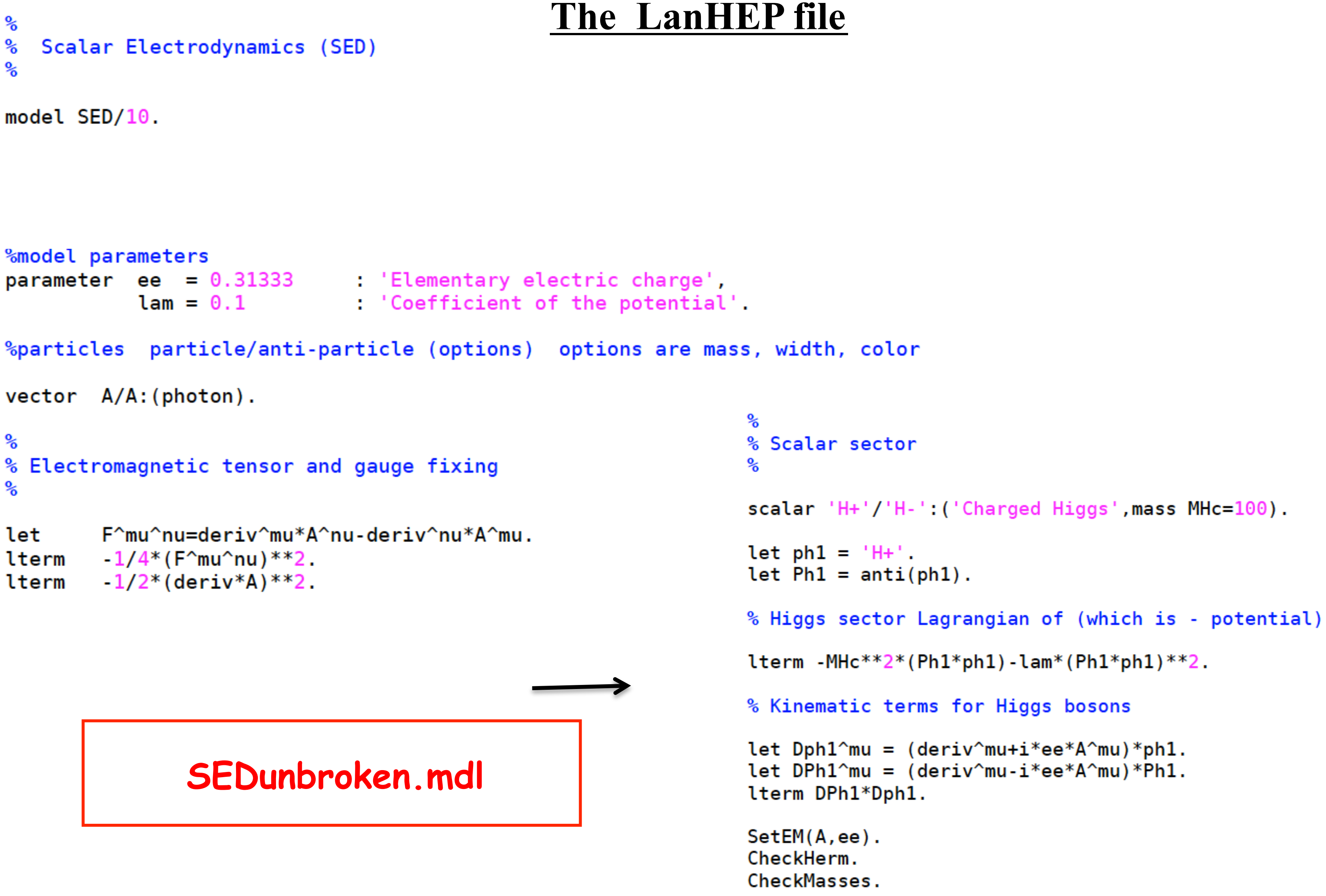
From directory /soft/Rsantos/idpasctools (done)
cp SEDunbroken.mdl /home/G*/lanhep/

Creating working directory (comphep) (already created)
make setup WDIR=/home/G*/comphep

Creating working directory (calchep) (already created)
make setup WDIR= → ./mkUsrDir

Scalar Electrodynamics

Building the Lagrangian and generating the Feynman Rules – The LanHEP file



```
%
%  Scalar Electrodynamics (SED)
%

model SED/10.




%model parameters
parameter  ee  = 0.31333     : 'Elementary electric charge',
           lam = 0.1         : 'Coefficient of the potential'.

%particles  particle/anti-particle (options)  options are mass, width, color

vector  A/A:(photon).

%
% Electromagnetic tensor and gauge fixing
%

let     F^mu^nu=deriv^mu*A^nu-deriv^nu*A^mu.
lterm   -1/4*(F^mu^nu)**2.
lterm   -1/2*(deriv*A)**2.
```

```
%
% Scalar sector
%

scalar 'H+'/'H-':('Charged Higgs',mass MHc=100).

let ph1 = 'H+'.
let Ph1 = anti(ph1).

% Higgs sector Lagrangian of (which is - potential)

lterm -MHc**2*(Ph1*ph1)-lam*(Ph1*ph1)**2.

% Kinematic terms for Higgs bosons

let Dph1^mu = (deriv^mu+i*ee*A^mu)*ph1.
let DPh1^mu = (deriv^mu-i*ee*A^mu)*Ph1.
lterm DPh1*Dph1.

SetEM(A,ee).
CheckHerm.
CheckMasses.
```

SEDunbroken.mdl

Scalar Electrodynamics

Running the LanHEP file and include the model in CompHEP/CalcHEP

FR for CompHEP: in G*/lanhep dir → /soft/lanhep314/lhep SEDunbroken.mdl

→ Files created →

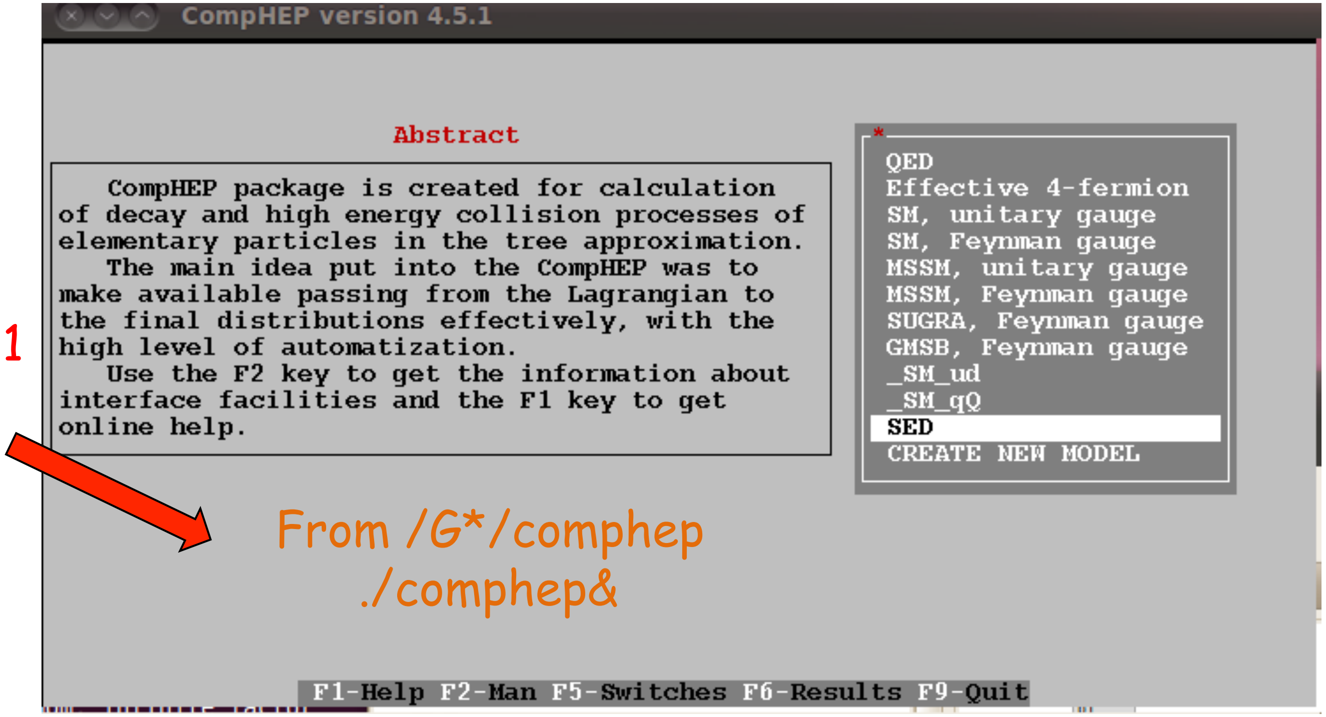
vars10.mdl
prtcls10.mdl
lgrng10.mdl
func10.mdl

→ Model in CompHEP

Look for the largest number of the files similar to the ones above. If it is *10.mdl change all files to *11.mdl. The model will appear automatically in the menu.

nautilus change *.10 to *.11
and
move all files to

/G*/comphep/models



```
   CompHEP package is created for calculation
of decay and high energy collision processes of
elementary particles in the tree approximation.
   The main idea put into the CompHEP was to
make available passing from the Lagrangian to
the final distributions effectively, with the
high level of automatization.
   Use the F2 key to get the information about
interface facilities and the F1 key to get
online help.
```

From /G*/comphep
./comphep&

Scalar Electrodynamics

Mastering CalcHEP/CompHEP

Enter menu selection

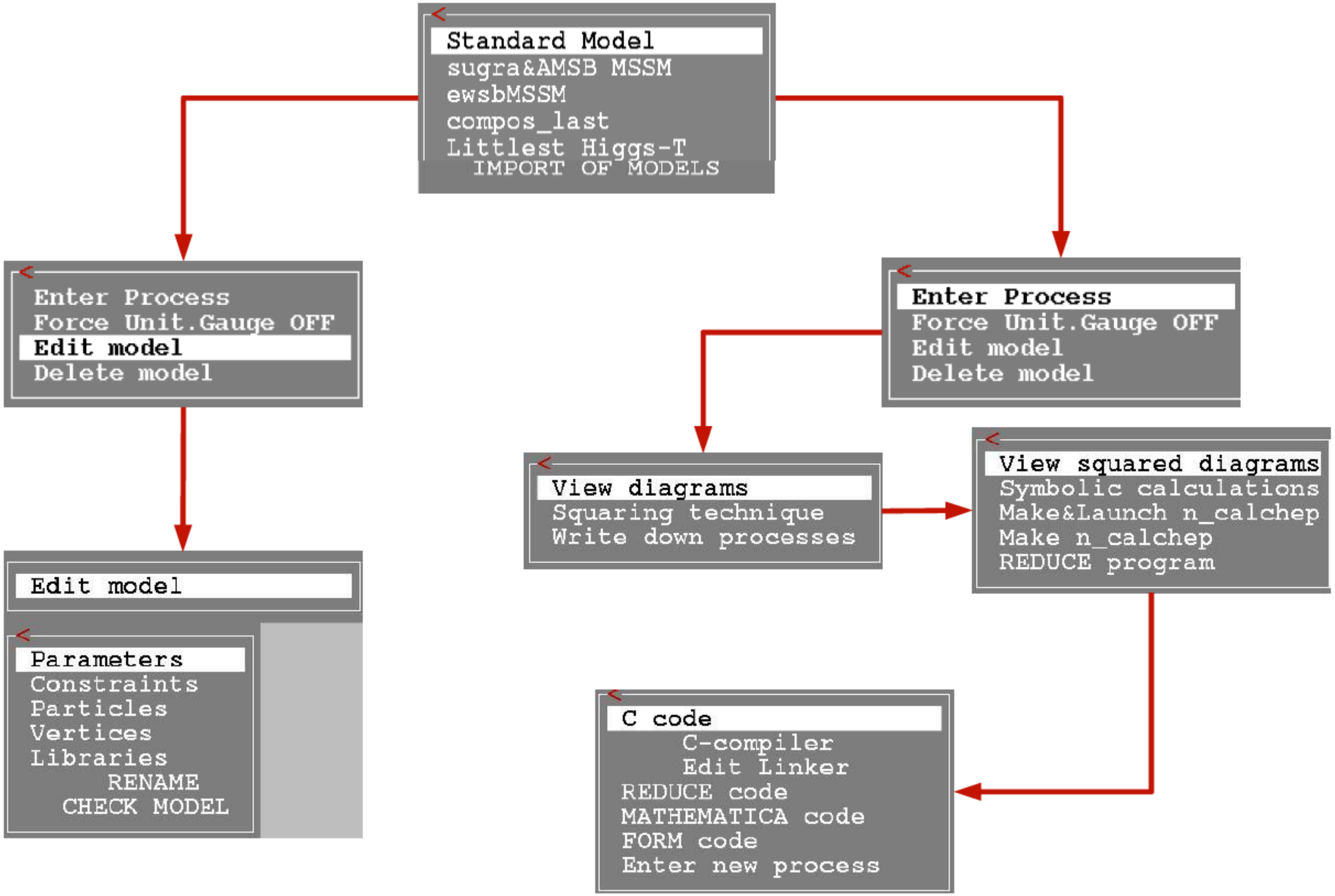
Exit menu selection

Help

Move up and down in each menu

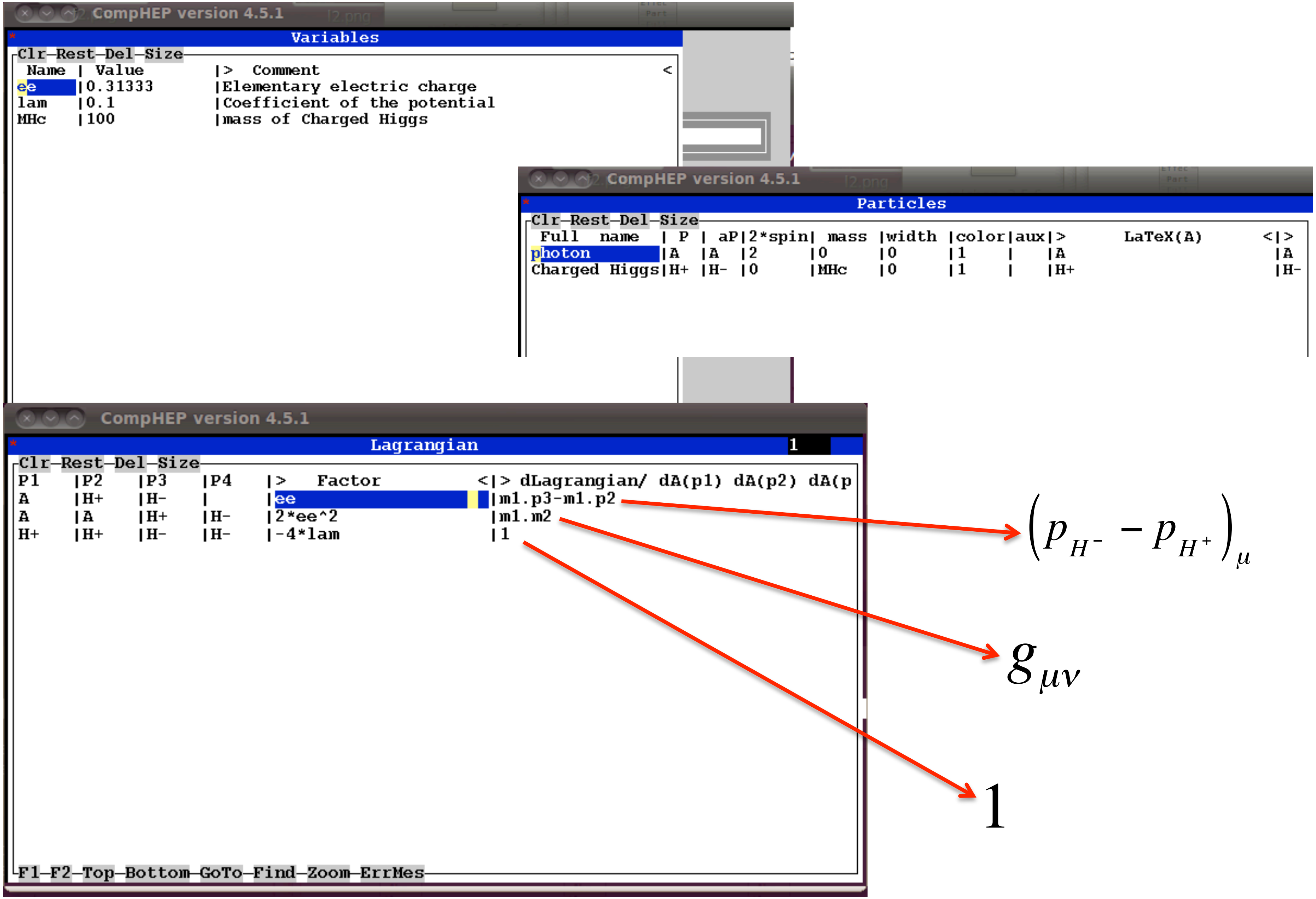
Scalar Electrodynamics

The CalcHEP/CompHEP menus



Scalar Electrodynamics

The model menu



```
                        Variables
Clr-Rest-Del-Size
 Name | Value          |>  Comment                         <
ee    |0.31333         |Elementary electric charge
lam   |0.1             |Coefficient of the potential
MHc   |100             |mass of Charged Higgs
```

```
                        Particles
Clr-Rest-Del-Size
 Full   name   | P | aP|2*spin| mass |width |color|aux|>    LaTeX(A)     <|>
photon         |A  |A  |2     |0     |0     |1    |   |A                 |A
Charged Higgs|H+ |H- |0     |MHc   |0     |1    |   |H+                |H-
```

```
                        Lagrangian                              1
Clr-Rest-Del-Size
P1    |P2    |P3    |P4    |>    Factor          <|> dLagrangian/ dA(p1) dA(p2) dA(p
A     |H+    |H-    |      |ee                   |m1.p3-m1.p2
A     |A     |H+    |H-    |2*ee^2               |m1.m2
H+    |H+    |H-    |H-    |-4*lam               |1




F1-F2-Top-Bottom-GoTo-Find-Zoom-ErrMes
```

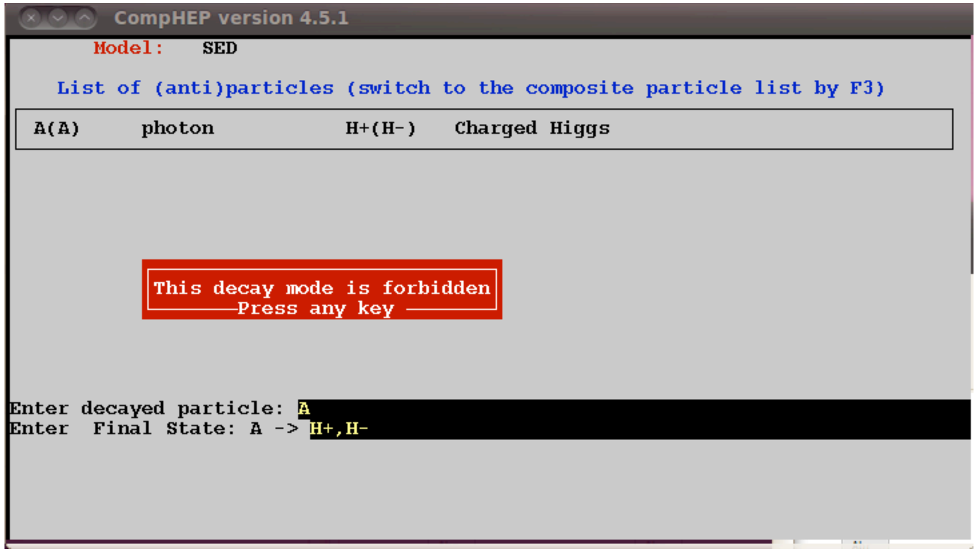
$$\left(p_{H^-} - p_{H^+}\right)_\mu$$

$$g_{\mu\nu}$$

$$1$$

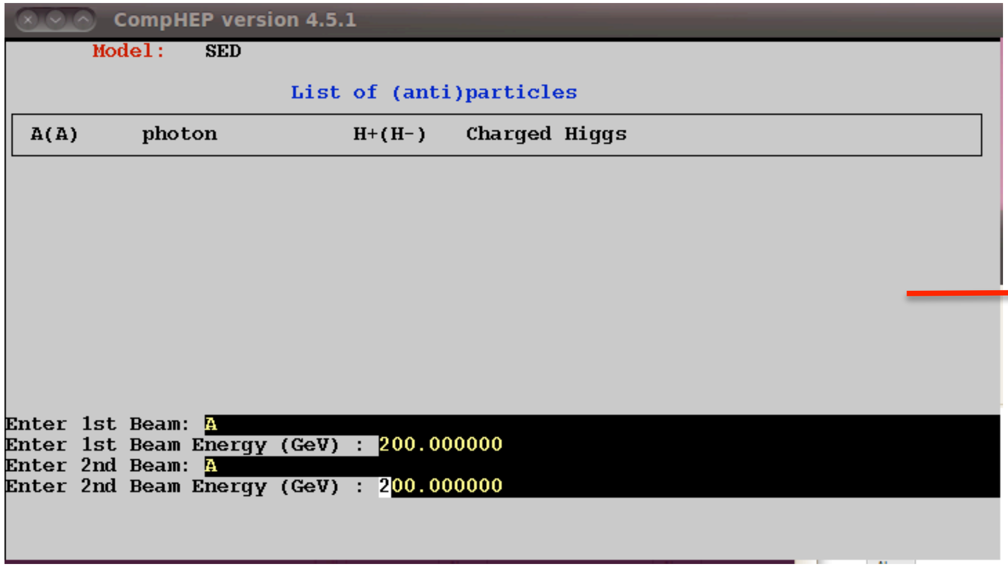
Scalar Electrodynamics

A simple calculation

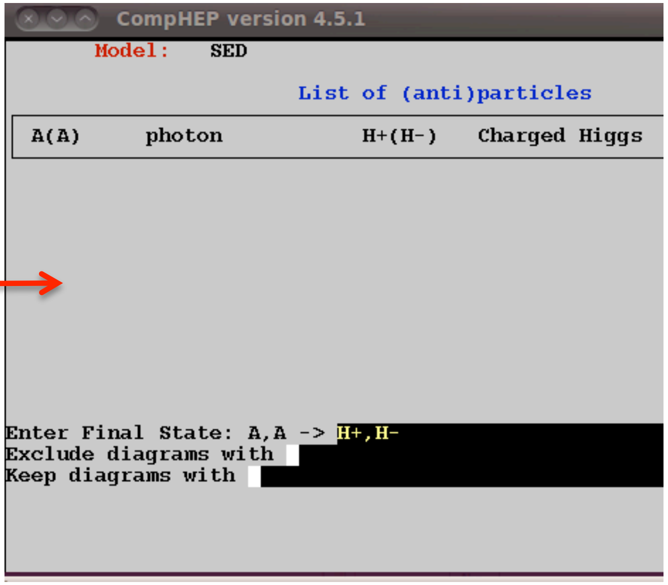


```
CompHEP version 4.5.1
      Model:    SED

   List of (anti)particles (switch to the composite particle list by F3)
 A(A)      photon            H+(H-)    Charged Higgs

           This decay mode is forbidden
                   Press any key

Enter decayed particle: A
Enter  Final State: A -> H+,H-
```

We could start with a decay…or not…



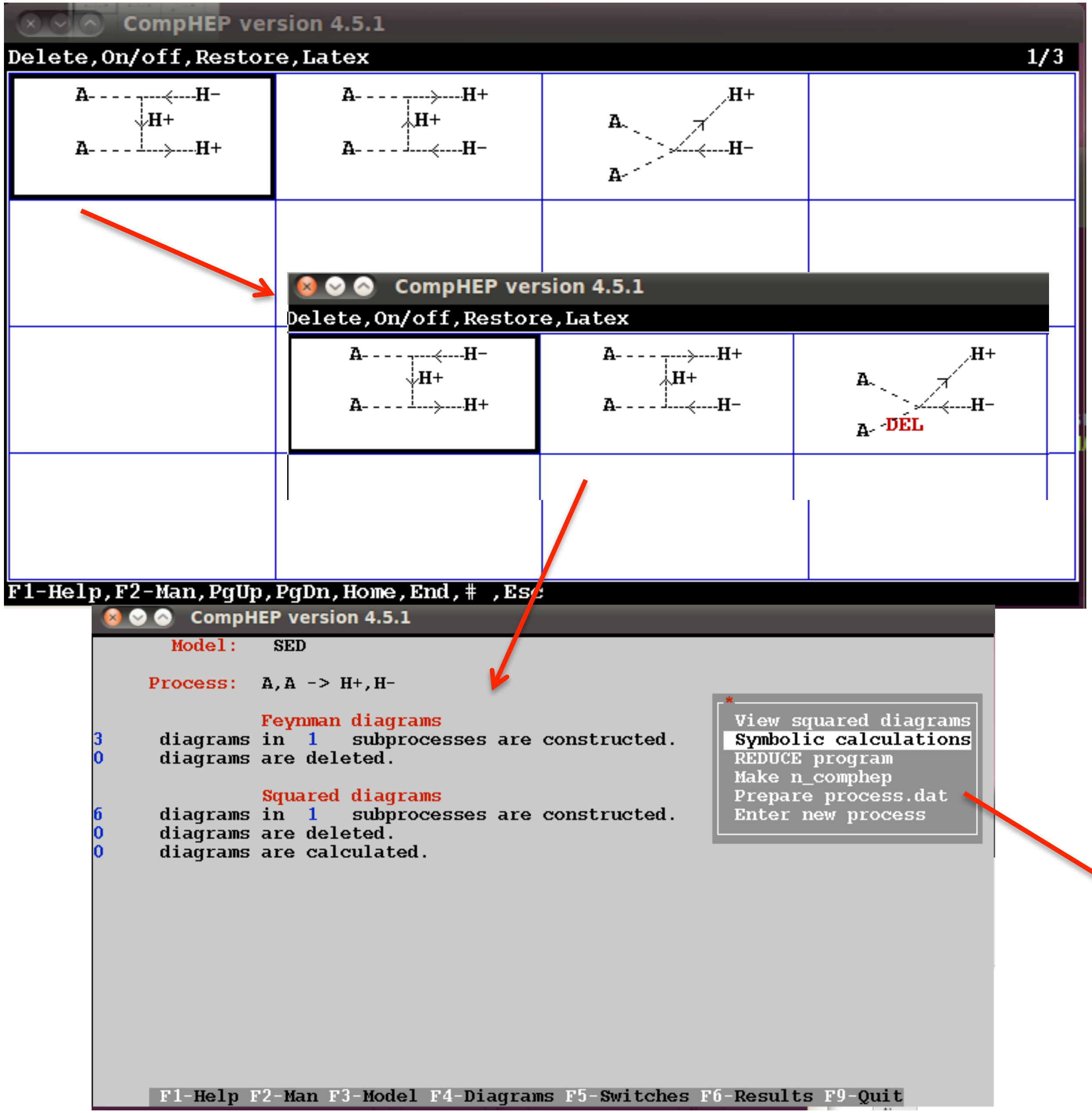
```
CompHEP version 4.5.1
      Model:    SED

                    List of (anti)particles
 A(A)      photon            H+(H-)    Charged Higgs

Enter 1st Beam: A
Enter 1st Beam Energy (GeV) : 200.000000
Enter 2nd Beam: A
Enter 2nd Beam Energy (GeV) : 200.000000
```



```
CompHEP version 4.5.1
      Model:    SED

                    List of (anti)particles
 A(A)      photon            H+(H-)    Charged Higgs

Enter Final State: A,A -> H+,H-
Exclude diagrams with
Keep diagrams with
```

Scalar Electrodynamics

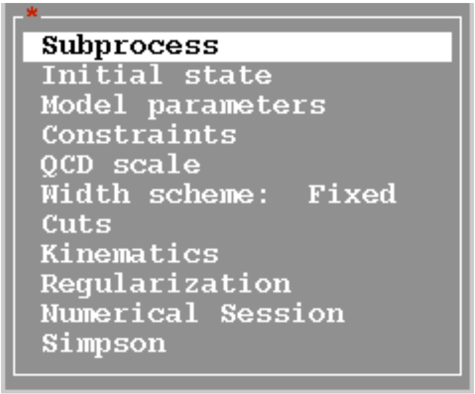
A simple calculation



```
CompHEP version 4.5.1
Delete,On/off,Restore,Latex                                      1/3
F1-Help,F2-Man,PgUp,PgDn,Home,End,#  ,Esc
```

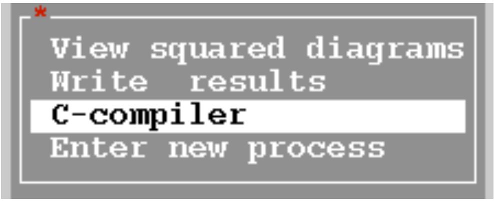
```
CompHEP version 4.5.1
    Model:    SED

   Process:   A,A -> H+,H-

              Feynman diagrams
3     diagrams in  1   subprocesses are constructed.
0     diagrams are deleted.

              Squared diagrams
6     diagrams in  1   subprocesses are constructed.
0     diagrams are deleted.
0     diagrams are calculated.

  F1-Help F2-Man F3-Model F4-Diagrams F5-Switches F6-Results F9-Quit
```

```
*
 View squared diagrams
 Symbolic calculations
 REDUCE program
 Make n_comphep
 Prepare process.dat
 Enter new process
```



```
*
 Subprocess
 Initial  state
 Model parameters
 Constraints
 QCD scale
 Width scheme:  Fixed
 Cuts
 Kinematics
 Regularization
 Numerical Session
 Simpson
```

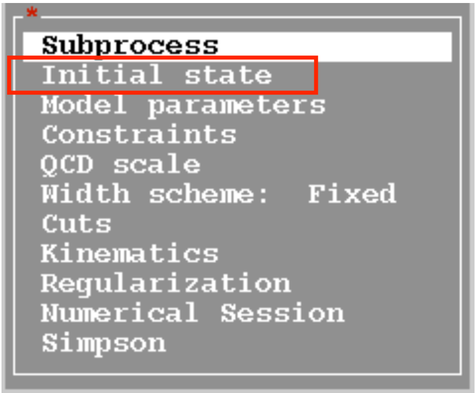
A new window appears



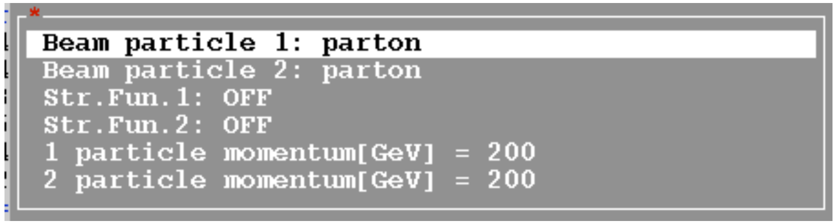
```
*
 View squared diagrams
 Write  results
 C-compiler
 Enter new process
```

Scalar Electrodynamics

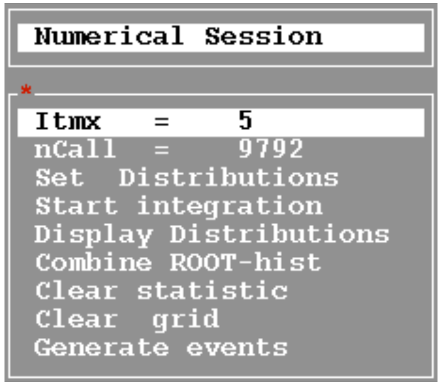
Parton Level



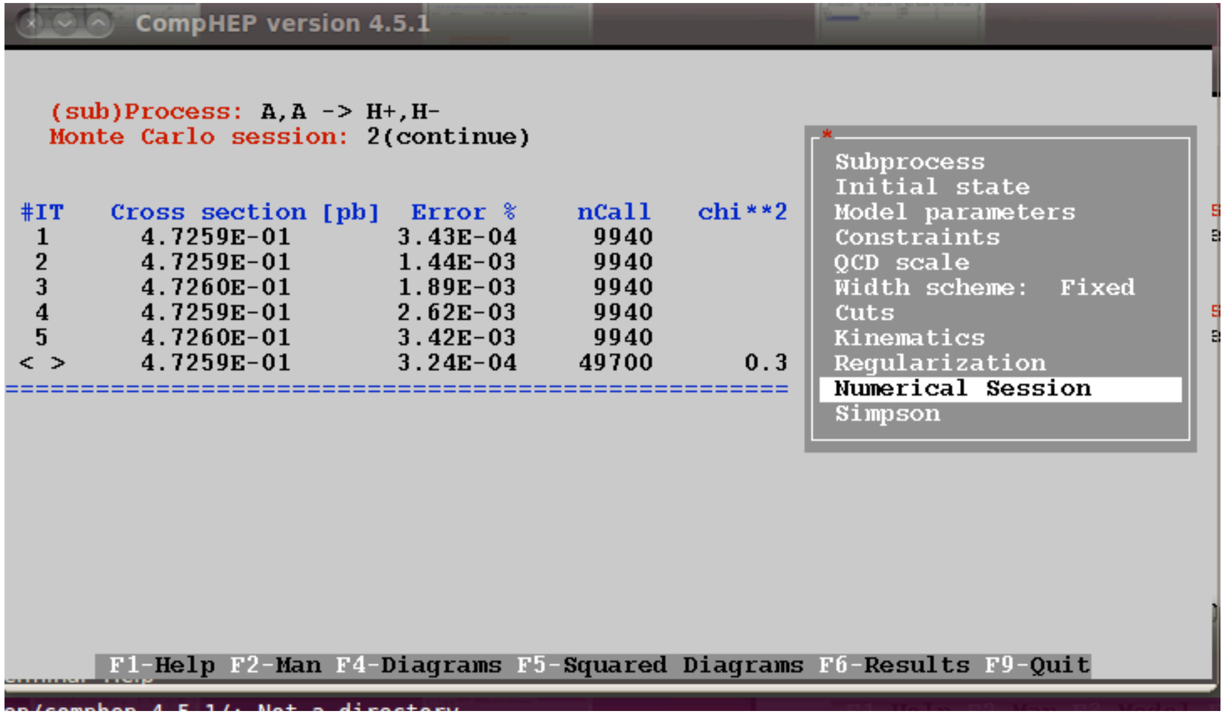
```
*
Subprocess
Initial state
Model parameters
Constraints
QCD scale
Width scheme:  Fixed
Cuts
Kinematics
Regularization
Numerical Session
Simpson
```



```
*
Beam particle 1: parton
Beam particle 2: parton
Str.Fun.1: OFF
Str.Fun.2: OFF
1 particle momentum[GeV] = 200
2 particle momentum[GeV] = 200
```



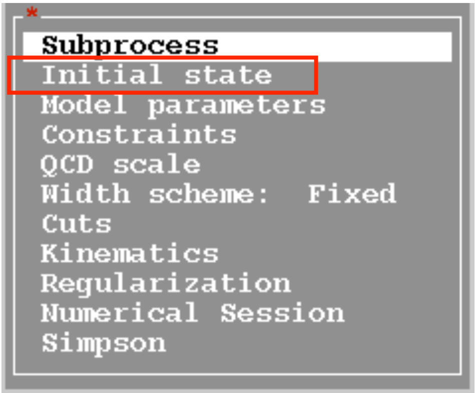
```
Numerical Session
*
Itmx    =     5
nCall   =     9792
Set  Distributions
Start integration
Display Distributions
Combine ROOT-hist
Clear statistic
Clear  grid
Generate events
```



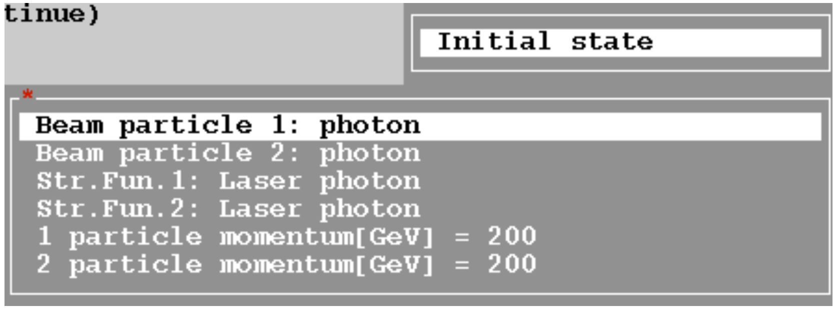
```
CompHEP version 4.5.1

 (sub)Process: A,A -> H+,H-
 Monte Carlo session: 2(continue)

#IT   Cross section [pb]  Error %     nCall    chi**2
 1      4.7259E-01        3.43E-04     9940
 2      4.7259E-01        1.44E-03     9940
 3      4.7260E-01        1.89E-03     9940
 4      4.7259E-01        2.62E-03     9940
 5      4.7260E-01        3.42E-03     9940
< >     4.7259E-01        3.24E-04    49700       0.3
==================================================

*
Subprocess
Initial state
Model parameters
Constraints
QCD scale
Width scheme:  Fixed
Cuts
Kinematics
Regularization
Numerical Session
Simpson

 F1-Help F2-Man F4-Diagrams F5-Squared Diagrams F6-Results F9-Quit
ep/comphep-4.5.1/: Not a directory
```

Scalar Electrodynamics

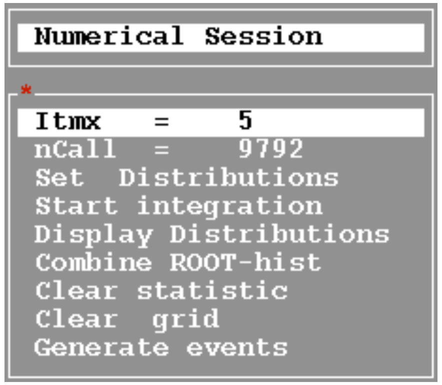
Structure function



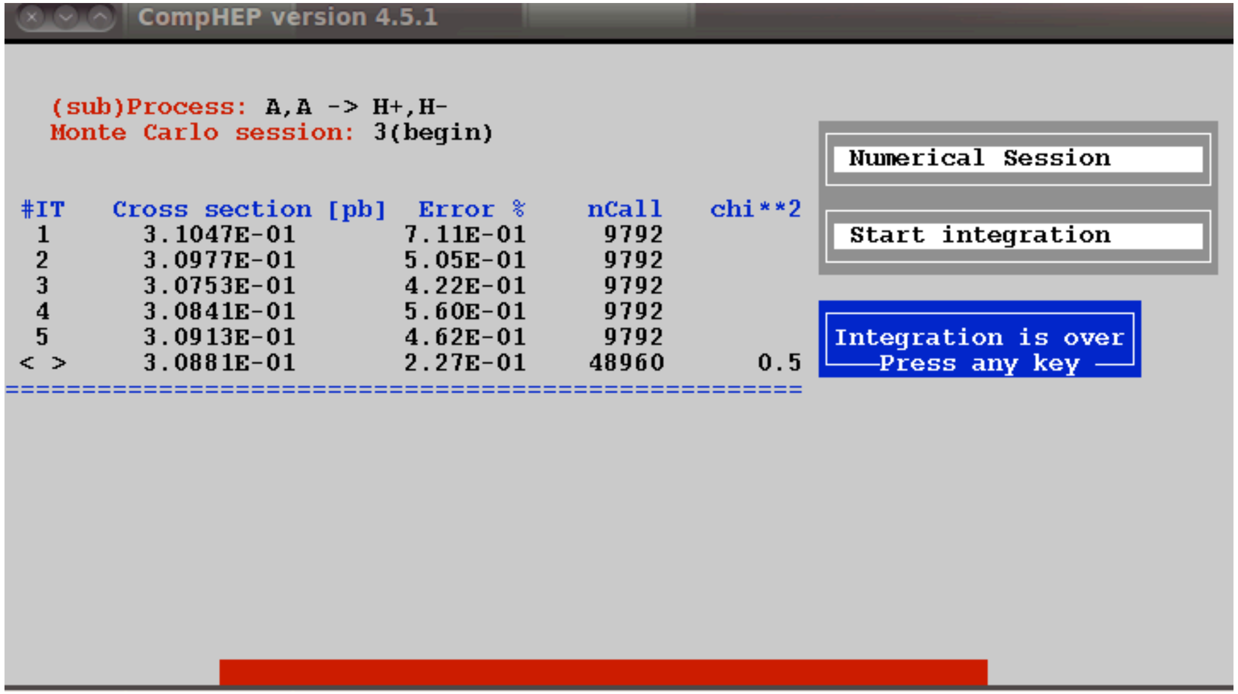
```
*
 Subprocess
 Initial state
 Model parameters
 Constraints
 QCD scale
 Width scheme:  Fixed
 Cuts
 Kinematics
 Regularization
 Numerical Session
 Simpson
```



```
tinue)                   Initial state
*
 Beam particle 1: photon
 Beam particle 2: photon
 Str.Fun.1: Laser photon
 Str.Fun.2: Laser photon
 1 particle momentum[GeV] = 200
 2 particle momentum[GeV] = 200
```



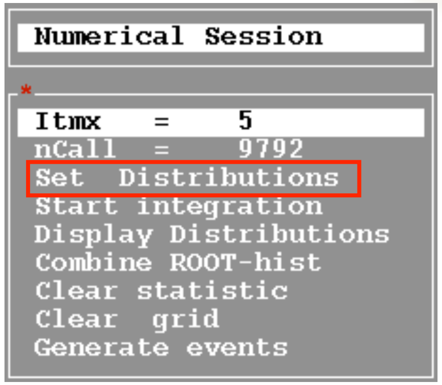
```
 Numerical Session
*
 Itmx    =     5
 nCall   =     9792
 Set  Distributions
 Start integration
 Display Distributions
 Combine ROOT-hist
 Clear statistic
 Clear  grid
 Generate events
```



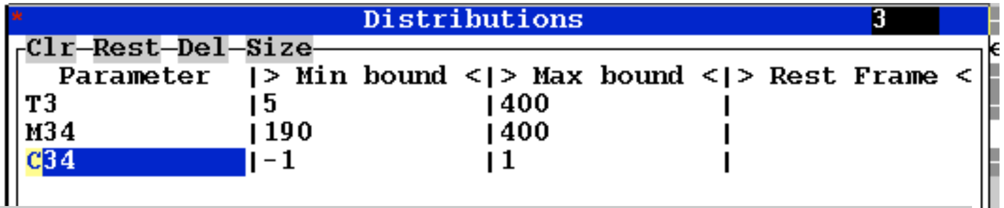
```
CompHEP version 4.5.1

  (sub)Process: A,A -> H+,H-
  Monte Carlo session: 3(begin)                       Numerical Session

#IT    Cross section [pb]   Error %     nCall   chi**2   Start integration
 1       3.1047E-01         7.11E-01     9792
 2       3.0977E-01         5.05E-01     9792
 3       3.0753E-01         4.22E-01     9792
 4       3.0841E-01         5.60E-01     9792            Integration is over
 5       3.0913E-01         4.62E-01     9792               Press any key
< >      3.0881E-01         2.27E-01    48960      0.5
===================================================
```

Scalar Electrodynamics

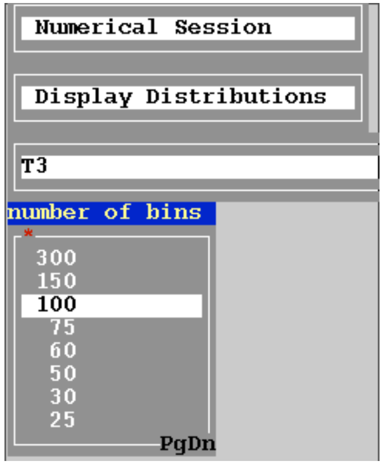
Distributions



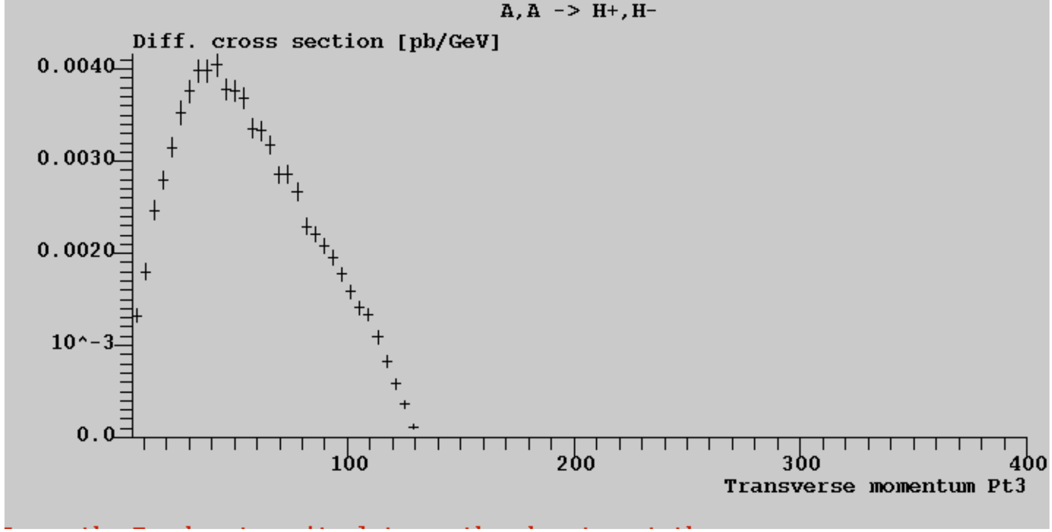
```
Numerical Session
*
Itmx    =     5
nCall   =     9792
Set  Distributions
Start integration
Display Distributions
Combine ROOT-hist
Clear statistic
Clear  grid
Generate events
```

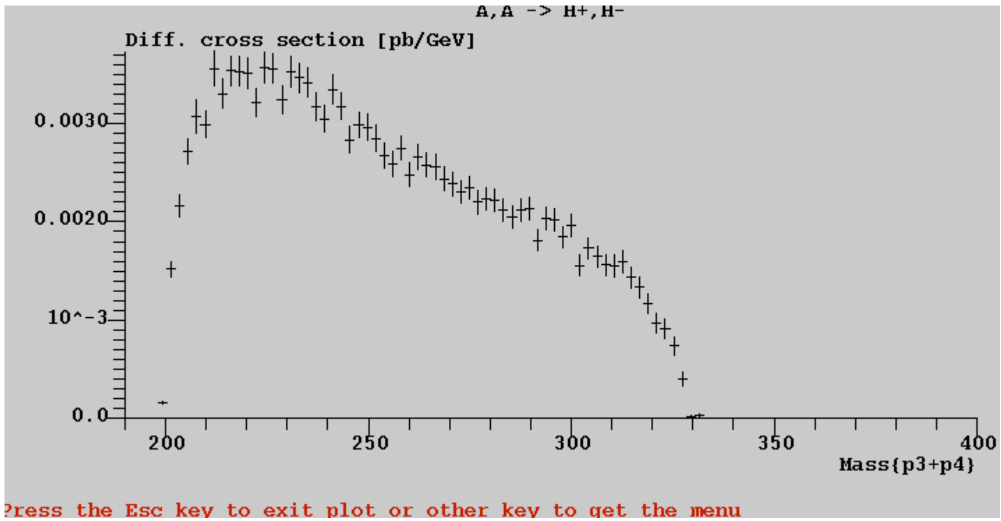


```
* Distributions                                   3
Clr-Rest-Del-Size
 Parameter   |> Min bound <|> Max bound <|> Rest Frame <
T3           |5            |400          |
M34          |190          |400          |
C34          |-1           |1            |
```



```
Numerical Session

Display Distributions

T3
number of bins
*
 300
 150
 100
  75
  60
  50
  30
  25
             PgDn
```

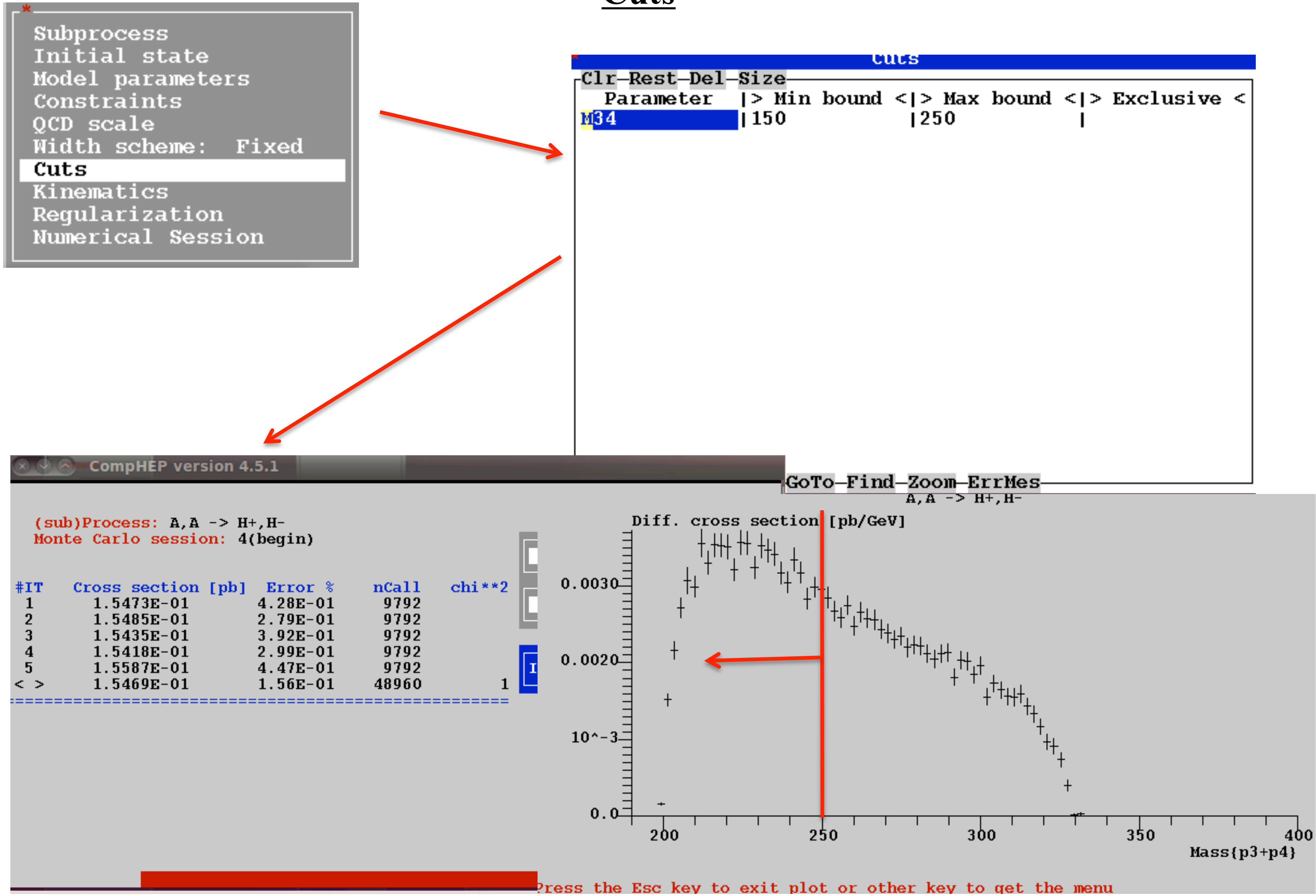




Press the Esc key to exit plot or other key to get the menu

Scalar Electrodynamics

Cuts



```
*
 Subprocess
 Initial state
 Model parameters
 Constraints
 QCD scale
 Width scheme:  Fixed
 Cuts
 Kinematics
 Regularization
 Numerical Session
```

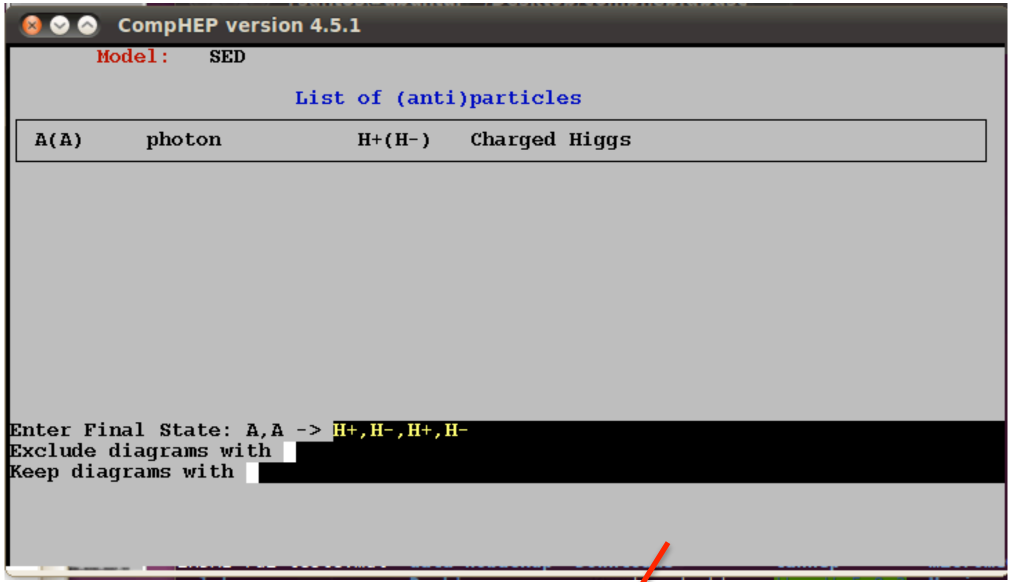
```
                              Cuts
Clr-Rest-Del-Size
  Parameter    |> Min bound <|> Max bound <|> Exclusive <
M34            |150          |250          |
```

```
CompHEP version 4.5.1

(sub)Process: A,A -> H+,H-
Monte Carlo session: 4(begin)

#IT  Cross section [pb]  Error %    nCall   chi**2
 1     1.5473E-01       4.28E-01    9792
 2     1.5485E-01       2.79E-01    9792
 3     1.5435E-01       3.92E-01    9792
 4     1.5418E-01       2.99E-01    9792
 5     1.5587E-01       4.47E-01    9792
< >    1.5469E-01       1.56E-01   48960        1
==================================================
```

```
GoTo-Find-Zoom-ErrMes
A,A -> H+,H-
Press the Esc key to exit plot or other key to get the menu
```

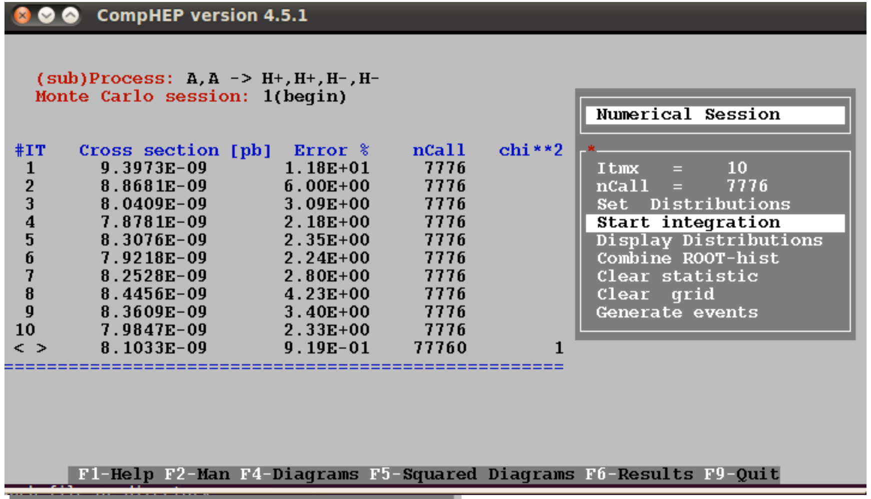
Scalar Electrodynamics

A not so simple calculation



CompHEP version 4.5.1

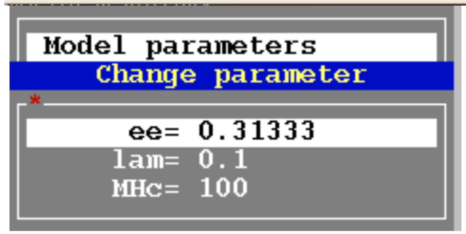
```
      Model:    SED

                  List of (anti)particles

 A(A)      photon            H+(H-)    Charged Higgs

Enter Final State: A,A -> H+,H-,H+,H-
Exclude diagrams with
Keep diagrams with
```



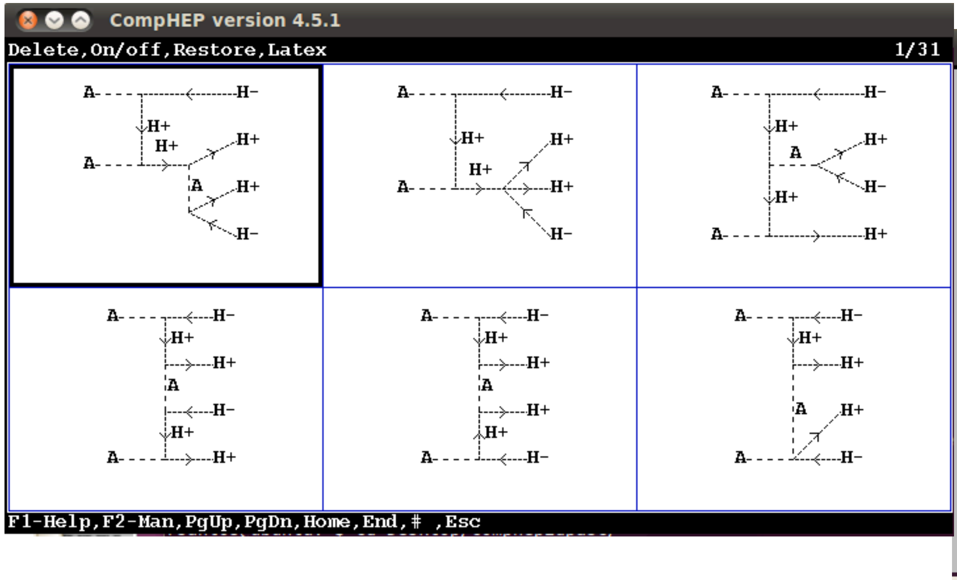
CompHEP version 4.5.1

```
 (sub)Process: A,A -> H+,H+,H-,H-
 Monte Carlo session: 1(begin)

#IT  Cross section [pb]  Error %    nCall   chi**2
 1      9.3973E-09       1.18E+01    7776
 2      8.8681E-09       6.00E+00    7776
 3      8.0409E-09       3.09E+00    7776
 4      7.8781E-09       2.18E+00    7776
 5      8.3076E-09       2.35E+00    7776
 6      7.9218E-09       2.24E+00    7776
 7      8.2528E-09       2.80E+00    7776
 8      8.4456E-09       4.23E+00    7776
 9      8.3609E-09       3.40E+00    7776
10      7.9847E-09       2.33E+00    7776
< >     8.1033E-09       9.19E-01   77760       1
==================================================
```

```
Numerical Session
 Itmx   =      10
 nCall  =     7776
```

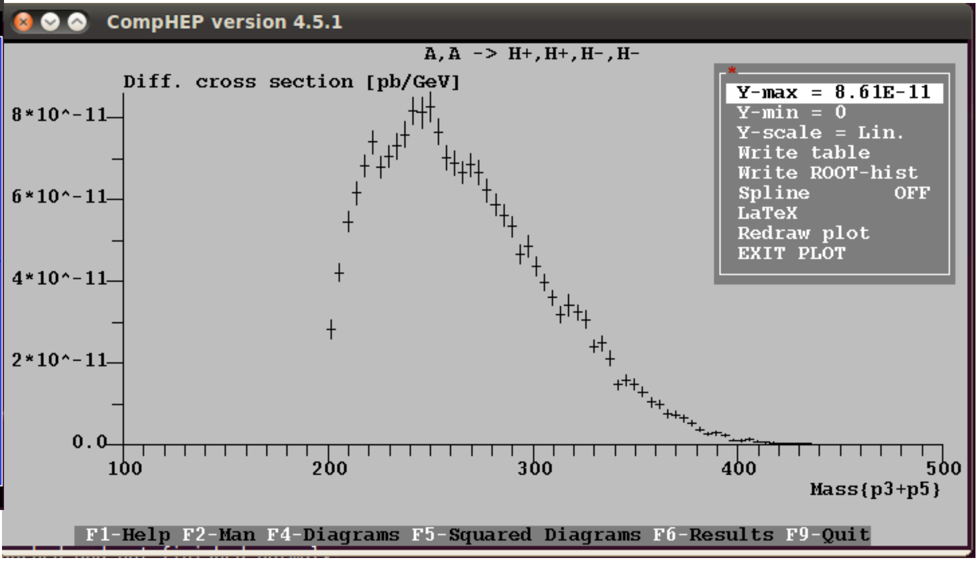


```
 Model parameters
  Change parameter

   ee= 0.31333
  lam= 0.1
  MHc= 100
```



CompHEP version 4.5.1

Delete,On/off,Restore,Latex
1/31
A
H-
H+
A
H+
H-
F1-Help,F2-Man,PgUp,PgDn,Home,End,# ,Esc



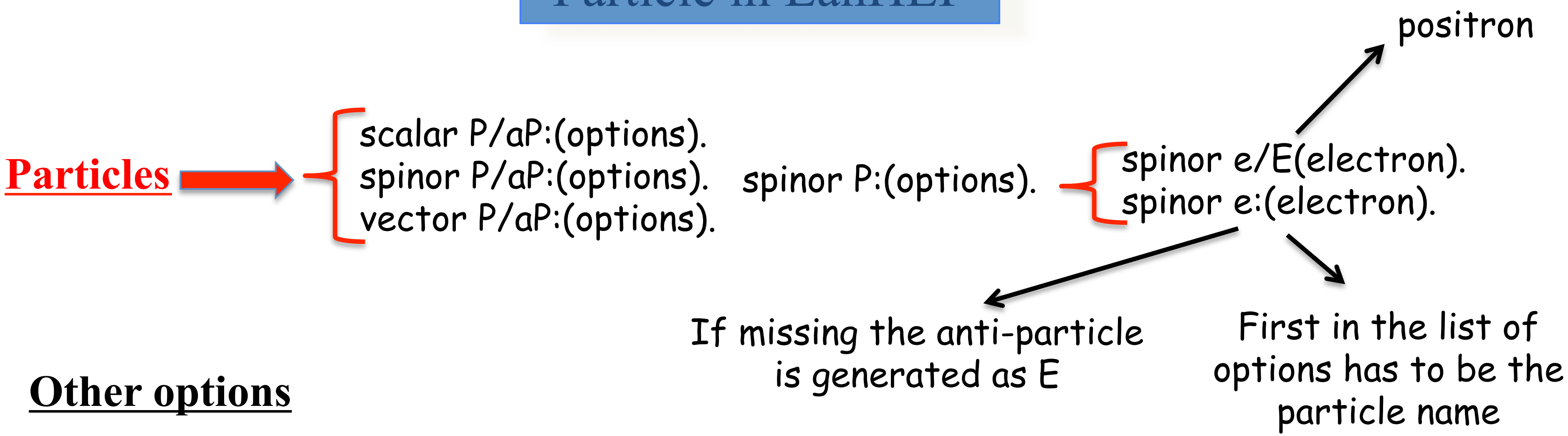
CompHEP version 4.5.1

```
Y-max = 8.61E-11
Y-min = 0
Y-scale = Lin.
Spline        OFF
```

and now for something completely different – the Larch

…or the SM and a 2HDM in LanHEP plus THE BATCH FILE in CalcHEP

Particle in LanHEP



Particles

scalar P/aP:(options).
spinor P/aP:(options).
vector P/aP:(options).

spinor P:(options).

spinor e/E(electron).
spinor e:(electron).

positron

If missing the anti-particle is generated as E

First in the list of options has to be the particle name

Other options

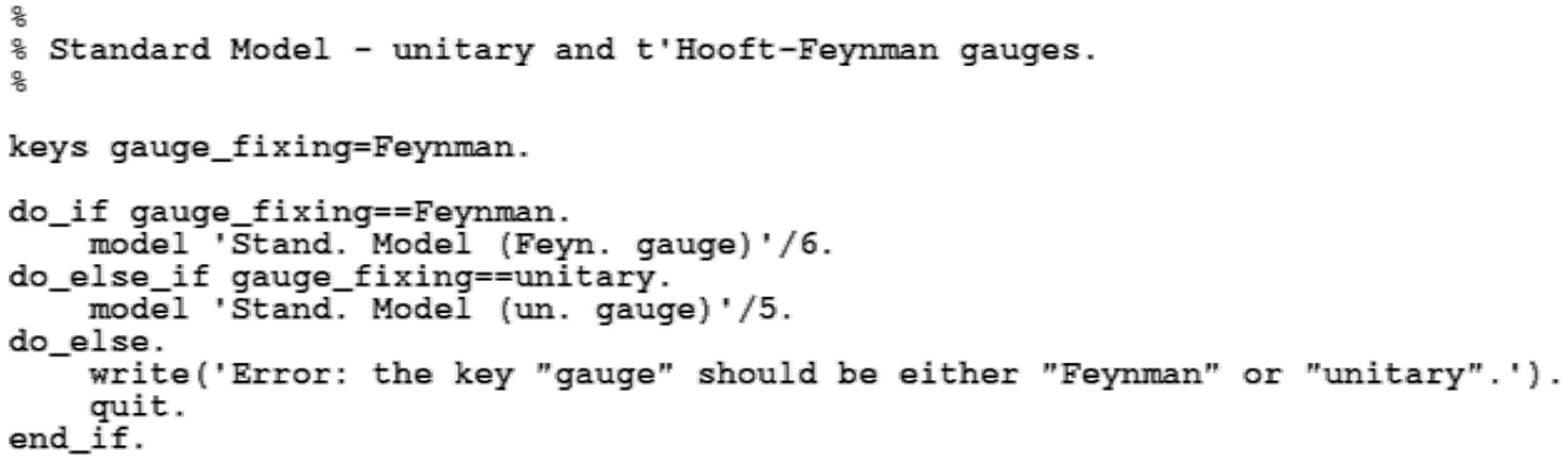
- mass   spinor e1/E1:(electron, mass Me = 0.005)   mass in GeV
- width   spinor t:('t-quark',color c3, mass Mtop = 175, width wtop = 1.6) width in GeV
- left/right spinor n2:('mu-neutrino',left) note the quotes in mu-neutrino
- gauge   vector Z/Z:('Z boson', mass MZ = 91.187, width wZ = 2.504,gauge)

Generates the names for Goldstone bosons (Z.f) and Ghosts (Z.c)

Built-in functions to define fields

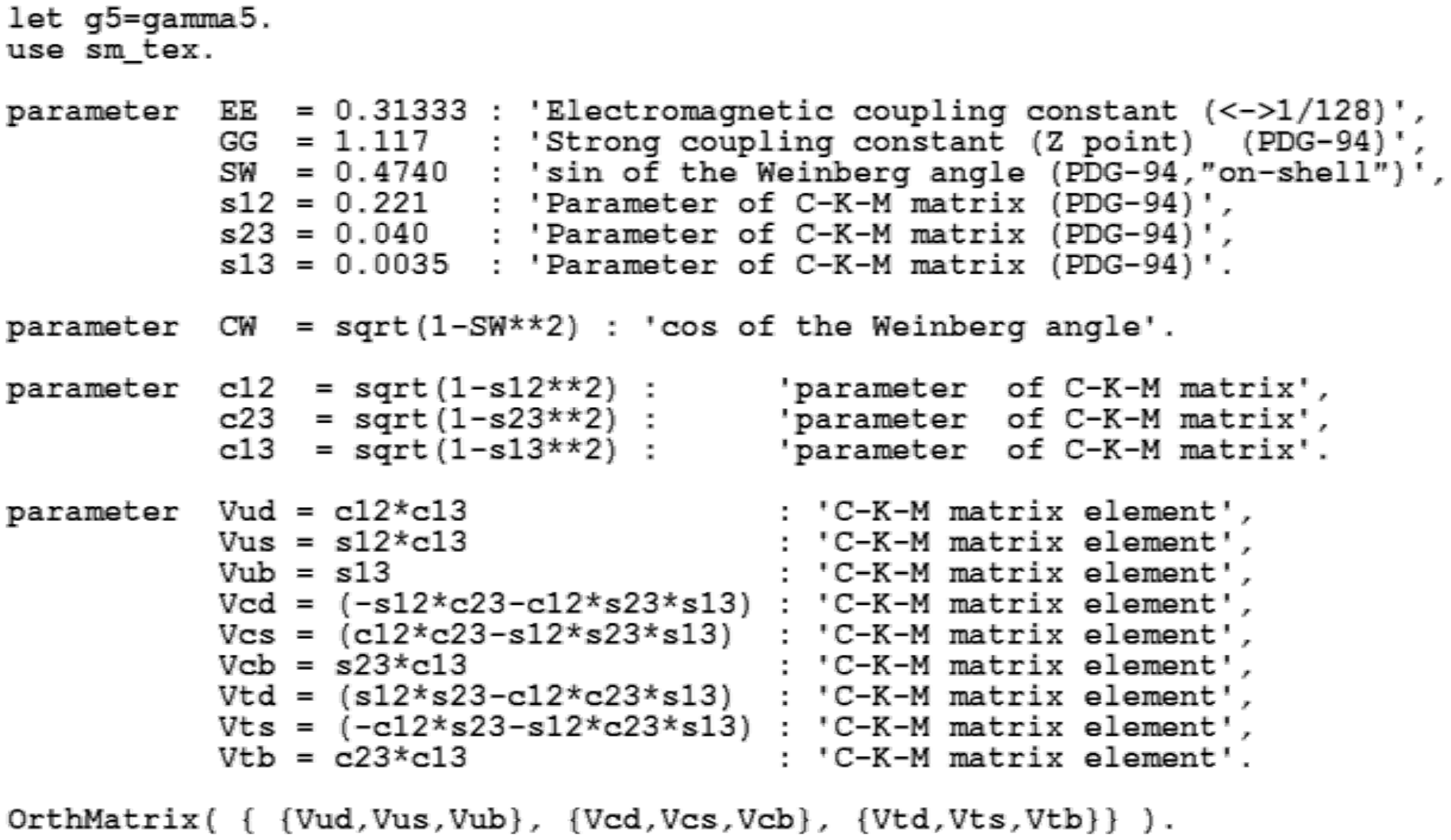
- Ghost field ghost(name)
- Goldstone boson field gsb(name)
- Anti-field anti(name)

Building the Standard Model in LanHEP



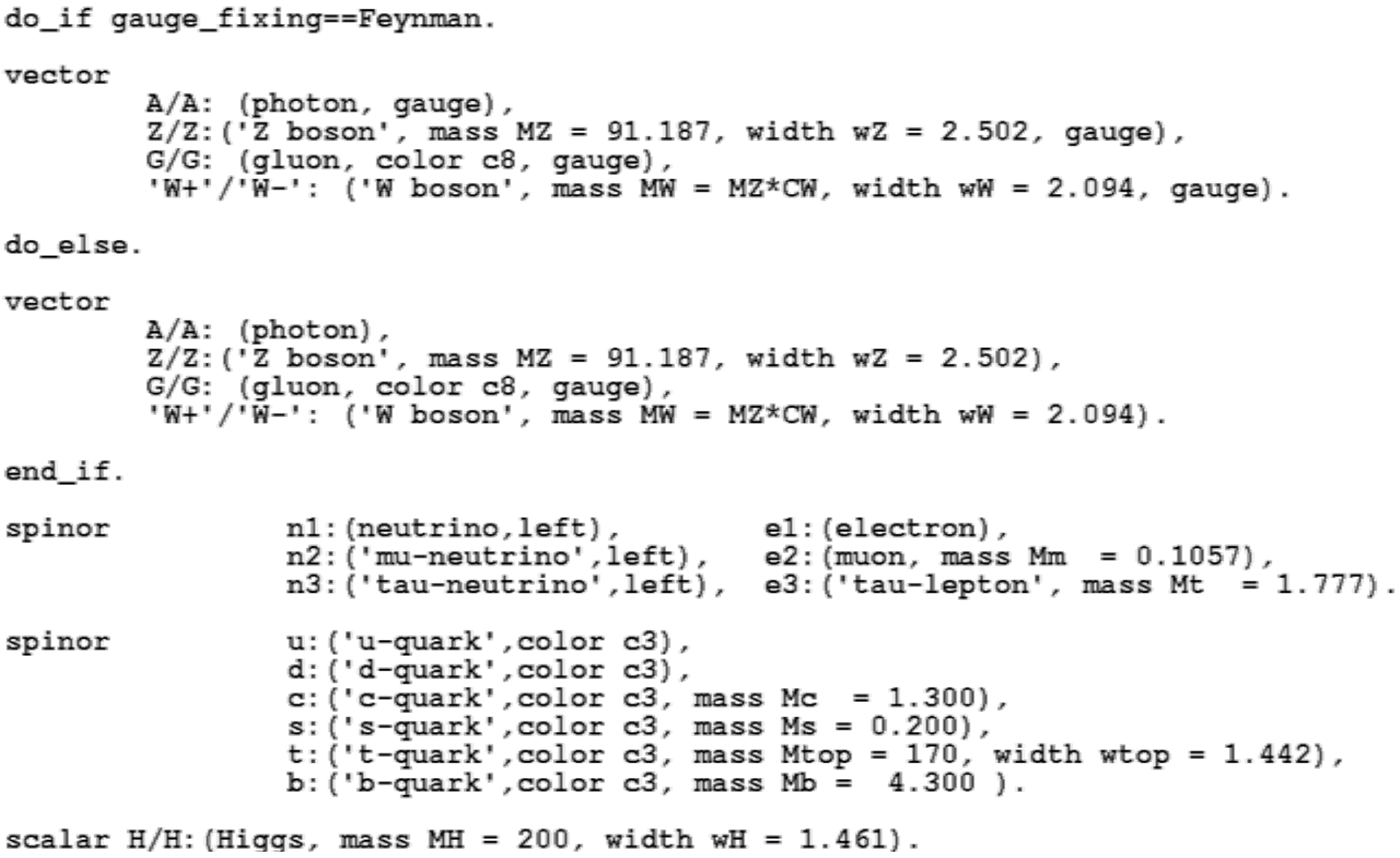
```
%
% Standard Model - unitary and t'Hooft-Feynman gauges.
%

keys gauge_fixing=Feynman.

do_if gauge_fixing==Feynman.
    model 'Stand. Model (Feyn. gauge)'/6.
do_else_if gauge_fixing==unitary.
    model 'Stand. Model (un. gauge)'/5.
do_else.
    write('Error: the key "gauge" should be either "Feynman" or "unitary".').
    quit.
end_if.
```

Building the Standard Model in LanHEP



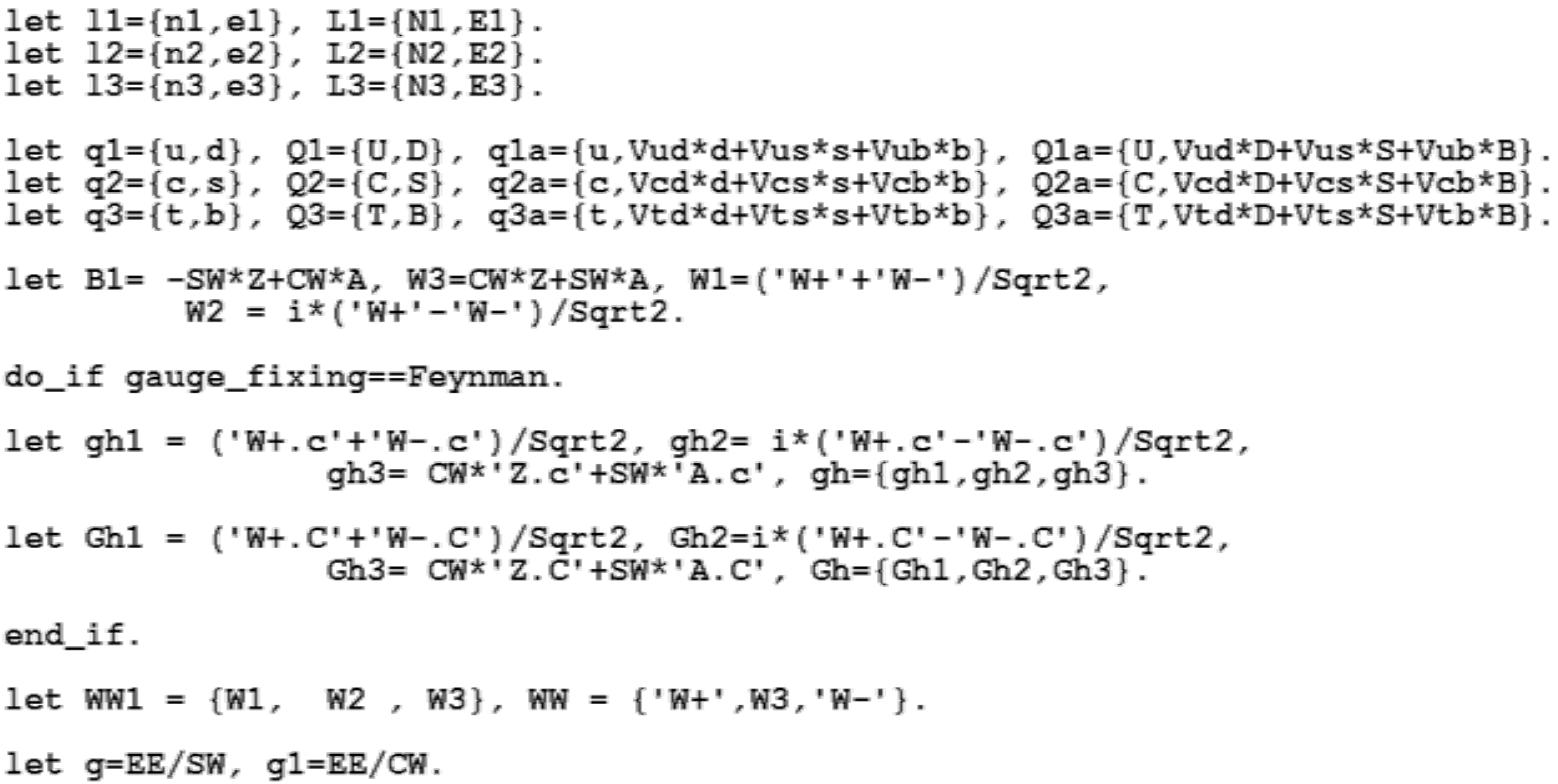
```
let g5=gamma5.
use sm_tex.

parameter  EE  = 0.31333 : 'Electromagnetic coupling constant (<->1/128)',
           GG  = 1.117   : 'Strong coupling constant (Z point)  (PDG-94)',
           SW  = 0.4740  : 'sin of the Weinberg angle (PDG-94,"on-shell")',
           s12 = 0.221   : 'Parameter of C-K-M matrix (PDG-94)',
           s23 = 0.040   : 'Parameter of C-K-M matrix (PDG-94)',
           s13 = 0.0035  : 'Parameter of C-K-M matrix (PDG-94)'.

parameter  CW  = sqrt(1-SW**2) : 'cos of the Weinberg angle'.

parameter  c12  = sqrt(1-s12**2) :      'parameter  of C-K-M matrix',
           c23  = sqrt(1-s23**2) :      'parameter  of C-K-M matrix',
           c13  = sqrt(1-s13**2) :      'parameter  of C-K-M matrix'.

parameter  Vud = c12*c13                : 'C-K-M matrix element',
           Vus = s12*c13                : 'C-K-M matrix element',
           Vub = s13                    : 'C-K-M matrix element',
           Vcd = (-s12*c23-c12*s23*s13) : 'C-K-M matrix element',
           Vcs = (c12*c23-s12*s23*s13)  : 'C-K-M matrix element',
           Vcb = s23*c13                : 'C-K-M matrix element',
           Vtd = (s12*s23-c12*c23*s13)  : 'C-K-M matrix element',
           Vts = (-c12*s23-s12*c23*s13) : 'C-K-M matrix element',
           Vtb = c23*c13                : 'C-K-M matrix element'.

OrthMatrix( { {Vud,Vus,Vub}, {Vcd,Vcs,Vcb}, {Vtd,Vts,Vtb}} ).
```

Building the Standard Model in LanHEP



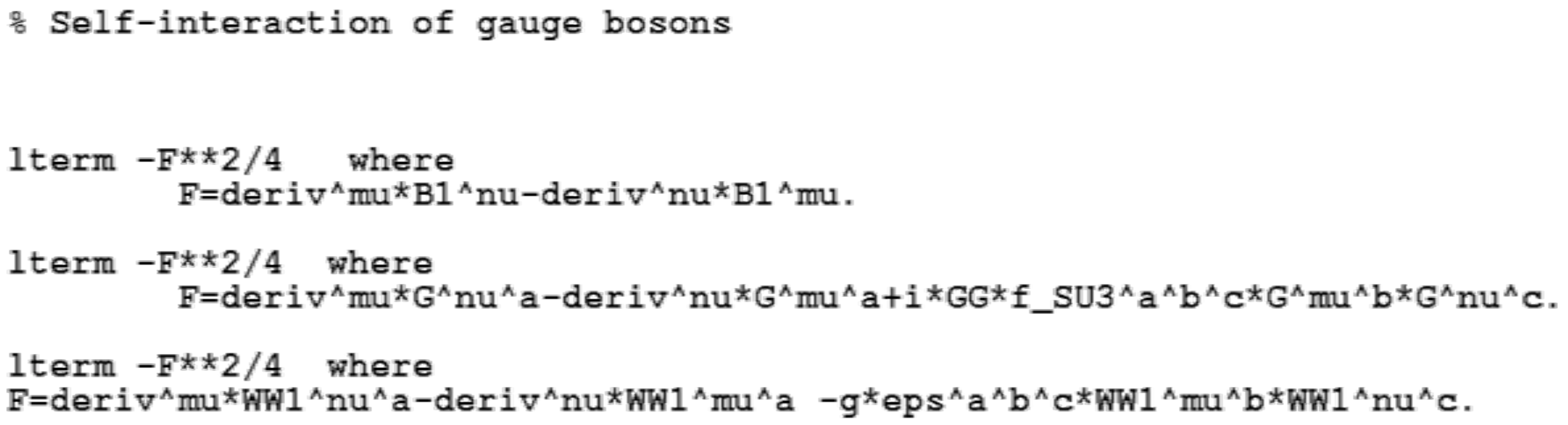
```
do_if gauge_fixing==Feynman.

vector
        A/A: (photon, gauge),
        Z/Z:('Z boson', mass MZ = 91.187, width wZ = 2.502, gauge),
        G/G: (gluon, color c8, gauge),
        'W+'/'W-': ('W boson', mass MW = MZ*CW, width wW = 2.094, gauge).

do_else.

vector
        A/A: (photon),
        Z/Z:('Z boson', mass MZ = 91.187, width wZ = 2.502),
        G/G: (gluon, color c8, gauge),
        'W+'/'W-': ('W boson', mass MW = MZ*CW, width wW = 2.094).

end_if.

spinor          n1:(neutrino,left),         e1:(electron),
                n2:('mu-neutrino',left),    e2:(muon, mass Mm  = 0.1057),
                n3:('tau-neutrino',left),   e3:('tau-lepton', mass Mt  = 1.777).

spinor          u:('u-quark',color c3),
                d:('d-quark',color c3),
                c:('c-quark',color c3, mass Mc  = 1.300),
                s:('s-quark',color c3, mass Ms = 0.200),
                t:('t-quark',color c3, mass Mtop = 170, width wtop = 1.442),
                b:('b-quark',color c3, mass Mb =  4.300 ).

scalar H/H:(Higgs, mass MH = 200, width wH = 1.461).
```

Building the Standard Model in LanHEP



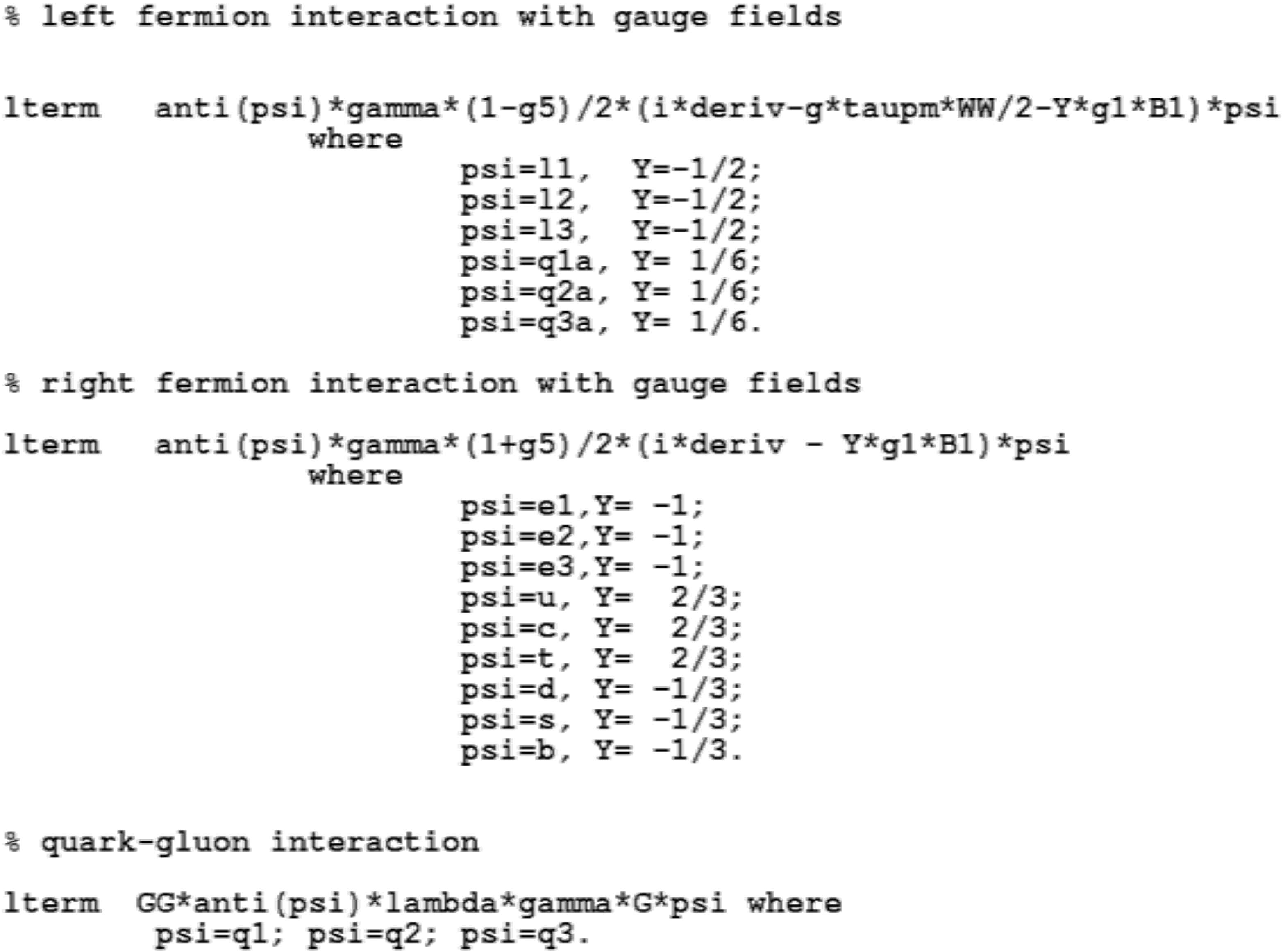
```
let l1={n1,e1}, L1={N1,E1}.
let l2={n2,e2}, L2={N2,E2}.
let l3={n3,e3}, L3={N3,E3}.

let q1={u,d}, Q1={U,D}, q1a={u,Vud*d+Vus*s+Vub*b}, Q1a={U,Vud*D+Vus*S+Vub*B}.
let q2={c,s}, Q2={C,S}, q2a={c,Vcd*d+Vcs*s+Vcb*b}, Q2a={C,Vcd*D+Vcs*S+Vcb*B}.
let q3={t,b}, Q3={T,B}, q3a={t,Vtd*d+Vts*s+Vtb*b}, Q3a={T,Vtd*D+Vts*S+Vtb*B}.

let B1= -SW*Z+CW*A, W3=CW*Z+SW*A, W1=('W+'+'W-')/Sqrt2,
         W2 = i*('W+'-'W-')/Sqrt2.

do_if gauge_fixing==Feynman.

let gh1 = ('W+.c'+'W-.c')/Sqrt2, gh2= i*('W+.c'-'W-.c')/Sqrt2,
                gh3= CW*'Z.c'+SW*'A.c', gh={gh1,gh2,gh3}.

let Gh1 = ('W+.C'+'W-.C')/Sqrt2, Gh2=i*('W+.C'-'W-.C')/Sqrt2,
                Gh3= CW*'Z.C'+SW*'A.C', Gh={Gh1,Gh2,Gh3}.

end_if.

let WW1 = {W1,  W2 , W3}, WW = {'W+',W3,'W-'}.

let g=EE/SW, g1=EE/CW.
```

Building the Standard Model in LanHEP



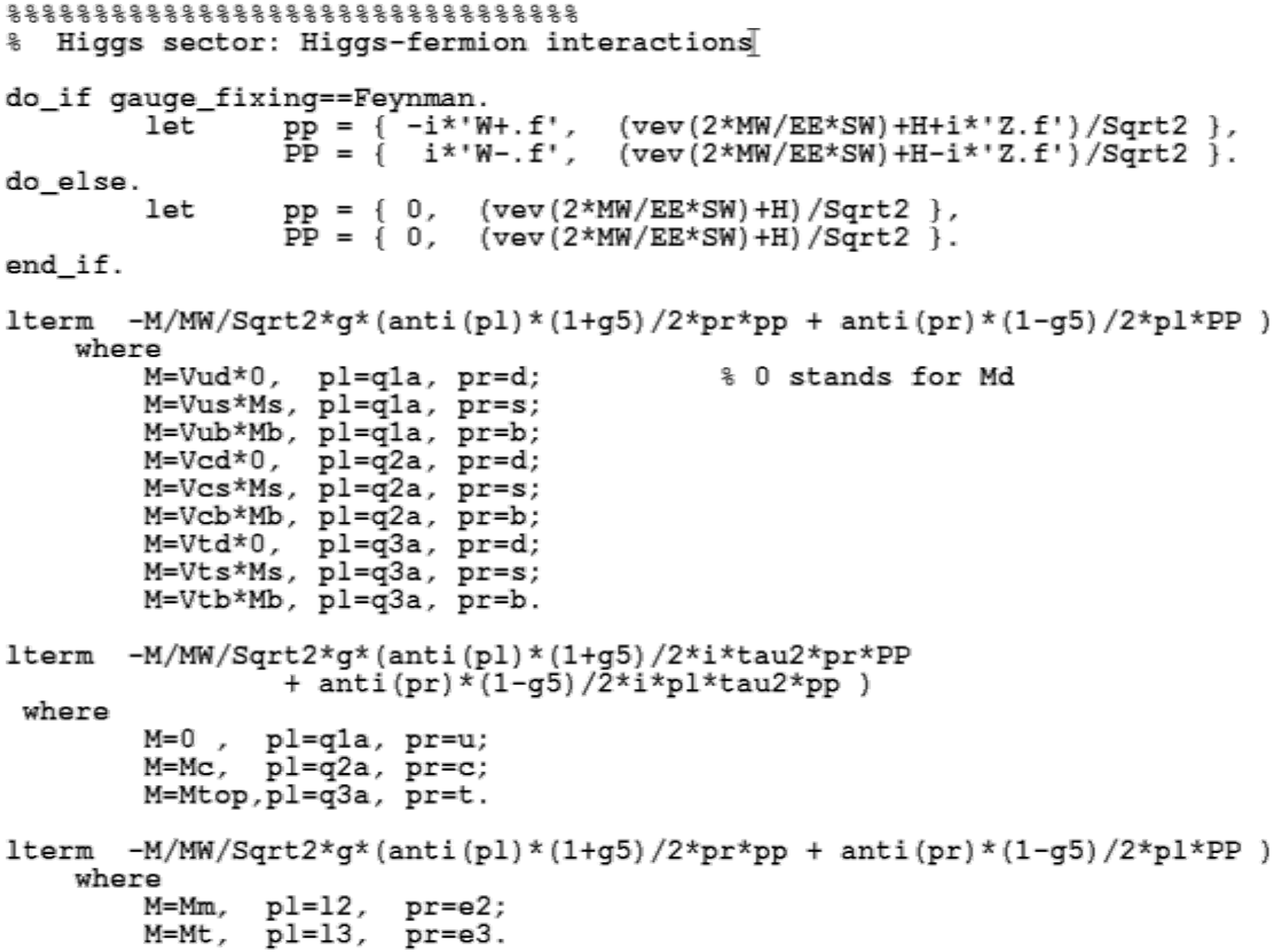
```
% Self-interaction of gauge bosons



lterm -F**2/4   where
        F=deriv^mu*B1^nu-deriv^nu*B1^mu.

lterm -F**2/4  where
        F=deriv^mu*G^nu^a-deriv^nu*G^mu^a+i*GG*f_SU3^a^b^c*G^mu^b*G^nu^c.

lterm -F**2/4  where
F=deriv^mu*WW1^nu^a-deriv^nu*WW1^mu^a -g*eps^a^b^c*WW1^mu^b*WW1^nu^c.
```

Building the Standard Model in LanHEP



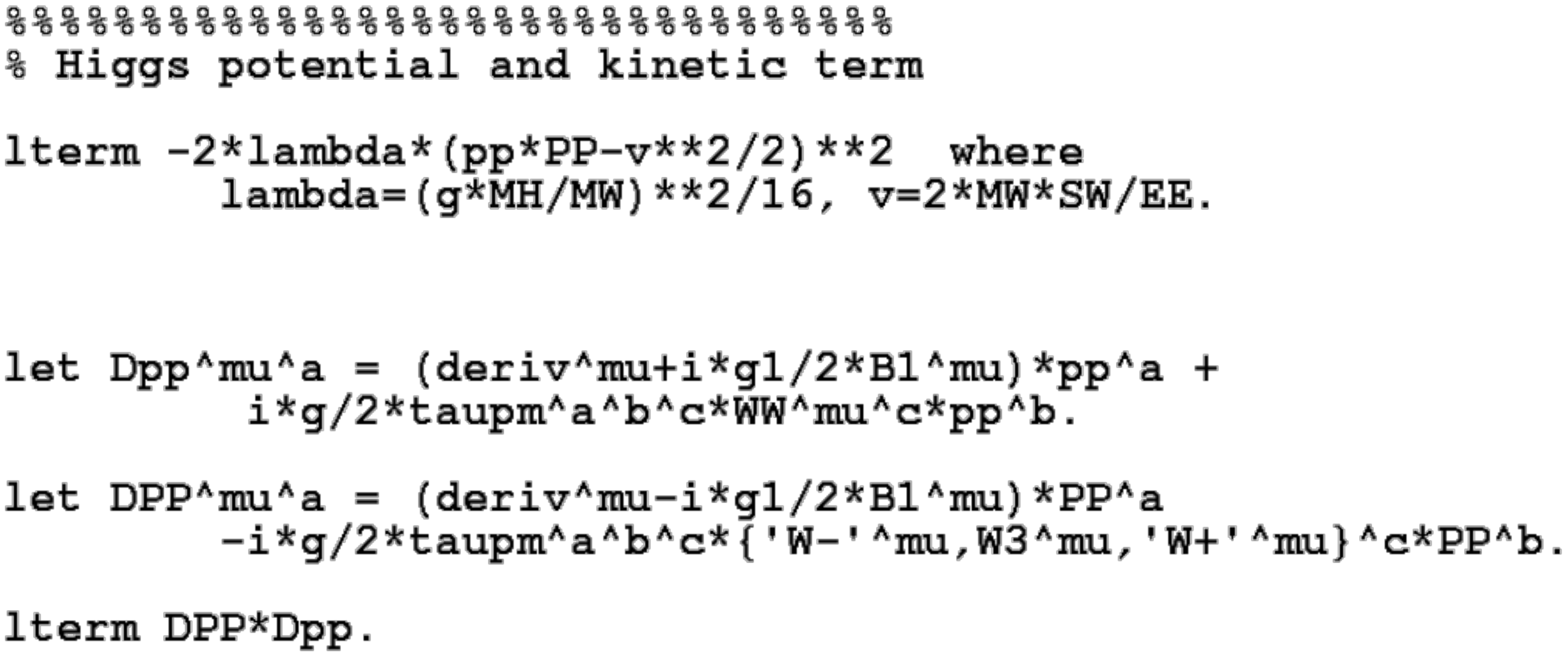
```
% left fermion interaction with gauge fields


lterm   anti(psi)*gamma*(1-g5)/2*(i*deriv-g*taupm*WW/2-Y*g1*B1)*psi
                where
                        psi=l1,  Y=-1/2;
                        psi=l2,  Y=-1/2;
                        psi=l3,  Y=-1/2;
                        psi=q1a, Y= 1/6;
                        psi=q2a, Y= 1/6;
                        psi=q3a, Y= 1/6.

% right fermion interaction with gauge fields

lterm   anti(psi)*gamma*(1+g5)/2*(i*deriv - Y*g1*B1)*psi
                where
                        psi=e1,Y= -1;
                        psi=e2,Y= -1;
                        psi=e3,Y= -1;
                        psi=u, Y=  2/3;
                        psi=c, Y=  2/3;
                        psi=t, Y=  2/3;
                        psi=d, Y= -1/3;
                        psi=s, Y= -1/3;
                        psi=b, Y= -1/3.


% quark-gluon interaction

lterm  GG*anti(psi)*lambda*gamma*G*psi where
        psi=q1; psi=q2; psi=q3.
```

Building the Standard Model in LanHEP



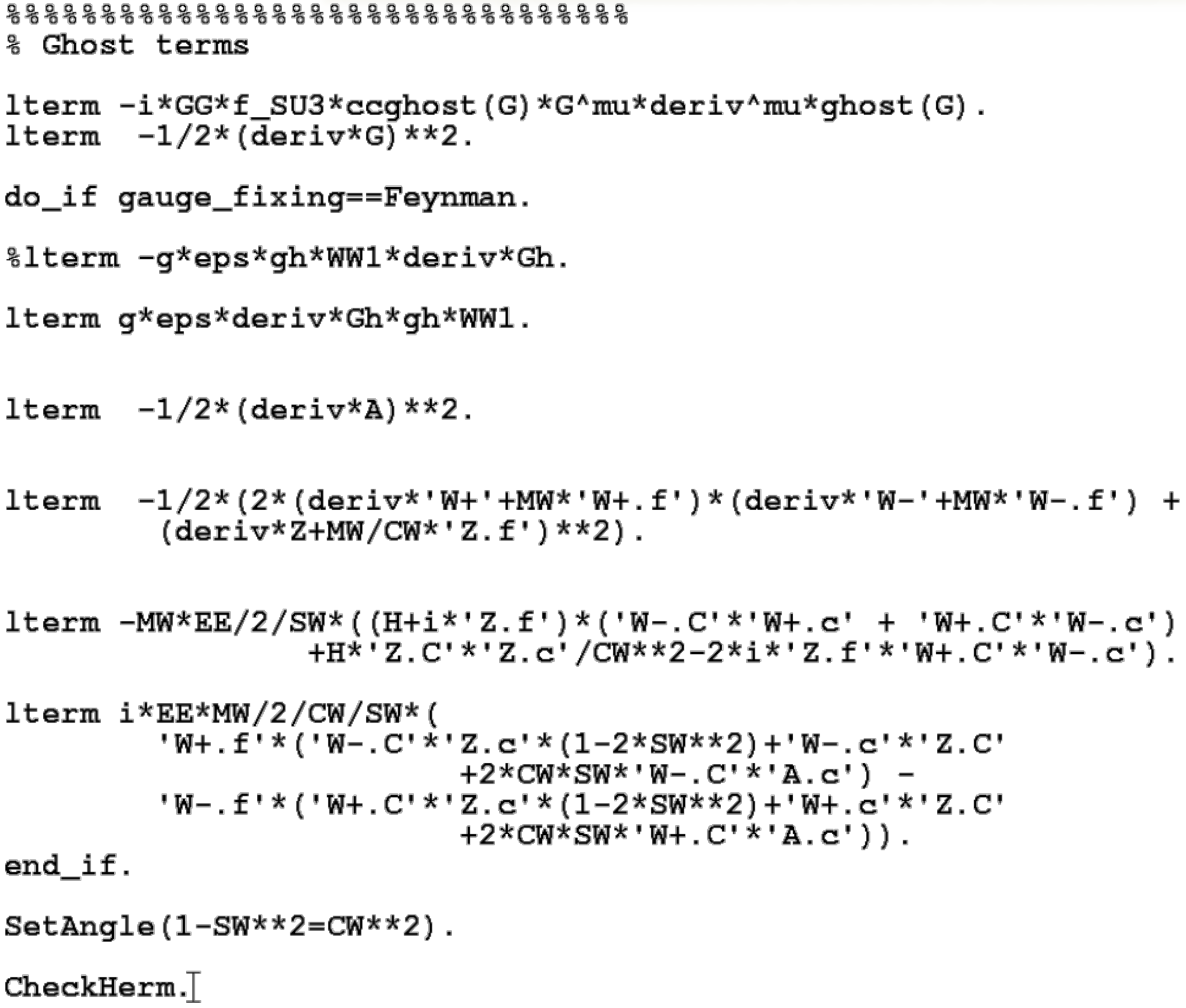
```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Higgs sector: Higgs-fermion interactions

do_if gauge_fixing==Feynman.
        let     pp = { -i*'W+.f',  (vev(2*MW/EE*SW)+H+i*'Z.f')/Sqrt2 },
                PP = {  i*'W-.f',  (vev(2*MW/EE*SW)+H-i*'Z.f')/Sqrt2 }.
do_else.
        let     pp = { 0,  (vev(2*MW/EE*SW)+H)/Sqrt2 },
                PP = { 0,  (vev(2*MW/EE*SW)+H)/Sqrt2 }.
end_if.

lterm  -M/MW/Sqrt2*g*(anti(pl)*(1+g5)/2*pr*pp + anti(pr)*(1-g5)/2*pl*PP )
    where
        M=Vud*0,  pl=q1a, pr=d;          % 0 stands for Md
        M=Vus*Ms, pl=q1a, pr=s;
        M=Vub*Mb, pl=q1a, pr=b;
        M=Vcd*0,  pl=q2a, pr=d;
        M=Vcs*Ms, pl=q2a, pr=s;
        M=Vcb*Mb, pl=q2a, pr=b;
        M=Vtd*0,  pl=q3a, pr=d;
        M=Vts*Ms, pl=q3a, pr=s;
        M=Vtb*Mb, pl=q3a, pr=b.

lterm  -M/MW/Sqrt2*g*(anti(pl)*(1+g5)/2*i*tau2*pr*PP
                + anti(pr)*(1-g5)/2*i*pl*tau2*pp )
 where
        M=0 ,  pl=q1a, pr=u;
        M=Mc,  pl=q2a, pr=c;
        M=Mtop,pl=q3a, pr=t.

lterm  -M/MW/Sqrt2*g*(anti(pl)*(1+g5)/2*pr*pp + anti(pr)*(1-g5)/2*pl*PP )
    where
        M=Mm,  pl=l2,  pr=e2;
        M=Mt,  pl=l3,  pr=e3.
```

Building the Standard Model in LanHEP



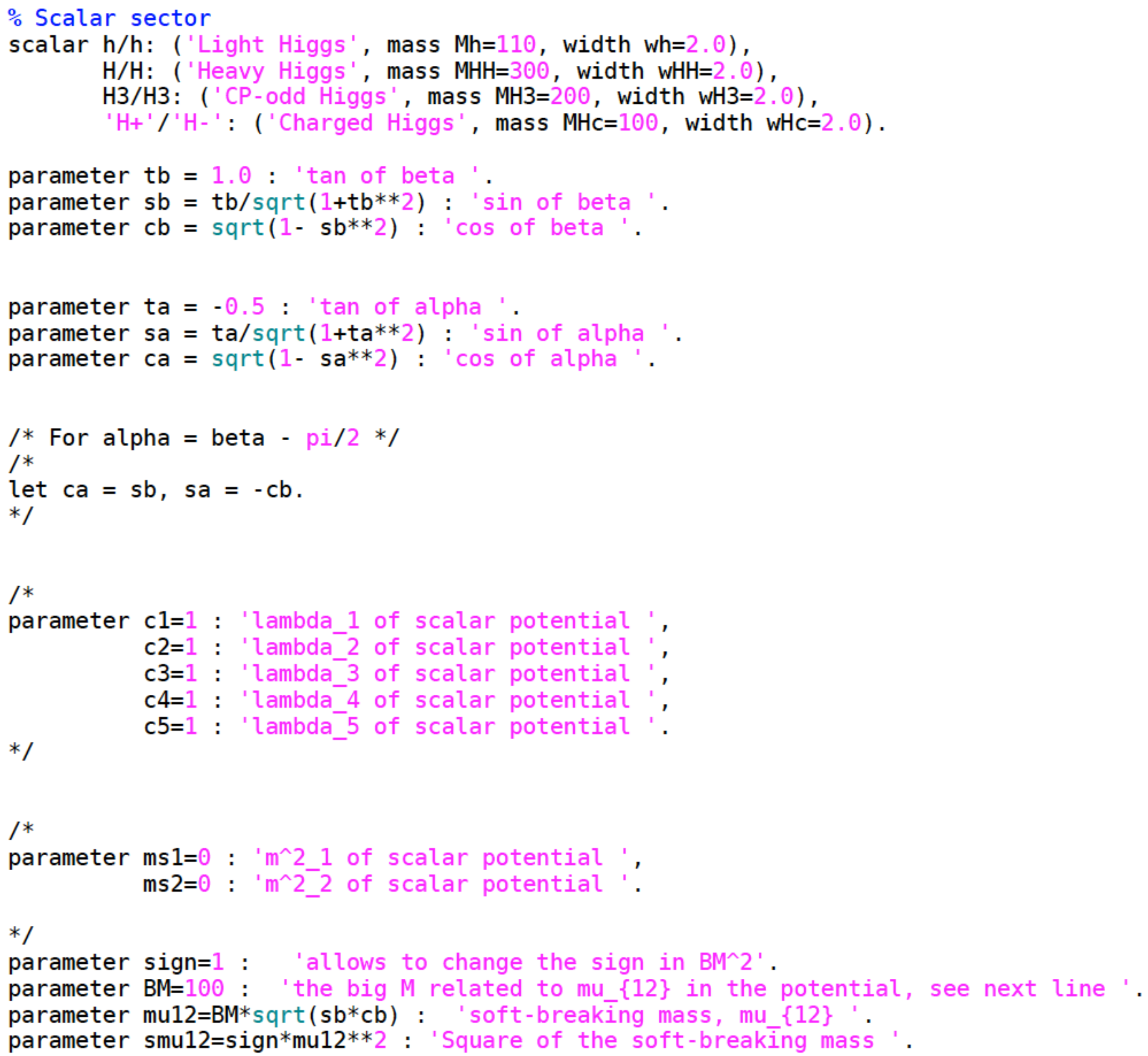
```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Higgs potential and kinetic term

lterm -2*lambda*(pp*PP-v**2/2)**2  where
        lambda=(g*MH/MW)**2/16, v=2*MW*SW/EE.



let Dpp^mu^a = (deriv^mu+i*g1/2*B1^mu)*pp^a +
         i*g/2*taupm^a^b^c*WW^mu^c*pp^b.

let DPP^mu^a = (deriv^mu-i*g1/2*B1^mu)*PP^a
        -i*g/2*taupm^a^b^c*{'W-'^mu,W3^mu,'W+'^mu}^c*PP^b.

lterm DPP*Dpp.
```

Building the Standard Model in LanHEP



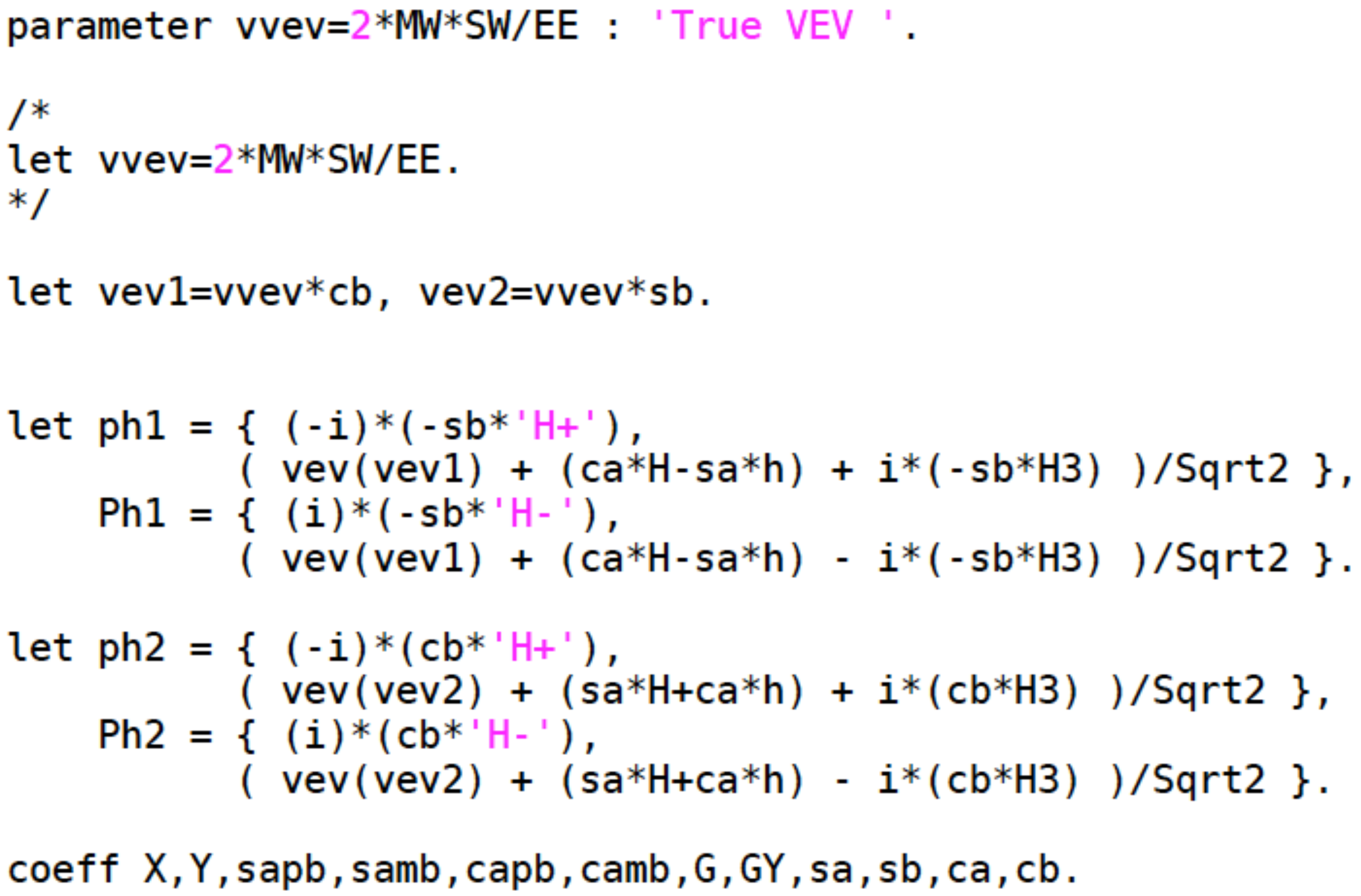
```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Ghost terms

lterm -i*GG*f_SU3*ccghost(G)*G^mu*deriv^mu*ghost(G).
lterm  -1/2*(deriv*G)**2.

do_if gauge_fixing==Feynman.

%lterm -g*eps*gh*WW1*deriv*Gh.

lterm g*eps*deriv*Gh*gh*WW1.


lterm  -1/2*(deriv*A)**2.


lterm  -1/2*(2*(deriv*'W+'+MW*'W+.f')*(deriv*'W-'+MW*'W-.f') +
        (deriv*Z+MW/CW*'Z.f')**2).


lterm -MW*EE/2/SW*((H+i*'Z.f')*('W-.C'*'W+.c' + 'W+.C'*'W-.c')
                +H*'Z.C'*'Z.c'/CW**2-2*i*'Z.f'*'W+.C'*'W-.c').

lterm i*EE*MW/2/CW/SW*(
        'W+.f'*('W-.C'*'Z.c'*(1-2*SW**2)+'W-.c'*'Z.C'
                        +2*CW*SW*'W-.C'*'A.c') -
        'W-.f'*('W+.C'*'Z.c'*(1-2*SW**2)+'W+.c'*'Z.C'
                        +2*CW*SW*'W+.C'*'A.c')).
end_if.

SetAngle(1-SW**2=CW**2).

CheckHerm.
```

And adding the 2HDM part



```
% Scalar sector
scalar h/h: ('Light Higgs', mass Mh=110, width wh=2.0),
       H/H: ('Heavy Higgs', mass MHH=300, width wHH=2.0),
       H3/H3: ('CP-odd Higgs', mass MH3=200, width wH3=2.0),
       'H+'/'H-': ('Charged Higgs', mass MHc=100, width wHc=2.0).

parameter tb = 1.0 : 'tan of beta '.
parameter sb = tb/sqrt(1+tb**2) : 'sin of beta '.
parameter cb = sqrt(1- sb**2) : 'cos of beta '.


parameter ta = -0.5 : 'tan of alpha '.
parameter sa = ta/sqrt(1+ta**2) : 'sin of alpha '.
parameter ca = sqrt(1- sa**2) : 'cos of alpha '.


/* For alpha = beta - pi/2 */
/*
let ca = sb, sa = -cb.
*/


/*
parameter c1=1 : 'lambda_1 of scalar potential ',
          c2=1 : 'lambda_2 of scalar potential ',
          c3=1 : 'lambda_3 of scalar potential ',
          c4=1 : 'lambda_4 of scalar potential ',
          c5=1 : 'lambda_5 of scalar potential '.
*/


/*
parameter ms1=0 : 'm^2_1 of scalar potential ',
          ms2=0 : 'm^2_2 of scalar potential '.

*/
parameter sign=1 :   'allows to change the sign in BM^2'.
parameter BM=100 :  'the big M related to mu_{12} in the potential, see next line '.
parameter mu12=BM*sqrt(sb*cb) :  'soft-breaking mass, mu_{12} '.
parameter smu12=sign*mu12**2 : 'Square of the soft-breaking mass '.
```

And adding the 2HDM part



```
parameter vvev=2*MW*SW/EE : 'True VEV '.

/*
let vvev=2*MW*SW/EE.
*/

let vev1=vvev*cb, vev2=vvev*sb.


let ph1 = { (-i)*(-sb*'H+'),
            ( vev(vev1) + (ca*H-sa*h) + i*(-sb*H3) )/Sqrt2 },
    Ph1 = { (i)*(-sb*'H-'),
            ( vev(vev1) + (ca*H-sa*h) - i*(-sb*H3) )/Sqrt2 }.

let ph2 = { (-i)*(cb*'H+'),
            ( vev(vev2) + (sa*H+ca*h) + i*(cb*H3) )/Sqrt2 },
    Ph2 = { (i)*(cb*'H-'),
            ( vev(vev2) + (sa*H+ca*h) - i*(cb*H3) )/Sqrt2 }.

coeff X,Y,sapb,samb,capb,camb,G,GY,sa,sb,ca,cb.
```

```
let c1=-smu12*sb/cb**3/vvev**2
        +(Mh**2*sa**2+MHH**2*ca**2)/vvev**2/cb**2.
let c2=-smu12*cb/sb**3/vvev**2
        +(Mh**2*ca**2+MHH**2*sa**2)/vvev**2/sb**2.
let c3=-smu12/cb/sb/vvev**2
        +2*MHc**2/vvev**2-sa*ca*(Mh**2-MHH**2)/vvev**2/cb/sb.
let c4=smu12/cb/sb/vvev**2+(MH3**2-2*MHc**2)/vvev**2.
let c5=smu12/cb/sb/vvev**2-MH3**2/vvev**2.



% This is Lagrangian terms which is -(potential)

%lterm -ms1*Ph1*ph1-ms2*Ph2*ph2+smu12*(Ph1*ph2+Ph2*ph1).
lterm -c1/2*(Ph1*ph1)**2.
lterm -c2/2*(Ph2*ph2)**2.
lterm -c3*(Ph1*ph1*Ph2*ph2).
lterm -c4*(Ph1*ph2*Ph2*ph1).
lterm -c5/2*(Ph1*ph2*Ph1*ph2+Ph2*ph1*Ph2*ph1).



% generate the Kinematic terms for Higgs bosons

let Dph1^mu^a = (deriv^mu+i*g1/2*B1^mu)*ph1^a
         +i*g/2*taupm^a^b^c*WW^mu^c*ph1^b.

let DPh1^mu^a = (deriv^mu-i*g1/2*B1^mu)*Ph1^a
         -i*g/2*taupm^a^b^c*{'W-'^mu,W3^mu,'W+'^mu}^c*Ph1^b.


let Dph2^mu^a = (deriv^mu+i*g1/2*B1^mu)*ph2^a
         +i*g/2*taupm^a^b^c*WW^mu^c*ph2^b.

let DPh2^mu^a = (deriv^mu-i*g1/2*B1^mu)*Ph2^a
         -i*g/2*taupm^a^b^c*{'W-'^mu,W3^mu,'W+'^mu}^c*Ph2^b.


lterm DPh1*Dph1.

lterm DPh2*Dph2.
```

```
% Yukawa couplings

lterm  -M/MW/sb/Sqrt2*g*(anti(pl)*(1+g5)/2*pr*ph2 + anti(pr)*(1-g5)/2*pl*Ph2 )
    where
        M=Vud*0,  pl=q1a, pr=d;          % 0 stands for Md
        M=Vus*Ms, pl=q1a, pr=s;
%       M=Vus*0, pl=q1a, pr=s;
        M=Vub*Mb, pl=q1a, pr=b;
        M=Vcd*0,  pl=q2a, pr=d;
        M=Vcs*Ms, pl=q2a, pr=s;
%       M=Vcs*0, pl=q2a, pr=s;
        M=Vcb*Mb, pl=q2a, pr=b;
        M=Vtd*0,  pl=q3a, pr=d;
        M=Vts*Ms, pl=q3a, pr=s;
%       M=Vts*0, pl=q3a, pr=s;
        M=Vtb*Mb, pl=q3a, pr=b.


lterm  -M/MW/sb/Sqrt2*g*(anti(pl)*(1+g5)/2*i*tau2*pr*Ph2
                + anti(pr)*(1-g5)/2*i*pl*tau2*ph2 )
 where
        M=0 ,  pl=q1a, pr=u;
        M=Mc,  pl=q2a, pr=c;


%       M=0,   pl=q2a, pr=c;
        M=Mtop,pl=q3a, pr=t.

lterm  -M/MW/sb/Sqrt2*g*(anti(pl)*(1+g5)/2*pr*ph2 + anti(pr)*(1-g5)/2*pl*Ph2 )
    where
%       M=Me,  pl=l1,  pr=e1;
        M=0,   pl=l1,  pr=e1;
        M=Mm,  pl=l2,  pr=e2;
%       M=0,   pl=l2,  pr=e2;
        M=Mt,  pl=l3,  pr=e3.
```

A different approach in CalcHEP/ CompHEP
The batch file

The batch file

```
###############################################
#  batch_file for CalcHEP                     #
#  bin/run_batch  batch-file-name             #
#  Lines beginning with # are ignored.        #
###############################################

###############################################
#  Model Info                                 #
#  Model is the exact model name.             #
#  Model changed specifies whether a change   #
#       was made to the model files.  Changes #
#       to the numerical values of external   #
#       parameters is ok.  Other changes      #
#       require that the process library be   #
#       recreated.  Values are True or False. #
#  Gauge specifies gauge.  Choices are        #
#       Feynman or unitary.                   #
###############################################
Model:          THDMII
Model changed:  False
Gauge:          Feynman

    Process:   p,p->to,j
    Decay:     to->bo,Hi
    Decay:     Hi->2*x

    Composite: p=u,U,d,D,c,C,s,S,b,B
    Composite: j=u,U,d,D,c,C,s,S,b,B
    Composite: to=t,T
    Composite: bo=b,B
    Composite: Hi=H+,H-
```

In your calchep dir
./calchep
import models
type models
and choose THDMII

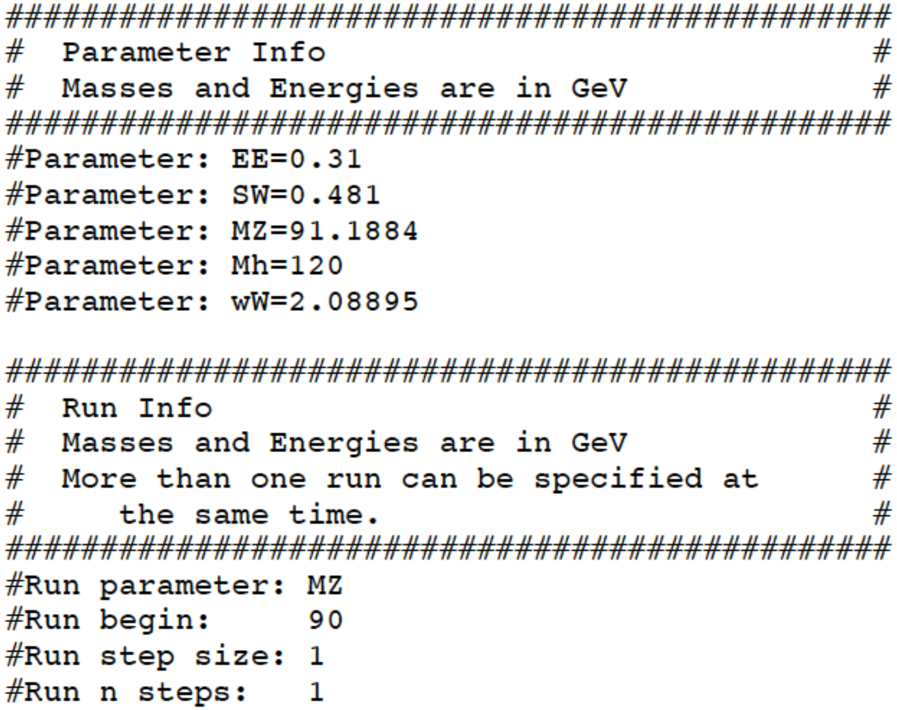
nautilus

move file
batch_file
from
/soft/Rsantos/idpasctool
to
/G*/calchep

```
pdf1:        cteq6l (proton)
pdf2:        cteq6l (proton)
```

```
##############################################
#  Momentum Info                             #
#    in GeV                                  #
##############################################
p1:          7000
p2:          7000
```

The batch file



```
###############################################
#  Parameter Info                             #
#  Masses and Energies are in GeV             #
###############################################
#Parameter: EE=0.31
#Parameter: SW=0.481
#Parameter: MZ=91.1884
#Parameter: Mh=120
#Parameter: wW=2.08895

###############################################
#  Run Info                                   #
#  Masses and Energies are in GeV             #
#  More than one run can be specified at      #
#     the same time.                          #
###############################################
#Run parameter: MZ
#Run begin:     90
#Run step size: 1
#Run n steps:   1
```

Start firefox&

Generate events from CalcHEP

From myname/comphep/

./calchep_batch batch_file

copy link and paste it in firefox

Enjoy!