

# Hands-on LanHEP and CalcHEP: Efficient Implementation and Exploration of Dark Matter Models

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# LanHEP package

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LanHEP: A Package for automatic generation of Feynman rules in gauge models, hep-ph/9608488

**LanHEP** is a powerful tool for automatically generating Feynman rules directly from a model's Lagrangian, written in a compact and intuitive form similar to that used in publications.

## Key Features

- Writes your Lagrangian in a clean and readable format.
- Automatically obtains Feynman rules in terms of physical fields and independent parameters.
- Supports summation over indices and recognises commonly used expressions such as covariant derivatives and gauge field strength tensors
- Export models in LaTeX, CompHEP, CalcHEP, UFO, and FeynArts formats
- Supports all class of models with particles upto spin 2 making it a key tool for BSM studies
- **Simple and User-Friendly Setup**
  - Requires only a C compiler (e.g. gcc) to build
  - You don't need to know the C language — LanHEP uses its own intuitive input format.

## Many advanced features

- Supports superpotential formalism
- Checks: BRST invariance, electric charge conservation, hermiticity
- Supports multiplets, matrices and much more — see the manual and this lecture

# LanHEP Installation Guide

## 1. Download the code

a) from Dark Tools github

`wget https://raw.githubusercontent.com/dimauromattia/darktools/main/lanhep/lhep403.tgz`

or

b) from the [HEP Tools site](#) → Link to HEP TOOLS directory → lanhep → lhep403.tgz

## 2. Unpack the archive

`tar -zxvf lhep403.tgz`

## 3. Enter the directory

`cd lanhep403`

## 4. Compile

`make`

*The **lhep** executable will be built — you can add it to your PATH for easy use, e.g. add*

`export PATH="$PATH:/path-to-lhep-file/"` line to .bashrc

**ex#1**

*install LanHEP*

# Running LanHEP

- example of LanHEP running

```
cd mdl  
./lhep -ca stand.mdl
```

*File sm\_tex processed, 0 sec.*

*File stand.mdl processed, 0 sec.*

where stand.mdl is the model in LanHEP format

- running lhep without arguments gives you the list of options for output formats

```
./lhep
```

Error: output format is not set. Use command line options:

- CompHEP or -co for CompHEP format;
- CalcHEP or -ca for CalcHEP format;
- FeynArts or -fa for FeynArts format;
- ufo for UFO format;
- tex for LaTeX format.

- e.g. you can run

```
./lhep -ufo stand.mdl  
./lhep -tex stand.mdl
```

to produce model in UFO format and the LaTeX formats respectively

- `./lhep -ca -OutDir outdir stand.mdl`

to write results into **outdir**

# An example of simplest model - QED

$$\mathcal{L}_{QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{e}\gamma^\mu(i\partial_\mu + g_e A_\mu)e - m\bar{e}e,$$
$$\mathcal{L}_{GF} = -\frac{1}{2}(\partial_\mu A^\mu)^2$$

```
model QED/1.  
parameter ge=0.31333: 'Electric charge'.  
spinor e1/E1:(electron, mass me=0.000511).  
vector A/A:(photon).  
let F^mu^nu=deriv^nu*A^mu-deriv^mu*A^nu.  
lterm -1/4*(F^mu^nu)**2 - 1/2*(deriv^mu*A^mu)**2.  
lterm E1*(i*gamma*deriv+ge*gamma*A-me)*e1.
```

qed.mdl

./lhep -ca qed.mdl

will produce model files in CalcHEP  
format

prtcls1.mdl, lgrng1.mdl,  
vars1.mdl, func1.mdl

./lhep -tex qed.mdl

will produce model files in LaTeX  
format

prtcls1.tex, lgrng1.tex,  
vars1.tex, func1.tex

lgrng1.tex  
contains

	Fields in the vertex	Variational derivative of Lagrangian by fields
	$E1_a \quad e1_b \quad A_\mu$	$ge \cdot \gamma_{ab}^\mu$

# The model structure in CalcHEP format: a set of ASCII tables

[prtcls1.mdl](#) : the list of particles and their properties

QED

Particles

Full	Name	P	aP	number	spin2	mass	width	color	aux	LaTeX(A)	LaTeX(A+)
electron		e1	E1	11	1	me	0	1		e1	E1
photon		A	A	22	2	0	0	1		A	A

[lgrng1.mdl](#) : particles interactions

QED

Lagrangian

P1	P2	P3	P4	>	Factor	< >	dLagrangian/ dA(p1) dA(p2) dA(p3)	<
E1	e1	A		ge		G(m3)		

[vars1.mdl](#) : independent model parameters

QED

Variables

Name	Value	> Comment	<
ge	0.31333	Electric charge	
me	0.000511	mass of electron	

other two files [func xxx.mdl](#) (dependent parameters) and [extlib xxx.mdl](#) (libraries to be linked) -- are empty for this simple model

# Syntax of LanHEP

- The LanHEP input file is the sequence of statements, each starts with a **special identifier** (such as **parameter**, **Iterm**, etc) and **ends with the full-stop '.' symbol**. Statement can occupy several lines
- **Identifiers:** Identifiers are the names of particles, parameters etc.
- **Constants:** integers, floating point numbers, strings
- **Comments:** '%' , '/\*' ... '\*/'
- **Order of the indices of the objects** (default, can be changed): [spinor, color c3, color c8, vector]
- **declaring new groups:** group color:SU(3).  
repres color:(c3/c3b,c8).
- **parameters** parameter name=value:comment.
- **particles** scalar  $P/aP$ : (options).  
spinor  $P/aP$ : (options).  
vector  $P/aP$ : (options).

See manual and this lecture for more details

# You can see/update default options are in calchep.rc file

% Definitions specific for CalcHEP format of Feynman rules.

keys OutputFormat=CalcHEP.

```
prtcformat fullname: 'Full Name',
    name:' P ', aname:' aP', pdg:' number ',
    spin2,mass,width, color, aux, texname: ' LaTeX(A) ',
    atexname:' LateX(A+) '.
```

```
prtcproperty pdg:(A=22, Z=23, 'W+'=24, G=21,
    q=1,
    d=1, u=2, s=3, c=4, b=5, t=6,
    n1=12, n2=14, n3=16,
    e1=11, e2=13, e3=15,
    ne=12, nm=14, nl=16,
    e=11, m=13, l=15,
~ne=1000012, ~nm=1000014, ~nl=1000016,
~e1=1000011, ~m1=1000013, ~l1=1000015,
~e2=2000011, ~m2=2000013, ~l2=2000015,
~eL=1000011, ~mL=1000013,
~eR=2000011, ~mR=2000013,

~u1=1000002, ~c1=1000004, ~t1=1000006,
~u2=2000002, ~c2=2000004, ~t2=2000006,
~uL=1000002, ~cL=1000004, ...
```

# Next example - QCD

- **Gauge interactions**  $L_{YM} = -\frac{1}{4}F^{a\mu\nu}F_{\mu\nu}^a$ ,  $F_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s f^{abc}G_\mu^b G_\nu^c$ ,  $G_\mu^a(x)$
- **Quark kinetic term**  $L_F = \bar{q}_i \gamma^\mu \partial_\mu q_i + g_s \lambda_{ij}^a \bar{q}_i \gamma^\mu q_j G_\mu^c$ ,
- **Gauge fixing term and Faddeev-Popov ghost term**  
 $\mathcal{L}_{GF} = -\frac{1}{2}(\partial_\mu G_a^\mu)^2 + i g_s f^{abc} \bar{c}^a G_\mu^b \partial^\mu c^c$ ,
- **LanHEP model file (qcd.mdl):**

```
model      QCD/2.  
parameter  gg= 1.13 : 'Strong coupling'.  
vector     G/G: (gluon, color c8, gauge).  
spinor    q:(quark, color c3, mass Mq=0.02).  
lterm     i*gg*f_SU3*ccghost(G)*G*deriv*ghost(G).  
lterm     Q*gamma*(i*deriv + gg*lambda*G)*q.  
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.
```

`./lhep -tex qcd.mdl`

will produce: `vars2.tex`, `prtcls2.tex`, `Igrng2.tex`

## Igrng2.tex

Fields in the vertex	Variational derivative of Lagrangian by fields
$G_{\mu p}$ $G_{\nu q}$ $G_{\rho r}$	$ggf_{pqr}(p_3^\nu g^{\mu\rho} - p_3^\mu g^{\nu\rho} + p_1^\rho g^{\mu\nu} - p_1^\nu g^{\mu\rho} - p_2^\rho g^{\mu\nu} + p_2^\mu g^{\nu\rho})$
$G.C_p$ $G.c_q$ $G_{\mu r}$	$-gg \cdot p_2^\mu f_{pqr}$
$Q_{ap}$ $q_{bq}$ $G_{\mu r}$	$gg \cdot \lambda_{pq}^r \gamma_{ab}^\mu$
$G_{\mu p}$ $G_{\nu q}$ $G_{\rho r}$ $G_{\sigma s}$	$gg^2(g^{\mu\rho}g^{\nu\sigma}f_{pqt}f_{rst} - g^{\mu\sigma}g^{\nu\rho}f_{pqt}f_{rst} + g^{\mu\nu}g^{\rho\sigma}f_{prt}f_{qst} - g^{\mu\sigma}g^{\nu\rho}f_{prt}f_{qst} + g^{\mu\nu}g^{\rho\sigma}f_{pst}f_{qrt} - g^{\mu\rho}g^{\nu\sigma}f_{pst}f_{qrt})$

# Vertices with colour particles in CalcHEP

- The CalcHEP Lagrangian tables do not describe explicitly the colour structure of a vertex.
- If colour particles are present in the vertex, the following implicit contractions are assumed (p, q, r are colour indices):

$\delta_{pq}$  for two color particles  $A_p^1$  and  $A_q^2$

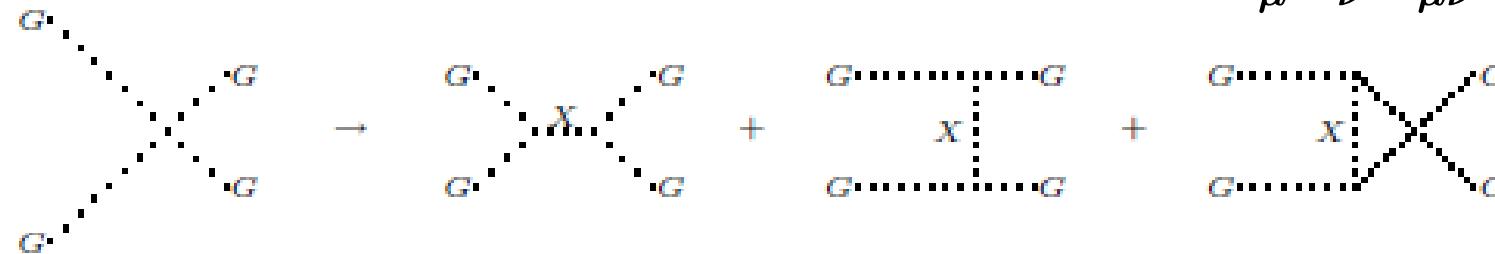
$\lambda_{pq}^r$  for three particles, which are colour triplet, antitriplet and octet

$f^{pqr}$  for three colour octets       $f^{pqr} G_\mu^p G_\nu^q G_\lambda^r$

# Vertices with colour particles in CalcHEP

- 4-gluon vertex can be split it into 3-legs vertices

$$f^{pqr} G_\mu^q G_\nu^r X_{\mu\nu}^p$$



- Here the field  $X_{\mu\nu}^p$  is a Lorenz tensor and colour octet, and this field has constant propagator
- If gluon name in CalcHEP is 'G'
- the name 'G.t' is used for this tensor particle; its indices are denoted as 'm' and 'M'

QCD  
Lagrangian

P1	P2	P3	P4	>	Factor	< > dLagrangian/ dA(p1) dA(p2) dA(p3)	<
G	G	G		gg		m2.p3*m1.m3-m1.p3*m2.m3+m3.p1*m1.m2-m2.p1*m1.m3-m3.p2*m1.m2+m1.p2*m2.m3	
G.C	G.c	G		-gg		m3.p2	
Q	q	G		gg		G(m3)	
G	G	G.t		gg*.Sqrt2/2		m1.m3*m2.M3-m1.M3*m2.m3	

$m1.m2$  in CalcHEP etc means  $g^{m1m2}$

# Vertices with colour particles in LanHEP

- The splitting of vertex with 4 colour particle into 3-particles vertices is done by LanHEP automatically: each vertex containing 4 colour particles is split to 2 vertices which are joined by automatically generated auxiliary field
- option `SplitCol1=N.`
  - *where N is a number:*
    - -1 remove all vertices with 4 color particles from Lagrangian;
    - 0 turn off multiplet level vertices splitting;
    - 1 allows vertices splitting with 4 color multiplets;
    - 2 allows vertices splitting with any 4 scalar multiplets except Higgs [default]
- option `SplitCol2=N.`
  - *where N is a number:*
    - 0 disable vertex level splitting;
    - 1 enable vertex level splitting (only for vertices with 4 color particles) [default]

# More details on LanHEP options and syntax

- **Specials** gamma, gamma5, moment, deriv, lambda, f\_SU3  
declaring new specials: special name: (islist) .
- **Orthogonal matrices** OrthMatrix( {{ $a_{11}$ ,  $a_{12}$ }, { $a_{21}$ ,  $a_{22}$ } } ).
- **Including files** read file. or use file. (no multiple reading)
- **Checking electric charge conservation** SetEM(photon, param).
- **Running LanHEP**  
*lhep filename options*  
-OutDir directory Set the directory for output files  
-InDir directory Set the directory where to search files  
-tex LanHEP generates LaTeX files  
-frc If -tex option is set, forces LanHEP to split 4-fermion and 4-color vertices just as it is made for CompHEP files.  
-texLines num Set number of lines in LaTeX tables  
-texLineLength num Controls width of the Lagrangian

# Default groups and specials in LanHEP: mdl/hep.rc

```
special gamma:(spinor,cspinor,vector).
special gamma5:(spinor,cspinor).
special '(1+gamma5)/2':(spinor,cspinor), '(1-gamma5)/2':(spinor,cspinor).
special moment:(vector).
special '__moment_start__':(vector), '__moment_end__'.
special epsv:(vector,vector,vector,vector).
special eps3v:(vector,vector,vector).
group color:SU(3).
repres color:(c3/c3b,c8,c6/c6b).
SetDefIndex(spinor,color c3, color c8, vector).
special lambda:(color c3, color c3b, color c8).
special f_SU3:(color c8, color c8, color c8).
special d_SU3:(color c8, color c8, color c8).
special eps_c3: (color c3, color c3, color c3),
               eps_c3b:(color c3b, color c3b, color c3b).
special k_c6:(color c3b, color c3b, color c6),
               k_c6b:(color c3, color c3, color c6b).
special l_c6:(color c6, color c6b, color c8).
let deriv=-i*moment.
special deriv5.
let '__deriv_start__'=-i*'__moment_start__'.
let tau1={{0,1},{1,0}}, tau2={{0,i},{-i,0}}, tau3={{1,0},{0,-1}}.
let tau={tau1,tau2,tau3}.
```

# SM Lagrangian with LanHEP

The latest version of SM implementation comes with CalcHEP and micrOMEGAs, located in **model\_src** folder of the CalcHEP distribution (also in LanHEP mdl folder)  
**model\_src** contains LanHEP source files for SM and Inert Doublet Model

```
model_src: sm.inc idm.lhep sm.lhep README
```

```
sm.lhep      keys gauge_fixing=Feynman, CKMdim=1, hgg=On,
                  h4G=Off.
                  do_if hgg==On.
                  do_if h4G==On.
                      model 'SM(+hgg+h4G)'/3.
                  do_else.
                      model 'SM(+hgg)'/2.
                  end_if.
                  do_else.
                      model 'SM'/1.
                  end_if.

                  read 'sm.inc'.
                  CheckHerm.
                  CheckMasses.
```

# SM Lagrangian with LanHEP: sm.inc - parameters

```
% Standard Model - unitary and t'Hooft-Feynman gauges.  
external_func(alphaQCD,1).  
external_func(McEff,1).  
. . . . .  
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 0.474 - "on-shell", 481 - "MS-bar" )'.  
parameter CW = sqrt(1-SW**2) : 'cos of the Weinberg angle'.  
parameter Q=100: 'Scale of effective running masses',  
    MW=80.385: 'W boson mass',  
    GF=EE**2/(2*SW*MW)**2/Sqrt2 : ' experimental value 1.166E-5 [1/GeV^2]',  
    MZ=MW/CW: 'Z boson mass',  
    Mtp =172.5:'Top quark pole mass',  
    McMc =1.23: 'Mc(Mc) MS-BAR',  
    MbMb =4.25: 'Mb(Mb) MS-BAR',  
    alphaSMZ=0.1184:'Srtong alpha(MZ)',  
    LamQCD=initQCD5(alphaSMZ,McMc,MbMb,Mtp),  
    Mb=MbEff(Q),  
    Mc=McEff(Q),  
    Ms=MqEff(0.096,Q): 's-quark effective mass via 2MeV running one' .
```

# SM Lagrangian with LanHEP: sm.inc - particles

```
do_if gauge_fixing==Feynman.  
vector  
    A/A: (photon, gauge),  
    Z/Z:('Z boson', mass MZ, width wZ = auto, gauge),  
    G/G: (gluon, color c8, gauge),  
    'W+/'W-': ('W boson', mass MW, width ww = auto, gauge).  
do_else.  
  
vector  
    A/A: (photon, gauge),  
    Z/Z:('Z boson', mass MZ, width wZ = auto),  
    G/G: (gluon, color c8, gauge),  
    'W+/'W-': ('W boson', mass MW, width ww = auto).  
end_if.  
  
spinor ne/Ne:(neutrino, left),          e:(electron),  
      nm/Nm:('mu-neutrino', left),     m:(muon),  
      nl/Nl:('tau-neutrino', left),   l:(('tau-lepton', mass Ml = 1.777).  
  
spinor u:('u-quark',color c3),  
      d:('d-quark',color c3),  
      c:('c-quark',color c3, mass Mc),  
      s:('s-quark',color c3, mass Ms), . . .
```

# SM Lagrangian with LanHEP: sm.inc – CKM, 'lets'

```
parameter    s23 = 0.040   : 'Parameter of C-K-M matrix (PDG-94)',  
             s13 = 0.0035  : 'Parameter of C-K-M matrix (PDG-94)',  
             c23 = sqrt(1-s23**2),  
             c13 = sqrt(1-s13**2).  
  
parameter  Vud = c12*c13           ,  
          Vus = s12*c13           ,  
          Vub = s13              ,  
          Vcd = (-s12*c23-c12*s23*s13) ,  
          Vcs = (c12*c23-s12*s23*s13) ,  
          Vcb = s23*c13           ,  
          Vtd = (s12*s23-c12*c23*s13) ,  
          Vts = (-c12*s23-s12*c23*s13) ,  
          Vtb = c23*c13           .  
OrthMatrix( { {Vud,Vus,Vub}, {Vcd,Vcs,Vcb}, {Vtd,Vts,Vtb} } ).  
.  
.  
.  
let l1={ne,e}, L1={Ne,E}.  
let l2={nm,m}, L2={Nm,M}.  
let l3={nl,l}, L3={Nl,L}.  
  
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}.
```

# SM Lagrangian with LanHEP: sm.inc - interactions

```
%===== 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*W^nu^a-deriv^nu*W^mu^a+g2*eps^a^b^c*W^mu^b*W^nu^c.
```

```
%===== left fermion interaction with gauge fields
```

```
lterm i*anti(psi)*gamma*(1-g5)/2*(deriv-i*g2*tau*W/2-i*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.
```

$H\gamma\gamma$

## effective vertex with LanHEP

- The sm.inc contains the  $H\gamma\gamma$  implementation through  $\phi_H^2 F^{\mu\nu} F_{\mu\nu}$

```
let shd = { i*'W+.f', (vev(vevh)+h-i*'Z.f')/Sqrt2 }.
external_func(lAAhiggs,2).
```

```
parameter LAAh=-cabs(lAAhiggs(Mh,str(h))).
lterm LAAh*(shd*anti(shd)-vevh**2/2)/vevh*F**2 where
F=deriv^mu*A^nubar-deriv^nubar*A^mu.
```

**lAAhiggs(Mh,str(h))** is universal function which works with any BSM model – looks at any vertex which would contribute to  $H\gamma\gamma$

**IGGhiggs(Mh,str(h))** is universal function which works with any BSM model – looks at any vertex which would contribute to  $Hgg$

# $Hgg$ and auxiliary particles with LanHEP

$\phi_H^2 F^{\mu\nu} F_{\mu\nu}$  effective Lagrangian leads to 6-point  $Hhgggg$  vertex, LanHEP allows to realise this via auxiliary non-propagating fields

```
vector G2t/G2T: (G2T, mass Maux, color c8, aux ('!*')).
```

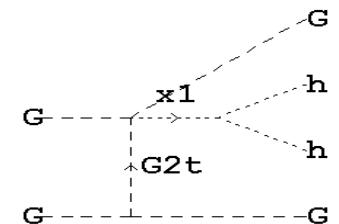
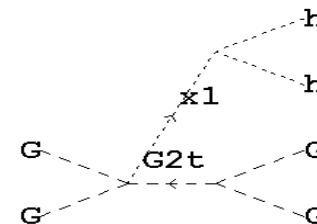
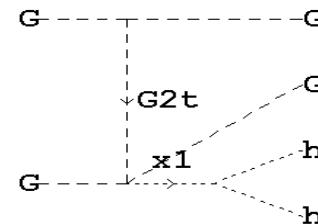
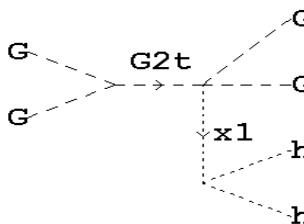
```
scalar x1/X1: (x1, mass Maux, aux ("!*")).
```

```
parameter LGGh=-cabs(lGGhiggs(Mh,str(h))).
```

```
lterm 1/vevh*LGGrQCDh*(shd*anti(shd)-vevh**2/2-vevh*h)*x1*Maux.
```

```
lterm (GG/2*f_SU3^a^b^c*G^n^a*G^m^b*'G2t.t'^^m^n^c)*(X1*Maux).
```

```
lterm GG/2*f_SU3^a^b^c*G^n^a*G^m^b*'G2T.t'^^m^n^c.
```



# Inert Higgs Doublet model implementation: idm . The

Inert Doublet model contains (IDM) two  $SU(2)$  doublets

$$H_1 = \begin{pmatrix} 0 \\ \langle v \rangle + h/\sqrt{2} \end{pmatrix}, \quad H_2 = \begin{pmatrix} \tilde{H}^+ \\ (\tilde{X} + i \cdot \tilde{H}_3)/\sqrt{2} \end{pmatrix}$$

The Lagrangian contains only *even* powers of  $H_2$  doublet

$$\begin{aligned} L &= (\text{SM terms}) \\ &+ D^\mu H_2^\dagger D_\mu H_2 - \mu^2 H_2^2 - \lambda_2 H_2^4 - \lambda_3 H_1^2 H_2^2 - \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ &- \frac{\lambda_5}{2} [(H_1^\dagger H_2)^2 + (H_2^\dagger H_1)^2] \end{aligned}$$

Because of symmetry  $H_2 \rightarrow -H_2$ , the lightest of  $\tilde{H}^+$ ,  $\tilde{X}$ ,  $\tilde{H}_3$  is stable

Parameters  $\mu, \lambda_3, \lambda_4$  can be expressed in terms of masses

New couplings are :  $\lambda_2$ ,  $\lambda_L = \lambda_3 + \lambda_4 + \lambda_5$

# IDM implementation: idm.lhe-parameters

```
keys gauge_fixing=Feynman, CKMdim=1, hgg=Off, h4G=Off.  
do_if hgg==On.  
    do_if h4G==On.  
        model 'IDM(+hgg+h4G)'/5.  
    do_else.  
        model 'IDM(+hgg)'/5.  
    end_if.  
do_else.  
    model 'IDM'/4.  
end_if.  
  
read 'sm.inc'.  
  
parameter MHX=111, MH3=222, MHC=333.  
parameter laL=0.01, la2=0.01.  
parameter mu2=MHX**2-laL*(2*MW/EE*SW)**2.  
parameter la3=2*(MHC**2-mu2)/(2*MW/EE*SW)**2.  
parameter la5=(MHX**2-MH3**2)/(2*MW/EE*SW)**2.  
parameter la4=2*laL-la3-la5.
```

# IDM implementation: - particles & interactions

```
scalar '~H3'/'~H3':('odd Higgs',pdg 36, mass MH3, width wH3 = auto).
scalar '~H+''/~H-':('Charged Higgs',pdg 37, mass MHC, width wHC=auto).
scalar '~X'/'~X' :('second Higgs', pdg 35, mass MHX, width wHX=auto).

let sId = { -i*'~H+', ('~X'+i*'~H3')/Sqrt2 },      % scalar inert doublet
      sID = anti(sId).                            % scalar inert anti-doublet

let DsId^mu^a = (deriv^mu-i*g1/2*B1^mu)*sId^a - i*g2/2*tau^a^b^c*w^mu^c*sId^b.
let DsID^mu^a = (deriv^mu+i*g1/2*B1^mu)*sID^a + i*g2/2*tau^b^a^c*w^mu^c*sID^b.

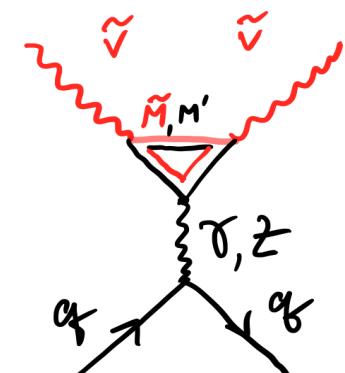
lterm DsID*DsId.
lterm -mu2*sId*sID.
lterm -la2*(sId*sID)**2.
lterm -la3*(shd*shD)*(sId*sID).
lterm -la4*(shd*sID)*(shD*sId).
lterm -la5/2*(shd*sID)**2 + AddHermConj.

CheckHerm.
CheckMasses.
```

# Fermionic Portal for Vector Dark Matter (FPVDM)

- It is the framework, representing the class of models  
[Deandrea, Moretti, Panizzi, Ross, Thongyoi, AB – arXiv:2204.03510,2203.04681]
- Various realisations are possible, including one or several VL fermions

$$\begin{aligned}\mathcal{L}_{FPVDM} &= -\frac{1}{4}(V_{D\mu\nu}^i)^2 + \bar{\Psi}iD\Psi + |D_\mu\Phi_D|^2 - V(\Phi_H, \Phi_D) \\ &\quad - (y'_{\alpha\beta}\bar{\Psi}_L^{i\alpha}\Phi_D f_R^{\text{SM}\beta} + h.c) - M_\Psi^{ij}\bar{\Psi}^i\Psi^j \\ V(\Phi_H, \Phi_D) &= -\mu_H^2\Phi_H^\dagger\Phi_H - \mu_D^2\Phi_D^\dagger\Phi_D + \lambda_H(\Phi_H^\dagger\Phi_H)^2 \\ &\quad + \lambda_D(\Phi_D^\dagger\Phi_D)^2 + \lambda_{HD}(\Phi_H^\dagger\Phi_H)(\Phi_D^\dagger\Phi_D)\end{aligned}$$



- $y'_{\alpha\beta}$  can have a flavour structure – to explain flavour anomalies
- $\lambda_{HD}$  can be negligible at tree-level, DM can be well-generated via FP
- the model with  $\Psi = \begin{pmatrix} \tilde{T} \\ T \end{pmatrix}$  and  $\lambda_{HD} = 0$  was explored

# FPVDM implementation in LanHEP

- Available at hepmdb: <https://hepmdb.soton.ac.uk/hepmdb:0322.0335> together with other many DM models for micrOMEGAs  
See also **m335.xxx.zip** and **s335.xxx.zip** in lanhep folder at DarkToll github
- The LanHEP file is: **FPVDM\_with\_TOP\_final.lhep**
- This model implementation uses various functions from [SLHAplus](#)  
Belanger, Christensen, Pukhov, Semenov CPC 182 (2011) 763-774, 1008.0181 [hep-ph]

```
OrthMatrix( {{H11,H21}, {H12,H22}} ).  
external_func(rDiagonal,*). parameter Hessian = rDiagonal(2,H11,H12,H22).  
external_func(MassArray,*). parameter EiHess1 = MassArray(Hessian,1),  
external_func(MixMatrix,*). EiHess2 = MassArray(Hessian,2).
```
- It also uses external function from additional library which includes loops to define the form-factors(FF) of DM,DM, photon interactions  
`external_func(FF,12).`
- There is also a command to add a line to extlib file:  
`extlib '$clic/VP.c $clic/vp0.c -I$clic -lm'.`

# Using the superpotential formalism in the MSSM and its extensions

- Superpotential – a polynomial  $W$  depending on scalar fields  $A_i$
- The most general form of the MSSM superpotential which does not violate gauge invariance and the SM conservation laws is:

$$W = \mu \epsilon_{ij} H_i^1 H_j^2 + \epsilon_{ij} Y_l^{IJ} H_i^1 L_j^I R^J + \epsilon_{ij} Y_d^{IJ} H_i^1 Q_j^I D^J + \epsilon_{ij} Y_u^{IJ} H_i^2 Q_j^I U^J$$

***which in LanHEP notation will take a form***

`keep_lets W.`

`let W=eps*(mu*H1*H2+ml*H1*L*R+md*H1*Q*D+mu*H2*Q*U) .`

Where  $H1, H2, L, R, Q, U, D$  should be defined above as doublets and singlets in terms of scalar particles.

`keep_lets` statement substitution of  $H1, H2, L, R, Q, U, D$  in terms of their components

# Using the superpotential formalism in the MSSM and its extensions

- Yukawa interactions are given by

$$-\frac{1}{2} \left( \frac{\partial^2 W}{\partial A_i \partial A_j} \Psi_i \Psi_j + H.c. \right)$$

*which in the LanHEP language will take form*

```
lterm = df(W,H1,H2)*fH1*fH2 - ... + AddHermConj.
```

where `fH1, fH2` should be defined above as fermionic partners of corresponding multiples, e.g.

```
let f_h1 = { Zn31*up(~o1)+Zn32*up(~o2)+Zn33*up(~o3)+Zn34*up(~o4),  
            Zm21*up('~-1-')+Zm22*up('~-2-') } .
```

# Using the superpotential formalism in the MSSM and its extensions

## ■ **FF<sup>\*</sup> term from scalar supersymmetric potential**

$$V = \frac{1}{2} D^a D^a + F_i^* F_i \quad \text{where} \quad F_i = \partial W / \partial A_i$$

in LanHEP notation will take a form

$$\text{lterm} - \text{df}(W, H1) * \text{df}(W_c, H1_c) - \dots$$

where  $W_c$  should be declared above as the conjugate superpotential

**FF<sup>\*</sup> term can be introduced even in shorter way as**

$$\text{lterm} - \text{dfdfc}(W, H1) - \dots$$

where  $\text{dfdfc}(W, H1)$  function evaluates the variational derivative, multiplies it by the conjugate expression and returns the result

# CalcHEP: Calculator for High Energy Physics

born as a CompHEP in 1989: MSU-89-63/140

Comput.Phys.Commun. 184 (2013) 1729-1769, 1207.6082 [hep-ph]

Alexander Pukhov, AB, Neil Christensen <http://theory.npi.msu.su/~pukhov/calchep.html>

- **CalcHEP** is a powerful tool for efficient and effective studies of high-energy physics (HEP) phenomenology in Beyond the Standard Model (BSM) scenarios. It enables a high level of automation in going from your favourite model to physical observables such as decay widths, branching ratios, cross sections, kinematic distributions, and parton-level events.
- **Highlights**
  - Convenient graphical interface – to **understand** process in details
  - Output of symbolic results (**Mathematica**, **REDUCE**, **FORM** formats)
  - Calculates particle widths 'on the fly'
  - Easy to modify an existing model (GUI) or to implement the new one (**LanHEP**, **FeynRules**)
  - Batch interface: **multidimensional scan of the parameter space**, produces LHE files in one run
  - Designed to study physics and present and future colliders: **LHA PDF**, **ISR+Beamstrahlung** for ILC
  - Modular structure: one can use it as a matrix element generator in other codes and packages (**e.g. GAMBIT**)
  - Has different modules for user modifications: **user-defined cuts**, **user form factor** etc.

# CalcHEP installation guide

## 1. Download the code

### a) from Dark Tools github

```
wget https://raw.githubusercontent.com/dimauromattia/darktools/main/calcheptools/calcheptools_3.9.2.tgz
```

or

### b) from the HEP Tools site

→ Go to HEP TOOLS → calcheptools → download calcheptools\_3.9.2.tgz

or

### c) from <http://theory.npi.msu.su/~pukhov/calcheptools.html>

```
wget https://theory.sinp.msu.ru/~pukhov/CALCHEP/calcheptools_3.9.2.tgz
```

## 2. Unpack the archive: `tar -zxvf calcheptools_3.9.2.tgz`

## 3. Enter the directory: `cd calcheptools_3.9.2`

## 4. Compile: `make`

## 5. Start CalcHEP: `cd work; ./calcheptools`

**ex#1**

*install CalcHEP*

# Compilation, potential problems and solutions

- To compile the CalcHEP source code you need:  
**C compiler, the X11 graphics library and the X11 include files**  
"CalcHEP is compiled successfully and can be started " is a good sign
- Supported operating systems: Linux, MacOS, SunOS, and Windows Subsystem for Linux (WSL)
- Potential problem
  - The most frequent compilation problem is due to the absence of the X11 include files: in this case CalcHEP will compile, however, it only runs in non-interactive mode: `./calchep` will give

Error: You have launched the interactive session for a version  
of CalcHEP that has been compiled without the X11 library.  
Presumably, the X11 development package is not installed on your computer.
  - the following additional package should be installed to run CalcHEP in GUI mode:  
`libX11-devel` on **Fedora/Scientific**; `libX11-dev` on **Ubuntu/Debian**; `xorg-x11-devel` on **SUSE**;  
**for MAC:** XQuartz is the official X11 server and client-side libraries for macOS get it from [xquartz.org](http://xquartz.org) or `brew install --cask xquartz` but do not forget to **restart** the system after the xquartz installation!
- Compilation for High Precision Calculations
  - Intel C compiler has a `_Quad` type, `-D QUAD` has to be added to `FlagsForSh` as  
`CFLAGS="-D_QUAD_ -fPIC -fsigned-char -Qoption,cpp,--extended_float_type"`

# Features/Limitations of CalcHEP

- Can evaluate any decay and scattering processes within any (user defined) model!
- Tree-level processes
- Squared Matrix Element calculation
  - no spin information for outgoing particles – spin averaged amplitude
- Limit on number of external legs (involved particles) and number of diagrams
  - official limit – 8 , unofficial – none
  - limit is set from the practical point of view:
    - ▶  $2 \rightarrow 6$  ( $1 \rightarrow 7$ ) set the essential time/memory limit
    - ▶ number of diagrams  $\sim 500$  set the disk space and the time limit

# <http://theory.npi.msu.su/~pukhov/calchep.html>

CalcHEP - a package for calculation of Feynman diagrams and integration over multi-particle phase space.

Authors - Alexander Pukhov, Alexander Belyaev, Neil Christensen

The main idea of CalcHEP is to enable one to go directly from the Lagrangian to the cross sections and distributions effectively, with a high level of automation. The package can be compiled on any Unix platform.

General information  
[Main features](#), [Acknowledgments](#), [Publications&Lectures](#), [Contributions](#)

Manual

[calchep\\_man\\_3.3.6.pdf](#) (manual for version 3.3.6, July 19, 2012)  
[HEP computer tools](#) (Lecture by Alexander Belyaev)

See also: [Dan Green, High Pt physics at hadron colliders](#) (Cambridge University Press)

**manual**

Code download.

[Installation](#) [Current version 3.9.2](#)(updated 05.03.2025) [New Options and Bugs Fixed](#) [All versions](#)

**new options and writeup!**

**arXiv:1207.6082**

[MSSM 10.14\(15.10.2014\)](#) [NMSSM 8.15\(25.08.2015\)](#) [CPVMSSM 10.14\(16.10.2014\)](#) [SUSY models By A.Semenov](#) [Lepto](#)  
models: [HEPMDB](#)

Related packages on Web:

Packages for model generation: [LanHEP](#) [FeynRules](#) [SARAH](#)  
RGE and spectrum calculation: [SuSpect](#) [Isajet](#) [SoftSUSY](#) [SPheno](#) [CPsuperH](#) [NMSSMTools](#)

Particle widths in MSSM: [SUSY-HIT](#) [HDECAY](#)

Parton showers: [PYTHIA](#)

Contacts

Email: [calchep@googlegroups.com](mailto:calchep@googlegroups.com)

Launchpad service: [Ask a question](#) [File a bug](#)

**Connected to launchpad system**



# ./calchep

```
CalcHEP_3.9.2/symb
CalcHEP - a package for Calculation in High Energy Physics
Version 3.9.2: Last correction March 5, 2025

Authors: Alexander Pukhov(Skobeltsyn Institute of Nuclear Physics,Moscow)
         Alexander Belyaev(University of Southampton)
         Neil Chistensen (University of Pittsburgh)

For contacts: email      : <calchep@googlegroups.com>
               Questions : https://answers.launchpad.net/calchep
               Bugs      : https://bugs.launchpad.net/calchep
               Code&Models: http://theory.sinp.msu.ru/~pukhov/calchep.html

The BSMs for CalcHEP were developed in collaboration with:
G.Belanger,F.Boudjema,A.Semenov

The package contains codes written by:
M.Donckt,V.Edneral,V.Ilyin,D.Kovalenko,A.Kryukov,G.Lepage,A.Semenov

Press F9 or click the box below to get
References, Contributions, Acknowledgments

This information is available during the session by means of the F9 key
```

# CalcHEP structure/modes

- **Graphical mode**

- ▶ symbolic part
- ▶ numerical part

- **Batch mode**

# Principle KEYS for CalcHEPs GUI



**Enter menu  
selection  
(forward)**



**Exit menu  
selection  
(back)**



**Help!**

# Starting CalcHEP

## Abstract

CalcHEP package is created for calculation of decay and high energy collision processes of elementary particles in the lowest order (tree) approximation. The main idea put into the CalcHEP was to make available passing from the lagrangian to the final distributions effectively with the high level of automatization.

Use F2 key to get information about interface facilities and F1 – as online help.

Questions: <https://answers.launchpad.net/calchep>

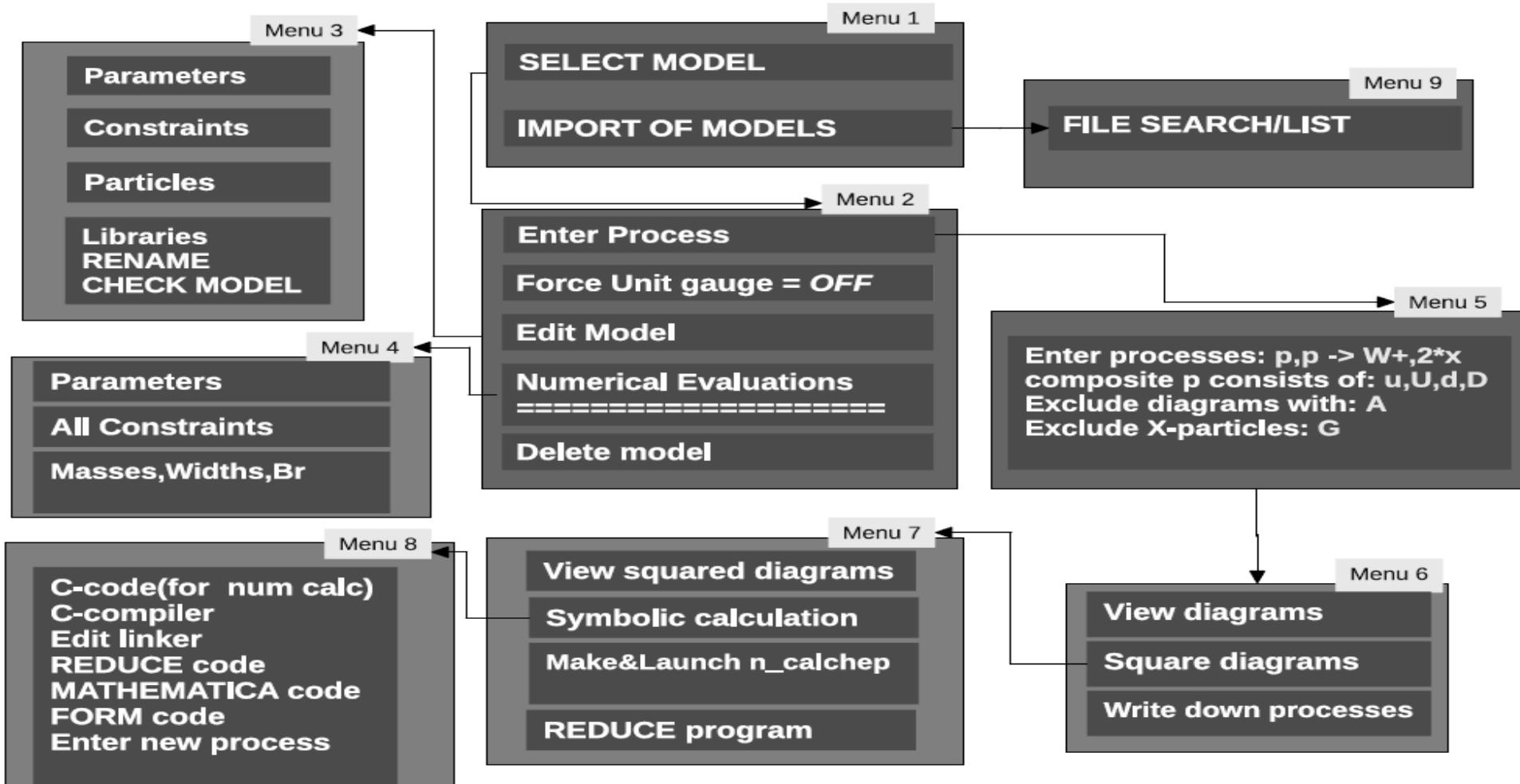
Bugs: <https://bugs.launchpad.net/calchep>

<

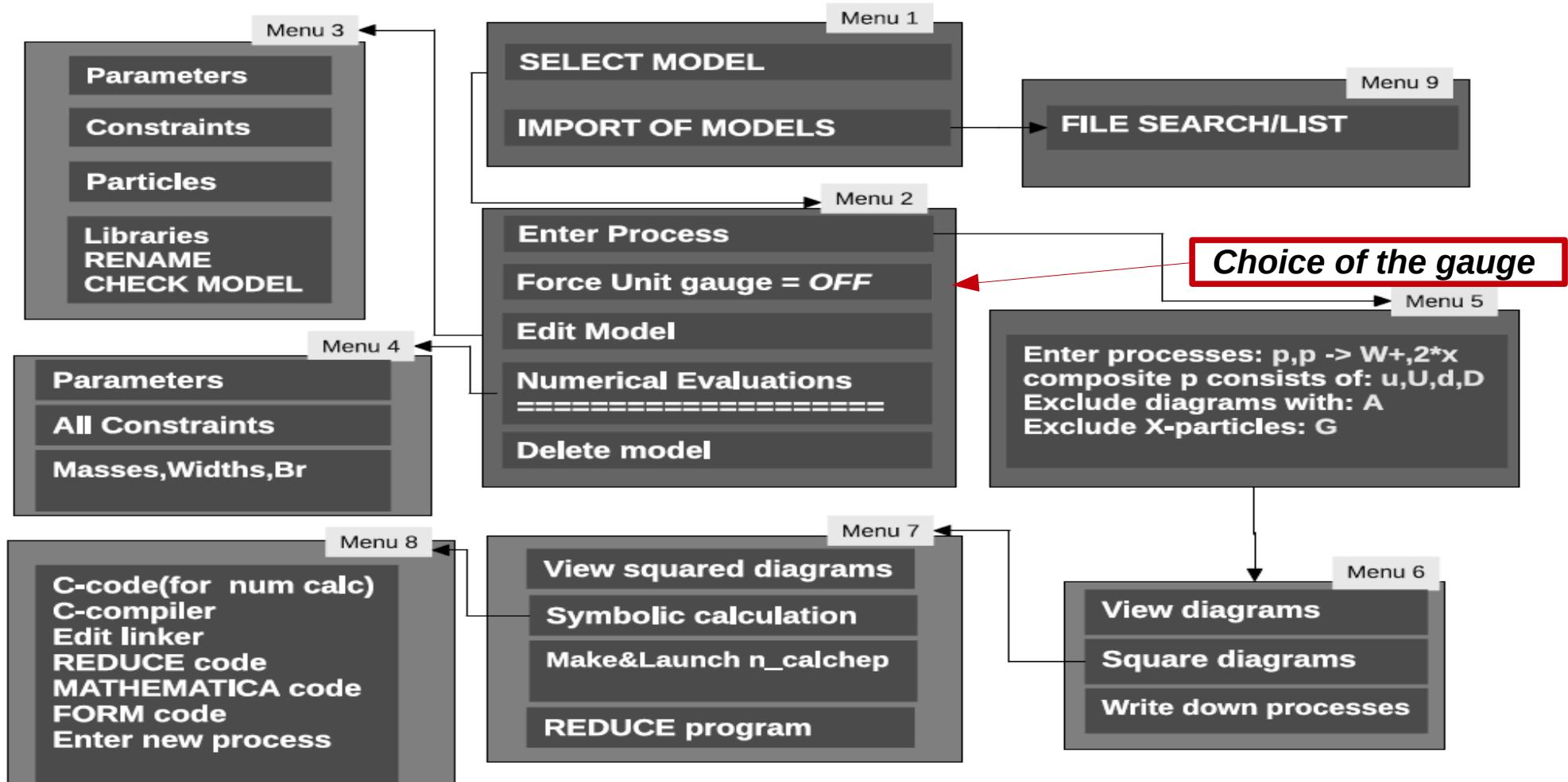
SM  
SM(+hgg)  
SM(+hgg+h4G)  
IDM  
IDM(+hgg)  
IMPORT MODEL

F1-Help F2-Man F5-Switches F6-Results F9-Ref F10-Quit

# CalcHEP menu structure: symbolic part



# CalcHEP menu structure: symbolic part



# Model choice and Process input

*Choose your gauge  
Edit Model*

*Enter Process  
Numerical Evaluation*

Model: SM

## Abstract

CalcHEP package is created for calculation of decay and high energy collision processes of elementary particles in the lowest order (tree) approximation. The main idea put into the CalcHEP was to make available passing from the lagrangian to the final distributions effectively with the high level of automatization.

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Questions: <https://answers.launchpad.net/calchep>

Bugs: <https://bugs.launchpad.net/calchep>

<  
Enter Process  
Force Unit.Gauge= OFF  
Edit model  
Numerical Evaluation  
=====  
Delete model

F1-Help F2-Man F5-Switches F6-Results F9-Ref F10-Quit

# The Model Structure

*Parameters  
Particles*

*Constraints  
Vertices*

Model : SM

**Abstract**

CalcHEP package is created for calculation of decay and high energy collision processes of elementary particles in the lowest order (tree) approximation. The main idea put into the CalcHEP was to make available passing from the lagrangian to the final distributions effectively with the high level of automatization.

Use F2 key to get information about interface facilities and F1 - as online help.

Questions:<https://answers.launchpad.net/calchep>  
Bugs:<https://bugs.launchpad.net/calchep>

Edit model

< Variables  
Constraints  
Particles  
Lagrangian  
Libraries  
RENAME  
CHECK MODEL

F1-Help F2-Man F5-Switches F6-Results F9-Ref

# Particles: prtclxx.mdl (spins 0,1/2,1,3/2,2)

Clr	Del	Size	Read	ErrMes	Particles										
					Full name	A	A	PDG	2*spin	mass	width	color	aux	LaTex (A)	La
					gluon	G	G	21	2	0	0	8	G	g	g
					photon	A	A	22	2	0	0	1	G	\gamma	\gamma
					Z-boson	Z	Z	23	2	MZ	!wZ	1	G	Z	Z
					W-boson	W+	W-	24	2	MW	!wW	1	G	W^+	W^-
					Higgs	h	h	25	0	Mh	!wh	1		h	h
					electron	e	E	11	1	0	0	1		e^-	e^+
					e-neutrino	ne	Ne	12	1	0	0	1	L	\nu_e	\bar{\nu}_e
					muon	m	M	13	1	Mm	0	1		\mu^-	\bar{\mu}
					m-neutrino	nm	Nm	14	1	0	0	1	L	\nu_\mu	\bar{\nu}_\mu
					tau-lepton	l	L	15	1	Ml	0	1		\tau^-	\bar{\tau}
					t-neutrino	nl	Nl	16	1	0	0	1	L	\nu_\tau	\bar{\nu}_\tau
					d-quark	d	D	1	1	0	0	3		d	\bar{d}
					u-quark	u	U	2	1	0	0	3		u	\bar{u}
					s-quark	s	S	3	1	0	0	3		s	\bar{s}
					c-quark	c	C	4	1	Mc	0	3		c	\bar{c}
					b-quark	b	B	5	1	Mb	0	3		b	\bar{b}
					t-quark	t	T	6	1	Mt	!wt	3		t	\bar{t}

F1 F2 Xgoto Ygoto Find Write

# Particles: prtclxx.mdl

Particles

Clr	Del	Size	Read	ErrMes	Full name	A	A	PDG	2*spin	mass	width	color	aux	LaTex (A)	La
					gluon	G	G	21	2	0	0	8	G	g	g
					photon	A	A	22	2	0	0	1	G	\gamma	\gamma
					Z-boson	Z	Z	23	2	MZ	!wZ	1	G	Z	Z
					W-boson	W+	W-	24	2	MW	!wW	1	G	W^+	W^-
					Higgs	h	h	25	0	Mh	!wh	1	h	h	h
					electron	e	E	11	1	0	0	1		e^-	e^+
					e-neutrino	ne	Ne	12	1	0	0	1	L	\nu_e	\bar{\nu}_e
					muon	m	M	13	1	Mm	0	1		\nu_\mu	\bar{\nu}_\mu
					m-neutrino	nm	Nm	14	1	0	0	1	L	\nu_\mu\nu_\mu	\bar{\nu}_\mu\bar{\nu}_\mu
					tau-lepton	l	L	15	1	Ml	0	1		\nu_\tau	\bar{\nu}_\tau
					t-neutrino	nl	Nl	16	1	0	0	1	L	\nu_\tau\nu_\tau	\bar{\nu}_\tau\bar{\nu}_\tau
					d-quark	d	D	1	1	0	0	3		d	\bar{d}
					u-quark	u	U	2	1	0	0	3		u	\bar{u}
					s-quark	s	S	3	1	0	0	3		s	\bar{s}
					c-quark	c	C	4	1	Mc	0	3		c	\bar{c}
					b-quark	b	B	5	1	Mb	0	3		b	\bar{b}
					t-quark	t	T	6	1	Mt	!wt	3		t	\bar{t}

**Higgs boson width will be calculated 'on the fly'**

# Independent parameters: varsxx.mdl

Clr	Del	Size	Read	ErrMes	Variables	1
					> Comment	<
EE		0.31333			Electromagnetic coupling constant ( $\sim 1/128$ )	
GG		1.117			Strong coupling constant (Z point) (PDG-94)	
SW		0.474			sin of the Weinberg angle 0.474 - "on-shell", 4	
Q		100			Scale of effective running masses	
MW		80.385			W boson mass	
Mtp		172.5			Top quark pole mass	
McMc		1.23			Mc (Mc) MS-BAR	
MbMb		4.25			Mb (Mb) MS-BAR	
alphaSMZ		0.1184			Srtong alpha(MZ)	
Ml		1.777			mass of tau-lepton	
Mh		125			mass of Higgs	

F1 F2 Xgoto Ygoto Find Write

# Dependent parameters(constraints): funcxx.mdl

```
          Constraints
Clr Del Size Read ErrMes
Name    |> Expression
CW      |sqrt(1-SW^2) % cos of the Weinberg angle
GF      |EE^2/(2*SW*MW)^2/Sqrt2 % experimental value 1.166E-5 [1/GeV^2]
MZ      |MW/CW % Z boson mass
LamQCD  |initQCD5(alphaSMZ, McMc, MbMb, Mtp)
Mb      |MbEff(Q)
Mc      |McEff(Q)
Ms      |MqEff(0.096, Q) % s-quark effective mass via 2MeV running one
LAAh    |-cabs(lAAhiggs(Mh, "h"))
LGGh    |-cabs(lGGhiggs(Mh, "h"))
aQCDh   |alphaQCD(Mh)/acos(-1)
RQCDh   |sqrt(1+149/12*aQCDh+68.6482*aQCDh^2-212.447*aQCDh^3)
B00000  |1-2*SW^2
B00001  |1-4*SW^2+4*SW^4

F1 F2 Xgoto Ygoto Find Write
```

# Feynman rules: lgrngxx.mdl

Lagrangian					1
Clr	Del	Size	Read	ErrMes	
P1	P2	P3	P4	> Factor -4*LAAh	< > dLagrangian/ dA(p1) dA(p2) dA(p3) p1.p2*m1.m2-m2.p1*m1.p2
A	A	h		EE	m3.p2*m1.m2-m1.p2*m2.m3-m2.p3*m1.m3+m
A	W+	W-		-i*EE*MW	m1.m2
A	W+ f	W- f		i*EE*MW	m1.m3
A	W+ f	W- f		-EE	m1.p3-m1.p2
A.C	W+.c	W-		EE	m3.p1
A.C	W-.c	W+		-EE	m3.p1
B	b	A		-EE/3	G(m3)
B	b	G		GG	G(m3)
B	b	Z		EE/(12*CW*SW)	4*SW^2*G(m3)-3*G(m3)*(1-G5)
B	b	Z. f		i*EE*Mb/(2*MW*SW)	G5
B	b	h		-EE*Mb/(2*MW*SW)	1
B	t	W-		EE*Sqrt2/(4*SW)	G(m3)*(1-G5)
B	t	W-. f		i*EE*Sqrt2/(4*MW*SW)	Mb*(1-G5)-Mt p*(1+G5)
C	c	A		2*EE/3	G(m3)
C	c	G		GG	G(m3)
C	c	Z		-EE/(12*CW*SW)	8*SW^2*G(m3)-3*G(m3)*(1-G5)
C	c	Z. f		-i*EE*Mc/(2*MW*SW)	G5
C	c	h		-EE*Mc/(2*MW*SW)	1
C	s	W+		EE*Sqrt2/(4*SW)	G(m3)*(1-G5)
C	s	W+. f		-i*EE*Sqrt2/(4*MW*SW)	Ms*(1+G5)-Mc*(1-G5)
D	d	A		-EE/3	G(m3)
D	d	G		GG	G(m3)
D	d	Z		EE/(12*CW*SW)	4*SW^2*G(m3)-3*G(m3)*(1-G5)

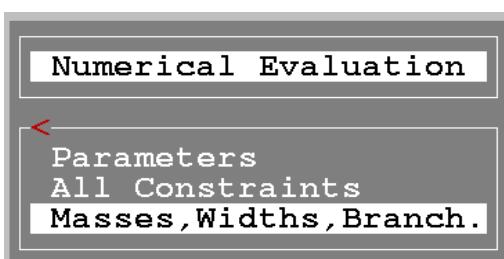
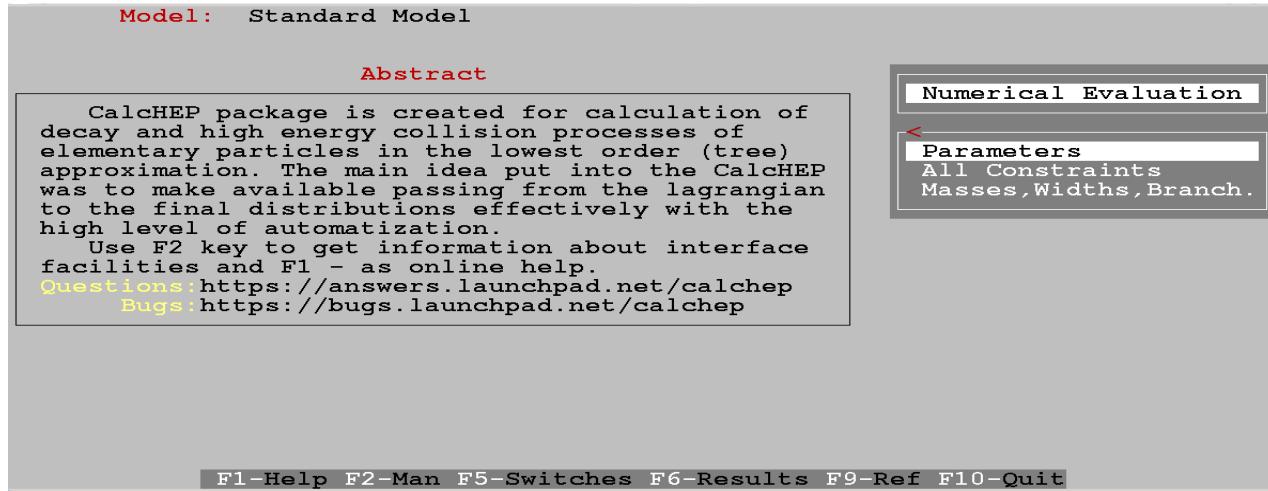
F1 F2 Xgoto Ygoto Find Write

# External Libraries: extlibxx.mdl

Typically is empty for simple models but can be used for any library which helps to build complicated model. E.g. mass spectra calculator for SUSY (involving RGE solutions etc)

```
* Libraries
Clr Del Size Read ErrMes
External libraries
/home/belyaev/calchep/MSSM/mLib.a <
%
%1.Default code for spectrum calculation and RGE solution
%attached to the model is SuSpect:
%http://www.lpta.univ-montp2.fr/users/kneur/Suspect/
%\bibitem{Djouadi:2002ze}
% A.~Djouadi, J.~L.~Kneur and G.~Moultaka,
% `SuSpect: A Fortran code for the supersymmetric and Higgs particle
% spectrum in the MSSM,''
% arXiv:hep-ph/0211331.
%
%2.The realization in terms of CalcHEP was done by
%\bibitem{Belanger:2004yn}
% G.~Belanger, F.~Boudjema, A.~Pukhov and A.~Semenov,
% `MicrOMEGAs: Version 1.3,''
% Comput.\ Phys.\ Commun.\ {\bf 174}, 577 (2006)
% [arXiv:hep-ph/0405253].
```

# Numerical evaluation of masses & branchings



All Particles -> SLHA

G	Zero
A	Zero
Z	9.1188E+01
W+	8.0385E+01
h	1.2500E+02
e	Zero
ne	Zero
m	1.0570E-01
rm	Zero
l	1.7770E+00
nl	Zero
d	Zero
u	Zero

PgDn

See results in file 'decaySLHA2.txt'  
Press any key

**ex#3:** Find the SM particles spectrum and Br ratios

# Syntax for the process

- the input syntax:  $P1,[P2] \rightarrow P3,P4 [,,...,[N^*x]]$
- hadron/composite particle scattering  
 $'p^*,p^*\rightarrow W+,b,B'$   
unknown particle are assumed to be composite,  
if you use ' $p^*$ ', the u,U,d,D,s,S,c,C,b,B,G structure will be used automatically
- wild cards/names for outgoing particles  
 $'H \rightarrow 2*x'$
- intermediate particles can be non-trivially excluded  
 $'W+ > 2, A>1, Z>3'$

**ex#4:** SM Higgs production cross section for  $e^+e^- \rightarrow Hz$  process versus the collider energy for 0.5-1.0 TeV range, 10 GeV step

# Symbolic session(1)

Model: SM

## List of particles (antiparticles)

A(A ) - photon	Z(Z ) - Z boson	G(G ) - gluon
W+(W- ) - W boson	ne(Ne ) - neutrino	e(E ) - electron
nm(Nm ) - mu-neutrino	m(M ) - muon	nl(Nl ) - tau-neutrino
l(L ) - tau-lepton	u(U ) - u-quark	d(D ) - d-quark
c(C ) - c-quark	s(S ) - s-quark	t(T ) - t-quark
b(B ) - b-quark	h(h ) - Higgs	

```
Enter process: p*,p*->W,b,B
composite 'p*' consists of: G,d,D,u,U,s,S,c,C,b,B
composite 'W' consists of: W+,W-
Exclude diagrams with [ ]
```

# Symbolic session (2)

Model: SM

Process:  $p^*, p^* \rightarrow W, b, B$

Feynman diagrams

88 diagrams in 8 subprocesses are constructed.  
0 diagrams are deleted.

**View diagrams**

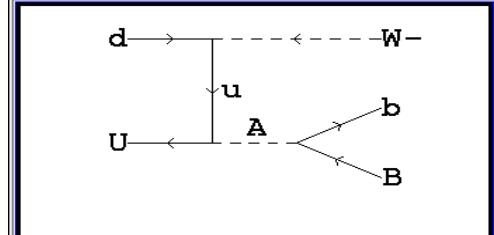
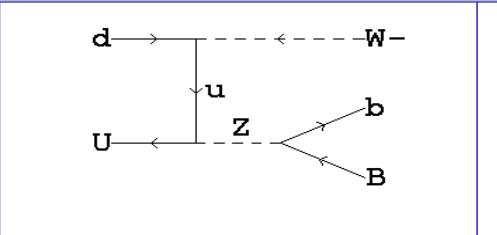
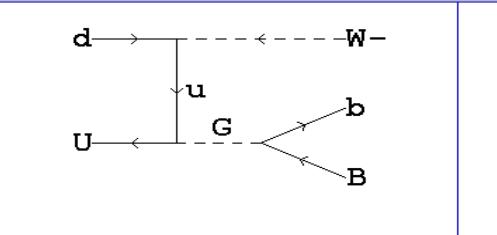
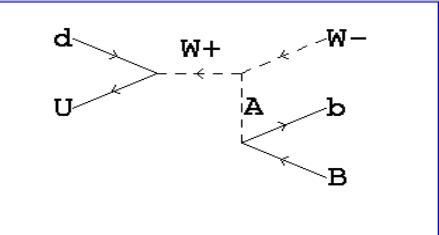
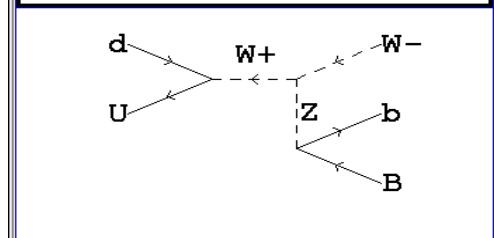
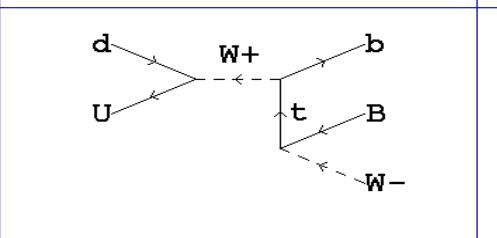
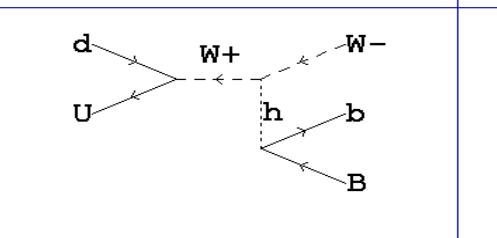
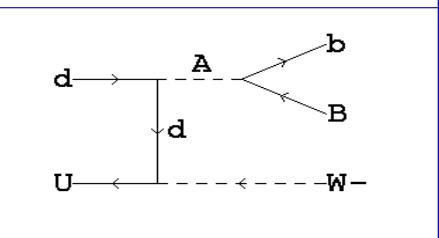
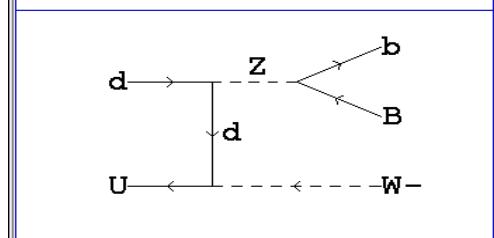
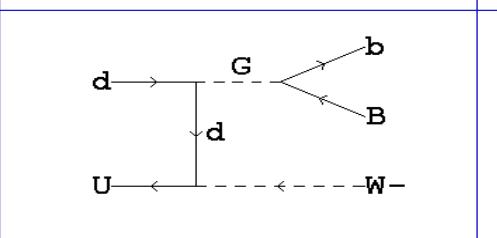
NN	Subprocess	Del	Rest
<			
1   d,U	$\rightarrow W-, b, B$	0	10
2   D,u	$\rightarrow W+, b, B$	0	10
3   u,D	$\rightarrow W+, b, B$	0	10
4   U,d	$\rightarrow W-, b, B$	0	10
5   s,C	$\rightarrow W-, b, B$	0	12
6   S,c	$\rightarrow W+, b, B$	0	12
7   c,S	$\rightarrow W+, b, B$	0	12
8   C,s	$\rightarrow W-, b, B$	0	12

F1-Help F2-Man F3-Model F5-Switches F6-Results F7-Del F8-UnDel F9-Ref F10-Quit

# Symbolic session (3)

Delete, On/off, Restore, Latex

1/10

F1-Help, F2-Man, PgUp, PgDn, Home, End, # , Esc

# Symbolic session (4)

```
Model: SM
Process: p*,p*->W,b,B
Feynman diagrams
88 diagrams in 8 subprocesses are constructed.
0 diagrams are deleted.

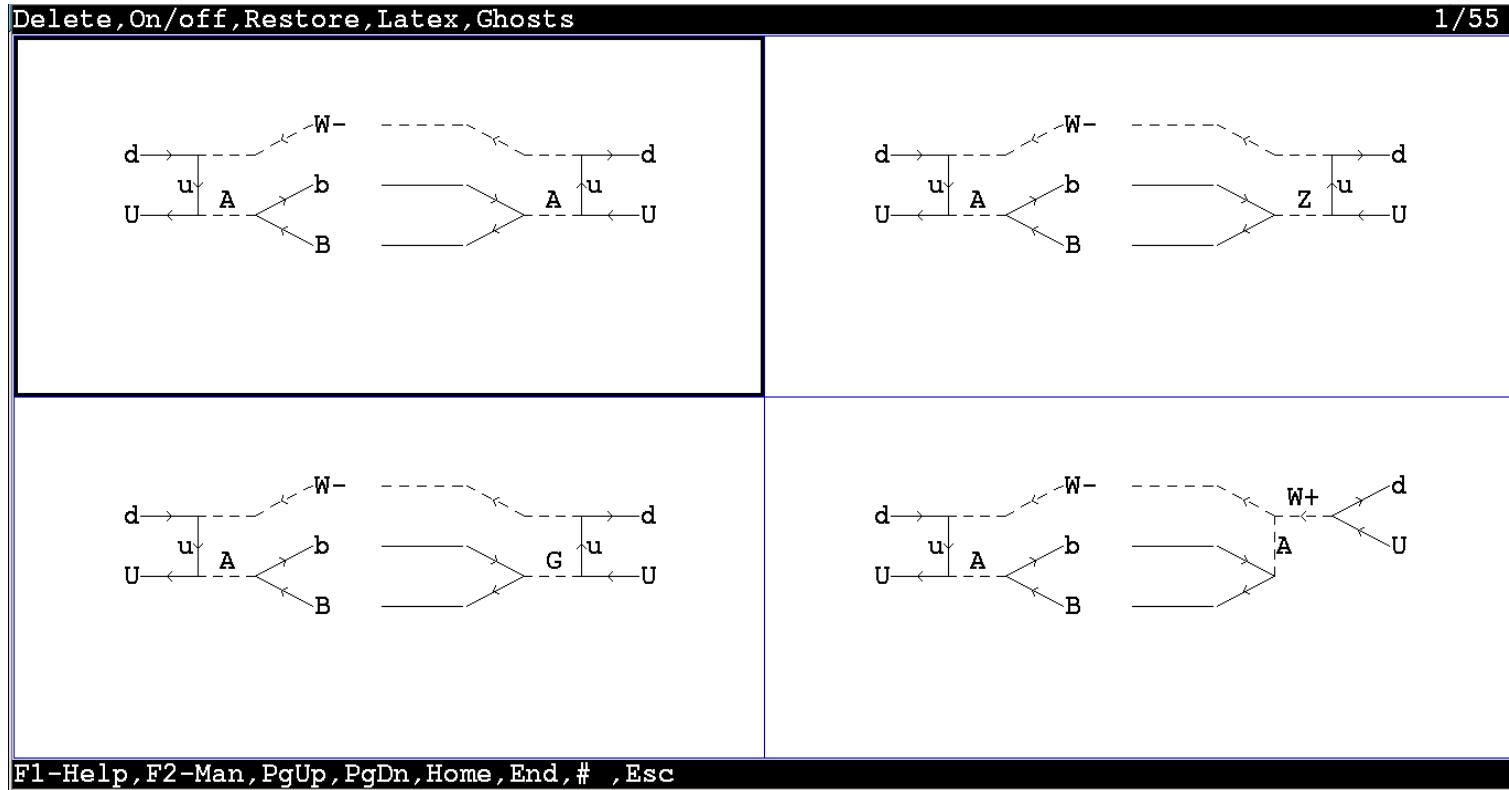
View squared diagrams

Squared diagrams
532 diagrams in 8 subprocesses are constructed.
0 diagrams are deleted.
0 diagrams are calculated.

NN Subprocess Del Calc Rest
<
1| d,U->W-,b,B | 0| 0| 55
2| D,u->W+,b,B | 0| 0| 55
3| u,D->W+,b,B | 0| 0| 55
4| U,d->W-,b,B | 0| 0| 55
5| s,C->W-,b,B | 0| 0| 78
6| S,c->W+,b,B | 0| 0| 78
7| c,S->W+,b,B | 0| 0| 78
8| C,s->W-,b,B | 0| 0| 78

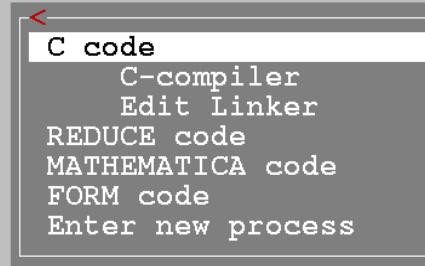
F1-Help F2-Man F3-Model F4-Diagrams F5-Switches F6-Results F9-Ref F10-Quit
```

# Symbolic session (5)



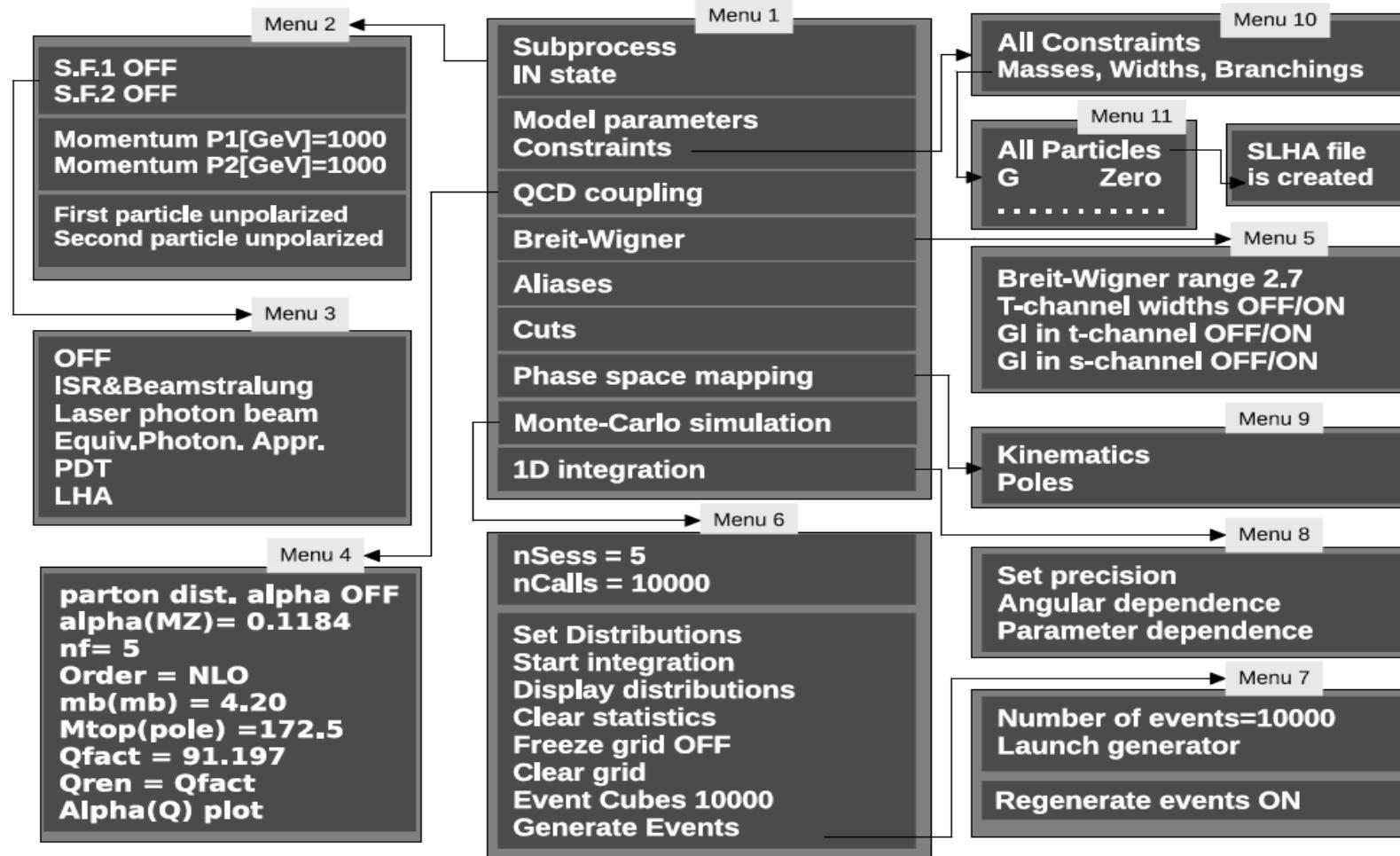
# Symbolic session (6)

```
Model: SM  
Process: p*,p*->W,b,B  
  
Feynman diagrams  
88 diagrams in 8 subprocesses are constructed.  
0 diagrams are deleted.  
  
Squared diagrams  
532 diagrams in 8 subprocesses are constructed.  
0 diagrams are deleted.  
532 diagrams are calculated.
```



F1-Help F2-Man F3-Model F4-Diagrams F5-Switches F6-Results F9-Ref F10-Quit

# Menu structure of the numerical part



# Numerical part(1)

```
(sub)Process: u, D -> W+, b, B  
Monte Carlo session: 1  
  
#IT Cross section[pb] Error[%] nCall Eff. chi^2
```

<  
Subprocess  
IN state  
Model parameters  
Constraints  
QCD alpha & scales  
Breit-Wigner  
Aliases  
Cuts  
Phase space mapping  
Monte Carlo simulation

F1-Help F2-Man F5-Options F6-Results F8-Calc F9-Ref F10-Quit

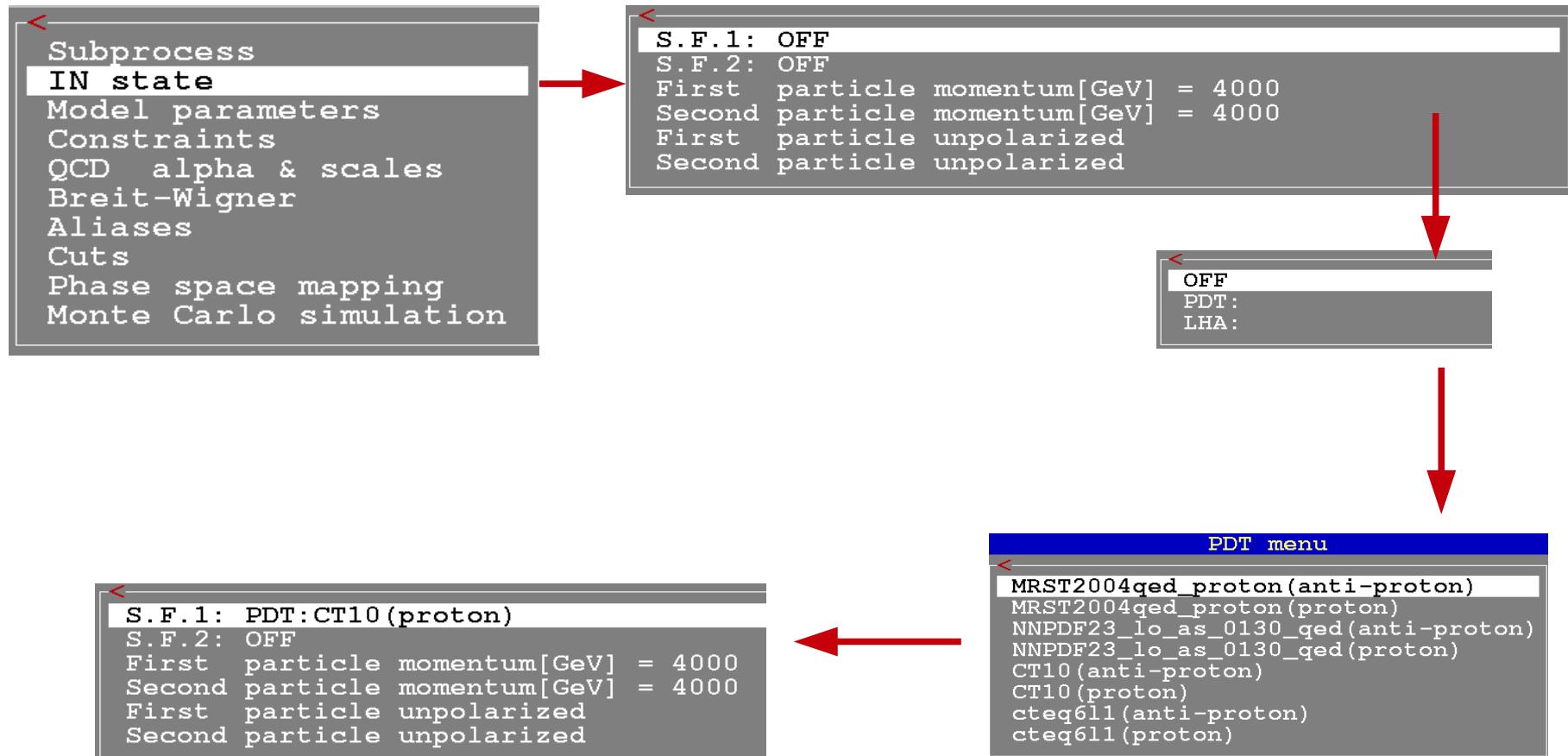
# Numerical part(2)

```
(sub)Process: d, U -> W-, b, B  
Monte Carlo session: 1  
  
#IT Cross section[pb] Error[%] nCall Eff. chi^2/(
```

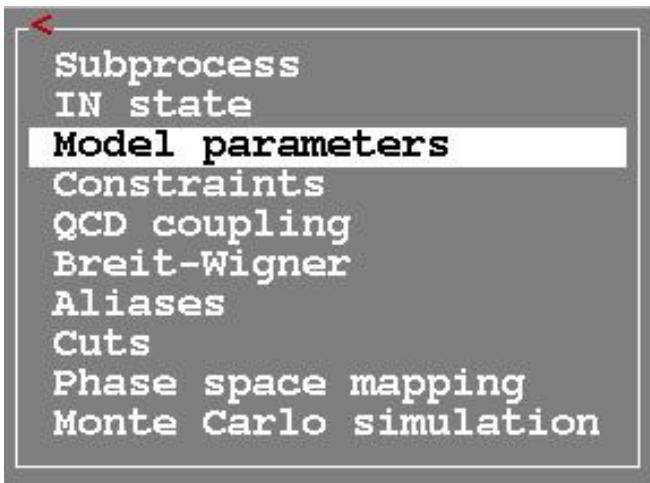
Subprocess						
d	U	->	W-	b	B	
D	u	->	W+	b	B	
u	D	->	W+	b	B	
U	d	->	W-	b	B	
s	C	->	W-	b	B	
S	c	->	W+	b	B	
c	S	->	W+	b	B	
C	s	->	W-	b	B	

F1-Help F2-Man F5-Options F6-Results F8-Calc F9-Ref

# control of the initial states and parton density functions



# model parameters



Model parameters	
Change parameter	
READ_FROM_FILE	
EE	3.1333E-01
SW	4.7400E-01
Q	1.0000E+02
MW	8.0385E+01
Mtp	1.7250E+02
McMc	1.2300E+00
MbMb	4.2500E+00
alphaSMZ	1.1840E-01
Ml	1.7770E+00
Mh	1.2500E+02

# dependent parameters (SM+ggH model)

```
< Subprocess  
IN state  
Model parameters  
Constraints  
QCD alpha & scales  
Breit-Wigner  
Aliases  
Cuts  
Phase space mapping  
Monte Carlo simulation
```

```
Constraints  
All Constraints  
Masses,Widths,Branching
```

Constraints

Display dependence

	Print to file
CW	8.8052E-01
GF	1.1954E-05
MZ	9.1292E+01
LamQCD	3.4641E-01
Mb	3.1986E+00
Mc	6.1137E-01
Ms	5.9444E-02
<b>LAAh</b>	<b>-7.8864E-06</b>
LGGr	-1.3054E-05
aQCDh	3.5959E-02

Constraints

Display dependence

LmbdAA	-7.8845E-06
--------	-------------

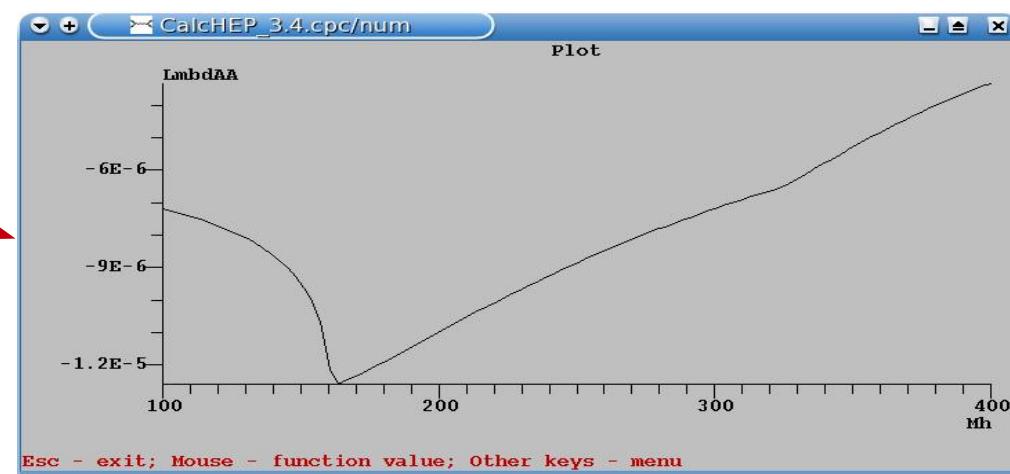
on parameter

Mh	1.2500E+02
----	------------

Plot

x-Min = 100  
x-Max = 400  
Npoints = 100

Display



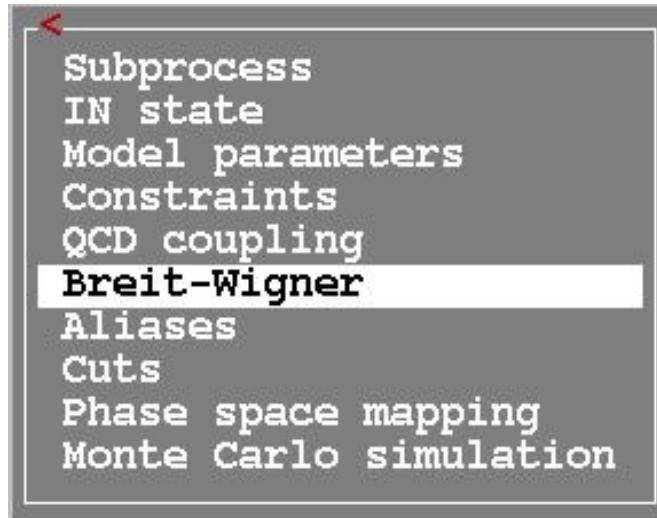
# QCD coupling and the QCD scale

```
< Subprocess  
IN state  
Model parameters  
Constraints  
QCD coupling  
Breit-Wigner  
Aliases  
Cuts  
Phase space mapping  
Monte Carlo simulation
```



```
QCD coupling  
QCD alpha  
<  
parton dist. alpha !ON  
alpha(MZ) = 0.1172  
nf = 5  
order= NLO  
mb(mb) = 4.200  
Mtop(pole) = 175.00  
Qfact= M12  
Qren = Qfact  
Alpha(Q) plot
```

# control of resonances



**Breit-Wigner**

**BreitWigner range 2.7**

T-channel widths	OFF
GI in t-channel	OFF
GI in s-channel	OFF

→ F1

\* n\_width\_1

This menu sets value R which defines range of implementation of Breit-Wigner formula. Namely it is used in the region where

$$|p^2-m^2| < R*m*w$$

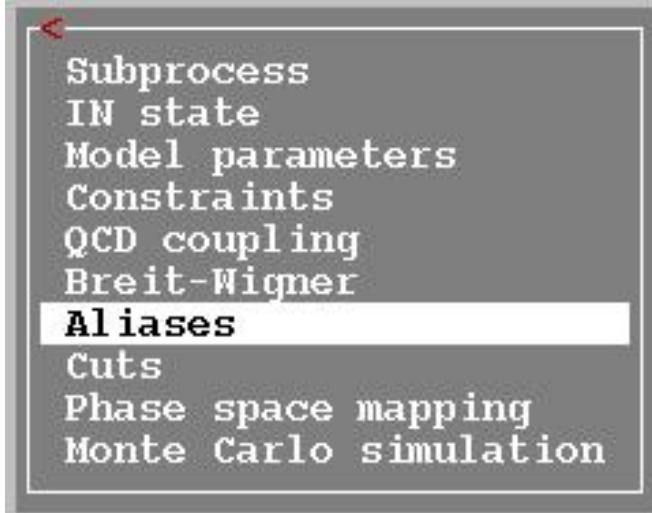
For region

$$|p^2-m^2| > \sqrt{R^2+1}*m*w$$

we use zero width propagator. In the intermediate region constant propagator interpolates both formulas.

In general Breit-Wigner leads to breaking of gauge invariance. In its turn it can lead to the lost of diagram cancellation. From the other side just in the point  $p^2=m^2$  the contribution of pole diagram have to be gauge invariant. Thus at this point cancellation between pole and non-pole diagrams is not expected. We assume that close to pole the problem also is not so serious. But far from the pole we ignore width and restore gauge invariance.

# Aliases



A screenshot of a software interface showing the 'Aliases' configuration panel. The title bar says 'Composites'. The table has columns: Clr, Del, Size, Read, ErrMes, and Name. The 'Name' column contains a placeholder 'Comma separated list of particles'. A row for 'Jet' is shown with the value 'u, U, d, D, s, S, c, C, G'. A red arrow points from the 'Aliases' option in the sidebar to the 'Name' column of the 'Jet' row.

Clr	Del	Size	Read	ErrMes	Name
					Comma separated list of particles
					Jet
					u, U, d, D, s, S, c, C, G

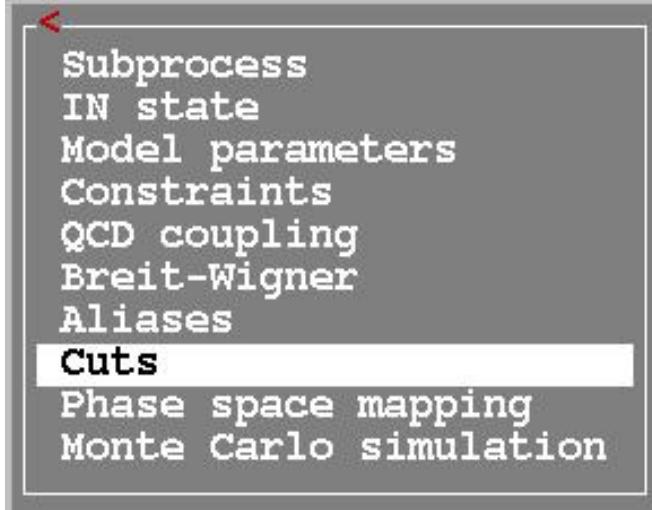
# setting kinematical cuts

<  
Subprocess  
IN state  
Model parameters  
Constraints  
QCD coupling  
Breit-Wigner  
Aliases  
**Cuts**  
Phase space mapping  
Monte Carlo simulation



		Cuts			5
	Clr	Del	Size	Read	ErrMes
Parameter				$\rightarrow$ Min bound	$\leftarrow$ Max bound $\leftarrow$
T(b)				120	
T(B)				120	
N(b)				-5	15
N(B)				-5	15
J(b,B)				10.5	

# setting kinematical cuts



→ Cuts 0

Parameter	> Min bound <	> Max bound <
*	n_cut	
This table applies cuts on the phase space. A phase space function is described in the first column. Its limits are defined in the second and the third columns. If one of these fields is empty then a one-side cut is applied.		
The phase space function is defined by its name which characterizes type of cut and a particle list for which the cut is applied.		
For example, "T(u)" means transverse momentum of 'u'-quark; T(u,D) means summary transverse momentum of quark pair.		
The following cut functions are available:		
A	- Angle in degree units;	
C	- Cosine of angle;	
J	- Jet cone angle;	
E	- Energy of the particle set;	
M	- Mass of the particle set;	
P	- Cosine in the rest frame of pair;	

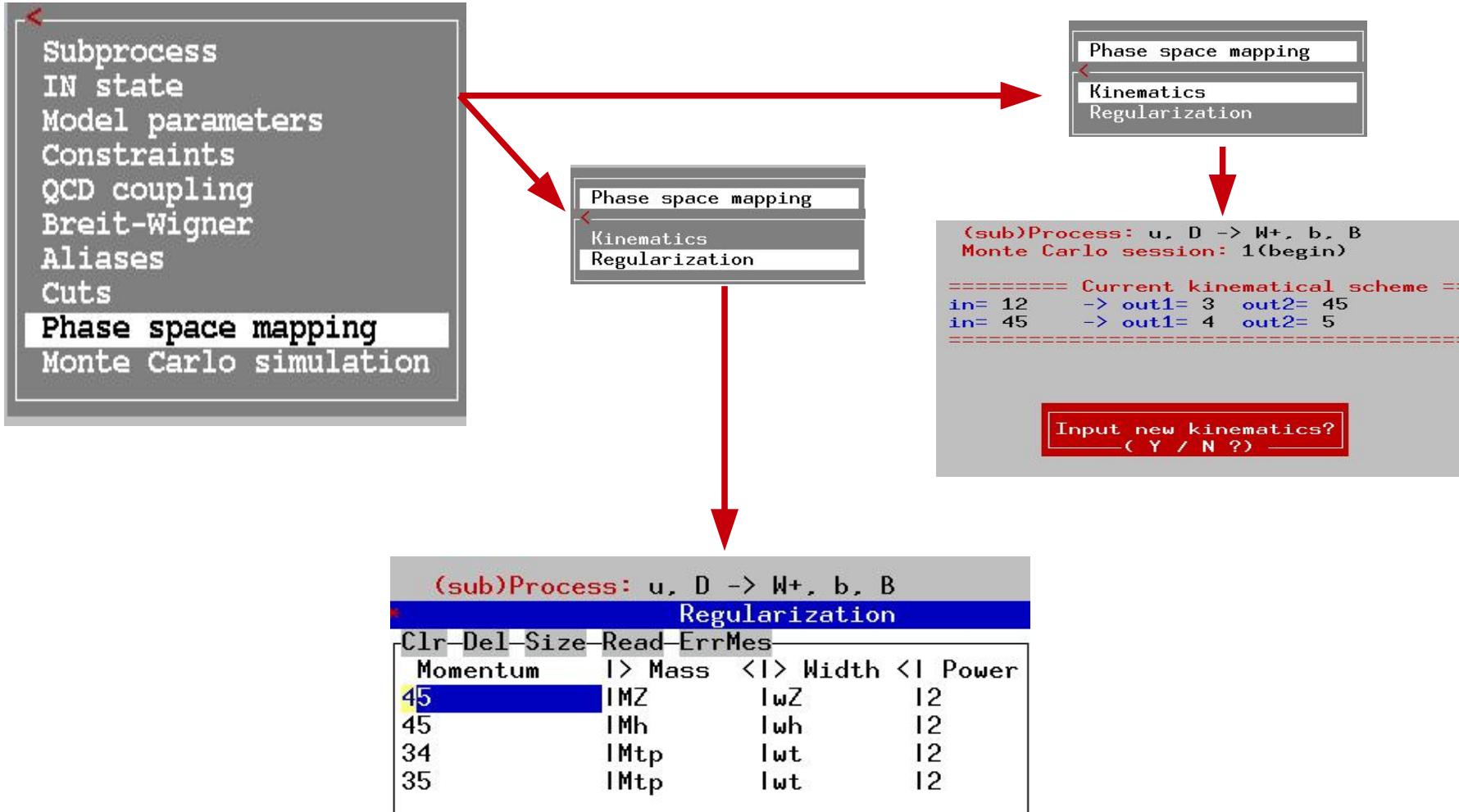
↓ F1

PgDn

→ Cuts 5

Parameter	> Min bound <	> Max bound <
T(b)	120	
T(B)	120	
N(b)	1-5	15
N(B)	1-5	15
J(b,B)	10.5	1

# phase-space mapping



# integration over the phase space

Subprocess  
IN state  
Model parameters  
Constraints  
QCD coupling  
Breit-Wigner  
Aliases  
Cuts  
Phase space mapping  
**Monte Carlo simulation**

(sub)Process: u, D → W+, b, B  
Monte Carlo session: 2(continue)

#IT	Cross section [pb]	Error %
6	9.5931E+00	7.10E-01
7	9.5686E+00	6.79E-01
8	9.5669E+00	6.82E-01
9	9.6892E+00	7.93E-01
10	9.6267E+00	7.51E-01
1	9.7757E+00	7.32E-01
clear statistics.		
2	9.6557E+00	6.82E-01
3	9.7464E+00	1.38E+00
4	9.6915E+00	1.05E+00
5	9.7032E+00	7.68E-01
< >	9.7095E+00	3.74E-01

Monte Carlo simulation

nSess = 5  
nCalls = 10000  
**Set Distributions**  
\*Start integration  
Display Distributions  
Clear statistic  
Freeze grid OFF  
Clear grid  
Event Cubes 10000  
Generate Events

Distributions

Parameter_11	Min_1	Max_1	Parameter_21	Min_2	Max_2
T(b)	10	1200			
T(B)	10	1200			
N(b)	1-5	15			
N(B)	1-5	15			
M(b,B)	10	1500			
M(W+,b)	10	1500			
T(b)	10	1500	M(b,B)	10	1500

CalcHEP/num

u, D → W+, b, B

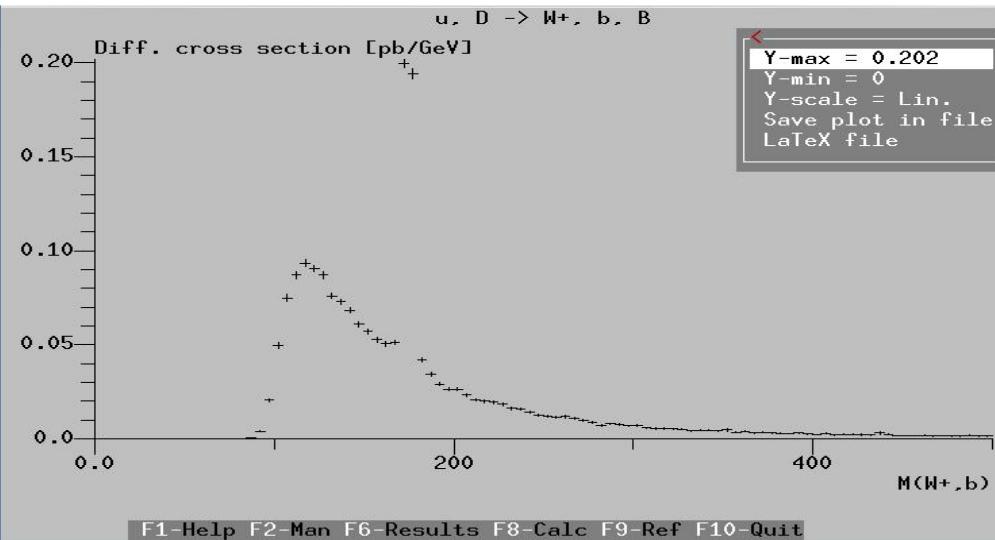
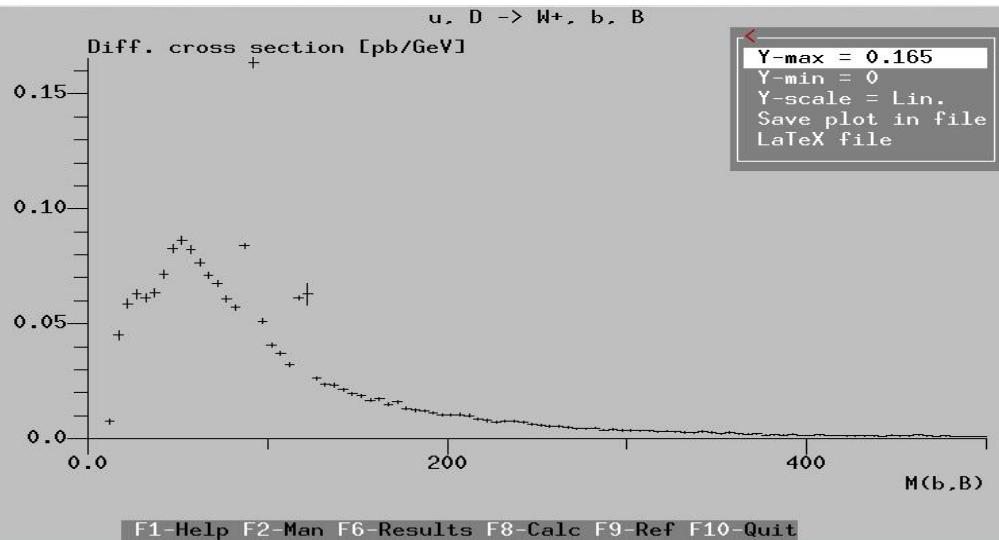
Diff. cross section [pb/GeV]

Y-max = 0.165  
Y-min = 0  
Y-scale = Lin.  
Save plot in file  
LaTeX file

F1-Help F2-Man F6-Results F8-Calc F9-Ref F10-Quit

The accuracy and the stability of the cross section indicate that you can trust your results

# Resulting $M_{bb}$ and $M_{Wtb}$ kinematical distributions



ex#5

1. Calculate WbB production rates at the LHC  
for PT b-jet > 20 GeV, b-Jet separation > 0.5, -3 < pseudorapidity < 3
2. Plot bb- and Wb invariant mass distributions for PT b-jet > 20 GeV and PT b-jet > 40 GeV

# events generations

```
Monte Carlo simulation
nSess = 5
nCalls = 10000
Set Distributions
*Start integration
Display Distributions
Clear statistic
Freeze grid      ON
Clear grid
Event Cubes 10000
Generate Events
```

2

```
Monte Carlo simulation
Generate Events
Number of events=10000
Launch generator
Regenerate events    ON
```

```
statistic
efficiency: 2.1E-02
Reached max: 4.9E+01
Mult. events: 6.4E-03
Neg.events: 0.0E+00
-----
Accept events?
( Y / N ? )
```

# File with events in the native CalcHEP format

```
#Type 2 -> 3
#Initial_state
P1_3=4.000000E+03 P2_3=-4.000000E+03
StrFun1="PDT:cteq6m(proton)" 2212
StrFun2="PDT:cteq6m(proton)" 2212
#PROCESS 2(u) -1(D) -> 24(W+) 5(b) -5(B)
#MASSES 0.000000000E+00 0.000000000E+00 8.0385000000E+01 3.2414139578E+00 3.2414139578E+00
#Cross_section(Width) 6.473084E+01
#Number_of_events 1000
#Events      P1_3 [Gev]      P2_3 [Gev]      P3_1 [Gev]      P3_2 [Gev]      P3_3 [Gev]      P4
1    7.0828325272E+02 -3.8182148276E+00 -5.8685533663E+00 2.4810106784E+00 6.8128552155E+02 1.995
1    1.5237718262E+02 -2.5952742306E+01 1.1734367441E+01 -2.1669699291E+01 5.6645397996E+01 4.499
1    7.2370755716E+02 -3.3186893665E+00 -3.4449322581E+00 -5.1815667765E+00 5.8508268207E+02 -3.584
1    2.6295673814E+02 -1.1370528114E+01 8.9463043464E+00 -3.4258266547E+00 2.2732569389E+02 -9.675
1    5.7099697940E+02 -3.3943984194E+01 7.2879879961E+00 -2.3531627752E+01 1.9857446272E+01 -8.750
1    3.6709401207E+02 -2.4124155464E+01 -4.8101350483E+00 6.6698730251E+01 2.0295672218E+02 -4.597
1    3.7196555447E+01 -4.1553021555E+02 -3.1735918986E+00 2.8330641675E-01 -6.6745521993E+00 4.343
1    4.0543944850E+01 -1.1104274125E+02 -8.2903700266E+00 -4.3292277920E+00 -9.0241583360E-01 6.562
1    4.0084952687E+02 -1.0215920577E+01 1.1427574950E+01 2.6016502364E+00 3.8645254998E+02 -4.666
1    2.2620009412E+01 -1.2387066011E+02 -5.0869818859E+00 1.1389105773E+01 -7.1200204784E+01 1.176
1    7.2046251695E+02 -2.1091178466E+01 -1.4887347954E+01 8.1292985197E+01 5.8742582956E+02 -5.134
1    6.8661185459E+01 -8.3534206530E+01 -5.5091602956E+00 -1.7099072377E+01 4.1559702536E+01 2.604
1    1.5145483971E+03 -3.1164597600E+00 -7.8325298677E+00 3.6606202670E+01 1.2782056265E+03 1.074
```

**GUI:** full control of details of the process  
**scripts:** automate calculation/generation/analysis  
**batch:** does everything (sym,num,plots,...) in one run

### Script example:

- **\$CALCHEP/bin/subproc\_cycle *nmax lumi***

e.g.

```
./bin/subproc_cycle 1000 100000
```

*You should run it from results dir where the n\_calchep binary is!*

*Will evaluate cross section and generate events*

- **\$CALCHEP/bin/event\_mixer Luminosity[1/fb] nevents event\_dirs**

*mixes subprocesses and connects production and decay events*

# useful scripts for numerical session

see `calchep_x.y.z/bin/` directory and `README` file!

- `subproc_cycle`                   `..bin/subproc_cycle 1000 100000`
- `sum_distr`                       `..bin/sum_distr distr_2 distr_3 > distr_sum`
- `show_distr`                       `..bin/show_distr distr_sum`
- `plot_view`                       `..bin/plot_view < tab_1.txt`
- `events2tab`
- `lhe2tab`
- `gen_events`
- `name_cycle`
- `pcm_cycle`
- `par_scan`
- `event_mixer`

## ex#6

produce LHE file  
and use `lhe2tab`  
to produce  
distributions from ex#5

# Example of running `subproc_cycle` for SM model

```
hepul:~/calchep/work_demo/work/results> ./bin/subproc_cycle 1000 40
```

1000 events are requested

Number of enents limited by flux 40 [1/fb]

```
#Subprocess 1 ( d, U -> W-, b, B ) Cross section = 5.2061E+00 pb (1.94E+00%) , 1000 events
#Subprocess 2 ( D, u -> W+, b, B ) Cross section = 8.1961E+00 pb (1.15E+00%) , 1000 events
#Subprocess 3 ( u, D -> W+, b, B ) Cross section = 8.2515E+00 pb (8.99E-01%) , 1000 events
#Subprocess 4 ( U, d -> W-, b, B ) Cross section = 5.2065E+00 pb (1.39E+00%) , 1000 events
#Subprocess 5 ( s, C -> W-, b, B ) Cross section = 8.9595E-01 pb (8.10E-01%) , 1000 events
#Subprocess 6 ( S, c -> W+, b, B ) Cross section = 8.8594E-01 pb (7.34E-01%) , 1000 events
#Subprocess 7 ( c, S -> W+, b, B ) Cross section = 9.0529E-01 pb (7.46E-01%) , 1000 events
#Subprocess 8 ( C, s -> W-, b, B ) Cross section = 9.0196E-01 pb (5.65E-01%) , 1000 events
```

3.045E+01 -total cross section[pb]

3690 -maximum number of events

1000 events are generated

Events in LHE format: events\_9\_16.lhe

**Total Cross Section 3.046E+01 [pb] (5.685E-01%)**

See details in directory 9\_16

# We need Events in LHE format to talk to MC generators!

- **bin/event\_mixer** *Luminosity[1/fb] nevents event\_dirs*

*mixes subprocesses and connects production and decay events*

```
bin/event_mixer 10 1000 pp_wbb w_2x
9.327E+00 -total cross section[pb]
3265 -maximum number of events
```

- **the output is event\_mixer.lhe file**

```
<LesHouchesEvents version="1.0">
<!--
File generated with CalcHEP-PYTHIA interface
-->
<header>
<slha>
</slha>
</header>
<init>
  2212  2212  7.00000006860E+03  7.00000006860E+03   -1      -1      -1      -1      3      1
  1.16593335502E+01  0.00000000000E+00  1.00000000000E+00
</init>
<event>
  7    1  1.0000000E+00  2.8420000E+02  -1.0000000E+00  -1.0000000E+00
    -3   -1    0    0    0  501  0.00000000000E+00  0.00000000000E+00  1.54424456520E+02
     4   -1    0    0  500    0  0.00000000000E+00  0.00000000000E+00  -1.30792414700E+02
    24    2    1    2    0    0  -9.99292465447E+01  -1.63668803915E+01  -6.48692987742E+01
     5    1    1    2  500    0  7.34149473360E+01  2.15593961832E+01  4.23390519202E+01
    -5    1    1    2    0  501  2.65142992097E+01  -5.19251579179E+00  4.61622886720E+01
   -11    1    3    3    0    0  -7.19345413730E+01  7.47572186340E-01  -8.03452022142E+01
    12    1    3    3    0    0  -2.79947051718E+01  -1.71144525779E+01  1.54759034400E+01
</event>
```

# Accessing all your results

- results are stored in “results” directory
- output files:
  - `n_calchep` numerical module
  - `prt_nn` protocol
  - `distr_nn_mm` summed distributions
  - `distr_nn` individual distribution
  - `events_nn.txt` events file
  - `list_prc.txt` list of processes
  - `qnumbers` definitions qnumbers – PYTHIA input with new prt
  - `session.dat` current session status – format is similar to  
`prt_nn one`
- for every new process the “results” directory is offered to be renamed or removed

# protocol prt\_nn

```
CalCHEP kinematics module
The session parameters:

#Subprocess 1 ( u, D -> W+, b, B )
#Session_number 1
#Initial_state inP1=7.000000E+03 inP2=7.000000E+03
Polarizations= { 0.000000E+00 0.000000E+00 }
StrFun1="PDT:cteq6m(proton)" 2212
StrFun2="PDT:cteq6m(proton)" 2212

#Physical_Parameters
    alfEMZ = 7.818060999999999E-03
    alfSMZ = 1.172000000000000E-01
    .....
#Cuts
*** Table ***
    Cuts
        Parameter |> Min bound <|> Max bound <|
T(b)          |20
T(B)          |20
    .....
#Regularization
*** Table ***
    Regularization
        Momentum |> Mass <|> Width <| Power |
45            |MZ           |wZ           |2
45            |Mh           |wh           |2
    .....
#END
=====
#IT   Cross section [pb]   Error %      nCall   chi**2
  1     2.0373E+00       3.30E+01     20000
  2     8.6164E+00       2.86E+01     20000
    .....
```

# scripts for numerical session

- **events2tab**

Parameters:

- 1- name of variable,
- 2- minimum limit,
- 3- maximum limit,
- 4- number of bins(<=300).

File with events must be passed to input.

`..../bin/events2tab "T(b)" 1 100 200 < events_1.txt >tab.txt`

`..../bin/tab_view < tab.txt`

- **name\_cycle**

1: Name of parameter

2: Initial value

3: Step

4: Number of steps

`..../bin/name_cycle Mh 100 10 11`

scripts are used by **calchep\_batch** interface – see below

# the most general scan with par\_scan

- Usage:

```
$CALCHEP/bin/par_scan < data_file
```

- Data file structure:

```
# Comments following the '#' symbol
par_name_1  par_name_2 ...  par_name_N & fun_name_1  fun_name_2 ...
    val11      val12      ....   val1N
    val21      val12      ....   val1N
    .....  
.....
```

- where par\_name\_i present free parameters of the models. Among them one also can write momenta of incoming particles as momentum1 and momentum2.
- fun\_name\_i is the name of constrained parameter which will be presented in output file
- Output file has the same structure as input plus calculated numerical values for constrained parameters, and an additional column for evaluated cross section with statistical error
- If you are not interested in the prt\_# files you can clean it using  

```
$CALCHEP/bin/par_scan clean < data_file
```

# CalcHEP batch interface

# CalcHEP batch interface: all results in one shot

```
Model:           SM(+hgg)
Model changed: False
Gauge:          Feynman
Process:        p,p->W,b,B
Decay:          W->le,n
#####
Composite:    p=u,U,d,D,s,S,c,C,b,B,G
Composite:    W=W+,W-
Composite:    le=e,E,m,M
Composite:    n=ne,Ne,nm,Nm
Composite:    jet=u,U,d,D,s,S,c,C,b,B,G
#####
pdf1:          PDT:cteq6l1(proton)
pdf2:          PDT:cteq6l1(proton)
p1:            6500
p2:            6500
#####
Run parameter: Mh
Run begin:     120
Run step size: 5
Run n steps:   3
#####
alpha Q :      M45
#####
Cut parameter: M(b,B)
Cut invert:    False
Cut min:       100
Cut max:
```

```
Kinematics : 12 -> 3, 45
Kinematics : 45 -> 4 , 5
Regularization momentum:1: 45
Regularization mass:1: Mh
Regularization width:1: wh
Regularization power:1: 2
#####
Dist parameter: M(b,B)
Dist min:       100
Dist max:       200
Dist n bins:   100
Dist title:    p,p->W,b,B
Dist x-title:  M(b,B) (GeV)
#####
Dist parameter: M(W,jet)
Dist min:       >> 100
Dist max:       >> 200
Dist n bins:   >> 100
Dist title:    p,p->W,b,B
Dist x-title:  M(W,jet) (GeV)
#####
Number of events (per run step): 10000
Filename:      pp_Wbb
#####
Parallelization method: local
Max number of nodes: 8
Max number of processes per node: 1
#####
nSess_1:       5
nCalls_1:      100000
nSess_2:       5
nCalls_2:      100000
```

# CalcHEP batch interface: running and monitoring

\$CALCHEP= path to calchep installation

```
cd $CALCHEP/work  
cp ..../utile/batch_file .  
./calchep_batch batch_file
```

CALCHEP= /home/belyaev/calchep/calchep\_x.y.z

calchep\_batch version x.yz

Processing batch:

Progress information can be found in the html directory.

Simply open the following link in your browser:

file:///.../calchep\_x.y.z/work/html/index.html

You can also view textual progress reports in

.../calchep\_x.y.z/work/html/ and the other .txt files in the html directory.

Events will be stored in the batch\_results directory.

# CalcHEP batch results

- results are located in **batch\_results** folder
- **\*.lhe.gz** : LHE event files
- **\*.jpg** : figures
- **\*.distr** : files with distributions which can be used  
to re-produce plots using **\$CALCHEP/bin/show\_distr**
- **\*.tgz** : zipped html folder with all numerical details, .txt and .html files of the  
batch run

# CalcHEP batch interface: running and monitoring

The screenshot shows a web browser window titled "CalcHEP Batch Details - Google Chrome". The address bar displays the URL "file:///home/belyaev/calchep/calchep\_3.7/work/html/index.html". The main content area is titled "CalcHEP Batch Details" and contains the following information:

**SM(+hgg)**

**Done!**

	Finished Time(hr)		
Symbolic	12/12	0.00	
$\sigma$	3/3	0.03	
Events	3/3	0.01	

**Left sidebar (links):**

- Home
- Symbolic Results
- Numerical Results
- Events Library
- Process Library
- Help

**Text at bottom left:**

Thank you for using  
CalcHEP!  
Please cite  
arXiv:1207.6082

# CalcHEP batch interface: running and monitoring

The screenshot shows a web browser window titled "CalcHEP Symbolic Details - Google Chrome". The address bar displays the URL "file:///home/belyaev/calchep/calchep\_3.7/work/html/symbolic.html". The main content area is titled "Symbolic Sessions" and features a section titled "SM(+hgg)". On the left side, there is a sidebar with links: Home, Symbolic Results, Numerical Results, Events Library, Process Library, and Help. Below these links, there is a message: "Thank you for using CalcHEP! Please cite arXiv:1207.6082". The right side of the page contains a table with two columns: "Processes" and "Removes Lib PID Time(hr)". The "Processes" column lists various particle interactions, and the "Removes Lib PID Time(hr)" column contains checkmarks indicating the availability of libraries and performance metrics.

Processes	Removes Lib PID Time(hr)
u,D->W+,b,B	✓
U,d->W-,b,B	✓
d,U->W-,b,B	✓
D,u->W+,b,B	✓
s,C->W-,b,B	✓
S,c->W+,b,B	✓
c,S->W+,b,B	✓
C,s->W-,b,B	✓
W+->ne,E	✓
W+->nm,M	✓
W-->Ne,e	✓
W-->Nm,m	✓
Widths	✓

# CalcHEP batch interface: running and monitoring

CalcHEP Numerical Details - Google Chrome

CalcHEP Numerical Details

file:///home/belyaev/calchep/calchep\_3.7/work/html/numerical.html

## Numerical Sessions

### SM(+hgg)

**Done!**

Scans	$\sigma$ (fb)	Running	Finished	Time (hr)	N events
Mh=120	1179	0/13	13/13	0.01	1000
Mh=125	1163	0/13	13/13	0.01	1000
Mh=130	1145	0/13	13/13	0.01	1000
				0.03	

Home  
Symbolic Results  
Numerical Results  
Events Library  
Process Library  
Help

Thank you for using  
[CalcHEP!](#)  
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[arXiv:1207.6082](#)

cs (fb)

Mh	cs (fb)
120	1179
122	1173
124	1167
126	1161
128	1155
130	1145

# CalcHEP batch interface: running and monitoring

Home  
Symbolic Results  
Numerical Results  
Events Library  
Process Library  
Help

Thank you for using  
CalcHEP!  
Please cite  
arXiv:1207.6082

## Numerical Sessions

### SM(+hgg)

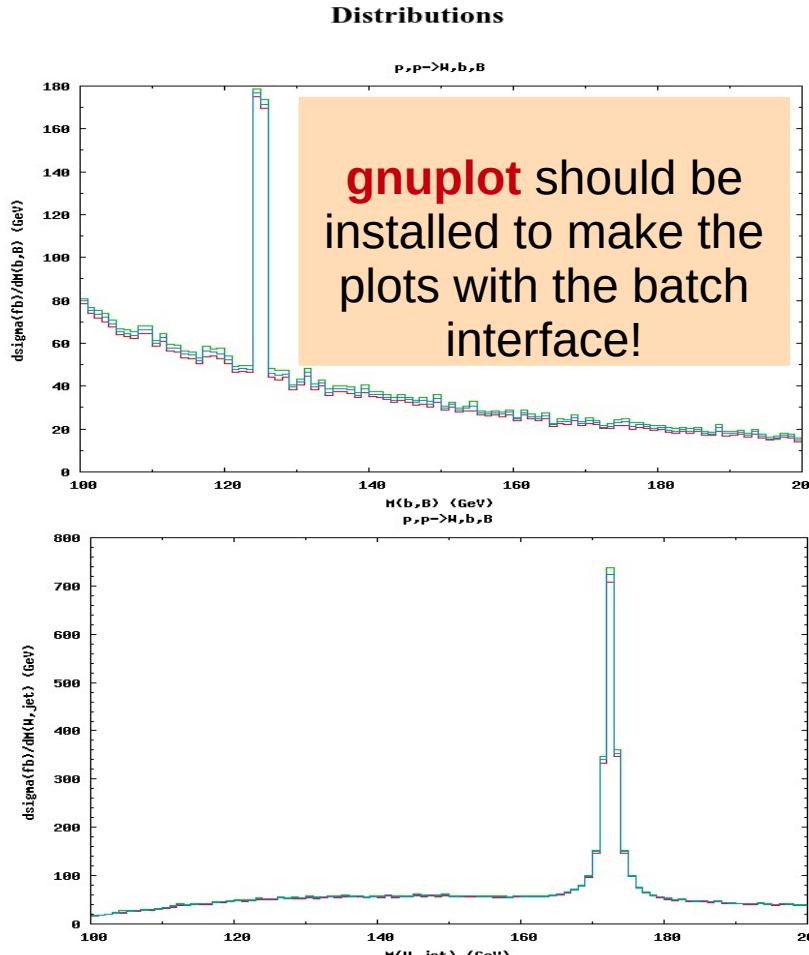
Done!

Processes	$\sigma$ (fb)	$\Delta\sigma$ (%)	PID	Time (hr)	N events	Details
u,D->W+,b,B	1552.8	0.8	28872	0.00	383/382	prt_1 session.dat
U,d->W-,b,B	829.4	0.52	28878	0.00	220/219	prt_1 session.dat
d,U->W-,b,B	837.46	1.1	28885	0.00	221/220	prt_1 session.dat
D,u->W+,b,B	1558.3	0.51	29100	0.00	384/383	prt_1 session.dat
s,C->W-,b,B	109.55	0.54	29104	0.00	42/41	prt_1 session.dat
S,c->W+,b,B	108.79	0.44	29109	0.00	41/40	prt_1 session.dat
c,S->W+,b,B	108.88	0.41	29116	0.00	41/40	prt_1 session.dat
C,s->W-,b,B	109.6	0.43	29123	0.00	42/41	prt_1 session.dat
Total	5214.8	0.34				

Decays	$\Gamma$ (GeV)	$\Delta\Gamma$ (%)	PID	Time (hr)	N events	Details
W+->ne,E	0.23293	0	29129	0.00	5099/5100	prt_1 session.dat
W+->nm,M	0.23293	0	29135	0.00	5099/5100	prt_1 session.dat
W-->Ne,e	0.23293	0	29142	0.00	5099/5100	prt_1 session.dat
W-->Nm,m	0.23293	0	29324	0.00	5099/5100	prt_1 session.dat

Widths	PID	Time (hr)	Details
Widths		29328	session.dat
Total	1163	0.01	1000/1000

**ex#7:** using calchep\_batch evaluate complete cross section for  $pp \rightarrow Wbb$  process with the same cuts as for ex#5



# CalcHEP batch interface: some additional features/tricks

- see <https://answers.launchpad.net/calchep> for many “tricky” questions/answers
- scanning over the collider energy

**Run parameter:** rtS

**Run begin:** 7

**Run step size:** 1

**Run n steps:** 2

**p1: 1000\*rtS/2**

**p2: 1000\*rtS/2**

rtS here is some “fake” parameter

- you can use “fake” parameter only if you define it as a loop parameter
  - It can be used in the cut statement (assigning cut to the symbol)
  - It can be assigned to the parameter model – this way you can handle a complicated scan

# CalcHEP batch interface: scanning with ‘fake’ parameters

## *an example:*

*Calculating SM background cross section for process  $pp \rightarrow e^+e^-$  across invariant mass range of 500GeV-3TeV, with cut of +/-400GeV around invariant mass.*

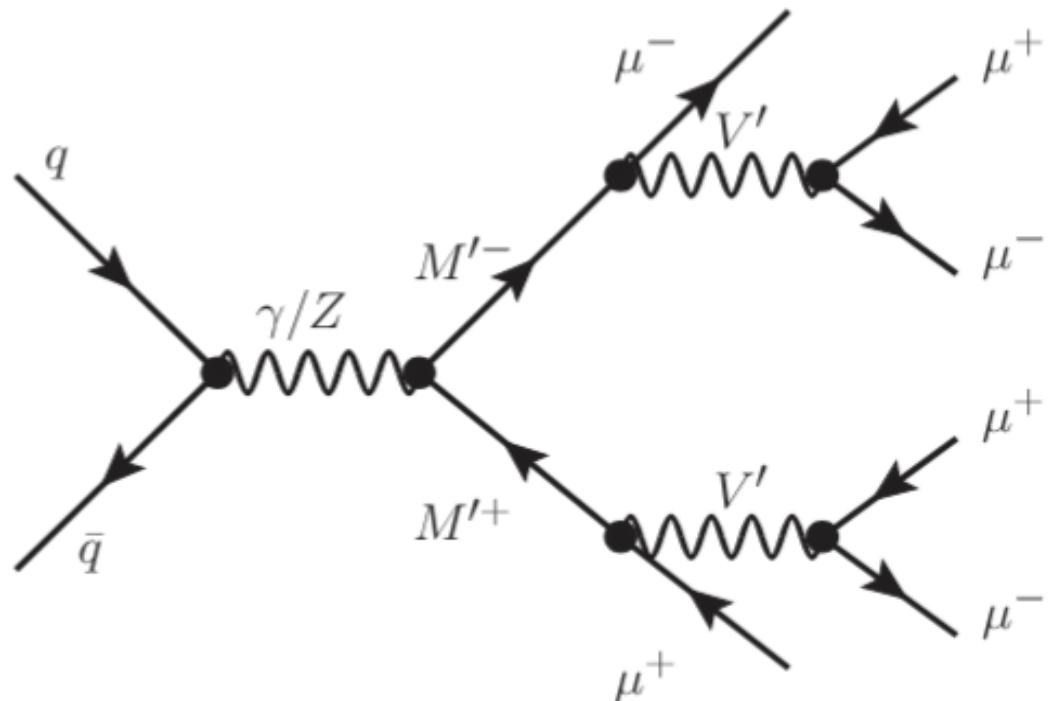
```

#####
# Run Info                                # Cut Info
#   #
# Masses and Energies are in GeV      # Must be in terms of the (production mode)
# More than one run can be specified # final state particles.
# at the same time.                  # :n: specifies which process.
#                                         # : means to apply to all processes.
#####
Run parameter: MASS
Run begin:    500
Run step size: 500
Run n steps:   6
Cut parameter: M(e,E)
Cut invert:    False
Cut min:       MASS-400
Cut max:       MASS+400

```

# Exploring FPVDM model with CalcHEP

$$\begin{aligned}\mathcal{L}_{FPVDM} = & -\frac{1}{4}(V_{D\mu\nu}^i)^2 + \bar{\Psi}iD\Psi + |D_\mu\Phi_D|^2 - V(\Phi_H, \Phi_D) \\ & - (y'_{\alpha\beta}\bar{\Psi}_L^{i\alpha}\Phi_D f_R^{\text{SM}\beta} + h.c) - M_\Psi^{ij}\bar{\Psi}^i\Psi^j\end{aligned}$$



model predicts genuine multi-fermion final states

# FPVDM model with CalcHEP: calculation of the 6 tops final state rate

Model: FPVDM\_with\_top  
Gauge: Feynman  
Process: p, p->Tp, tp  
Decay: Tp->V0, T  
Decay: tp->V0, t  
Decay: V0->t, T  
  
Composite: p=u, U, d, D, s, S, c, C, b, B, G  
  
pdf1: PDT:cteq6l1(proton)  
pdf2: PDT:cteq6l1(proton)  
  
p1: 6800  
p2: 6800  
  
Parameter: MV=400  
Parameter: Mh2=500  
Parameter: MtD=750  
Parameter: gd=0.1

Run parameter: Mtp  
Run begin: 800  
Run step size: 100  
Run n steps: 10  
  
alpha Q : Mtp  
  
Number of events (per run step): 1000  
  
Filename: FPVDM\_6T  
  
Parallelization method: local  
  
Max number of nodes: 8  
Max number of processes per node: 1

# Exploring FPVDM model with CalcHEP

## Numerical Sessions

Home

Symbolic Results

Numerical Results

Events Library

Process Library

Help

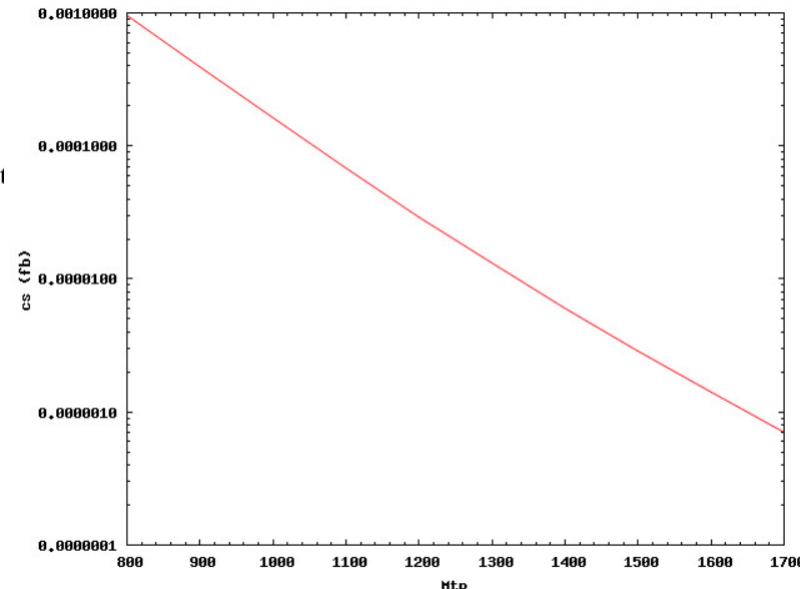
Thank you for using  
CalcHEP!

Please cite  
arXiv:1207.6082

### FPVDM\_with\_top

Done!

Scans	$\sigma$ (fb)	Running	Finished	Time (hr)	N event
Mtp=800	0.0009519	0/15	15/15	0.01	1000
Mtp=900	0.0003945	0/15	15/15	0.02	1000
Mtp=1000	0.0001612	0/15	15/15	0.02	1000
Mtp=1100	6.747 x10 <sup>-5</sup>	0/15	15/15	0.03	1000
Mtp=1200	2.913 x10 <sup>-5</sup>	0/15	15/15	0.04	1000
Mtp=1300	1.301 x10 <sup>-5</sup>	0/15	15/15	0.05	1000
Mtp=1400	6.005 x10 <sup>-6</sup>	0/15	15/15	0.07	1000
Mtp=1500	2.858 x10 <sup>-6</sup>	0/15	15/15	0.11	1000
Mtp=1600	1.398 x10 <sup>-6</sup>	0/15	15/15	0.01	1000
Mtp=1700	7.009 x10 <sup>-7</sup>	0/15	15/15	0.03	1000
					0.39



# Using c-modules without gui and batch (scan2.c)

```
//set model dir here
char mdldir[] = "/home/belyaev/Downloads/DarkTools/FPVDM";

// Set model number and number of points to collect, mdlNr is your model number
int mdlNr=1;
. . .

//a model to switch between to reset values when reloading
setModel(mdldir , mdlNr );
. . .

***** assign variable values *****/
/* the string is the calchep var name */
err=assignValW("MtD", MtD);
. . .

// width and branchings of a particle
wTP= pWidth("tp",&branchings_tp);
. . .

BrTP__Vp_t= findBr(branchings_tp,"V0,t");
BrTP__HD_t= findBr(branchings_tp,"HD,t");
```