CalcHEP: the status and the prospects

Alexander Belyaev

Southampton University & Rutherford Appleton LAB

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OUTLINE

- **Introduction to CalcHEP**
  - ***models and symbolic session***
  - ***numerical session and kinematical distributions***
  - ***event generation***

- **Automatized Introduction of new models with LanHEP**

- **CalcHEP batch Interface and link to MC generators**

- **Application of CalcHEP for SM and BSM at LHC/LC**

CalcHEP

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

- **Author(s)**
  - *Alexander Pukhov*

    (AB and Neil Christensen have joined the project in 2009)
    http://theory.npi.msu.su/~pukhov/calchep.html
- **Idea**
  - ***The effective study of HEP phenomenology passing at high level of automation from your favorite model to physical observables such as decay width, branching ratios, cross sections kinematic distributions, parton-level events, ...***
- **Analogous packages** **(matrix element generators)**

  http://www.ippp.dur.ac.uk/montecarlo/BSM/

  - ***CompHEP (Boos et al)***
  - ***MadGraph/MadEvent (Maltoni, Stelzer)***
  - ***Grace/Helas (Fujimoto et al)***
  - ***FeynArts/FeynCalc/FormCalc (Hahn et al)***
  - ***WHIZARD,O'mega (Moretti, Ohl, Reuter)***
  - ***Sherpa (Krauss et al)***

Features/Limitations of CalcHEP

- **Can evaluate any decay and scattering processes within any (user defined) model!**

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- **Squared Matrix Element calculation**
  - *no spin information for outgoing particles – spin averaged amplitude*

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:*
    - $2 \to 6$ ($1 \to 7$) set the essential time/memory limit
    - number of diagrams ~ 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 in CalcHEP was to enable one to go directly from the Lagrangian to the cross sections and distributions effectively, with the high level of automation. The package can be compiled on any Unix platform.

General information

- Main facilities , • Old Versions , • Acknowledgments • News&Bugs

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Manual

- calchep_man_2.3.5(ps.gz) (137 pages, 445KB, March 18, 2005)
- HEP computer tools (Lecture by Alexander Belyaev)

See also: Dan Green, High Pt physics at hadron colliders (Cambrige University Press)

Codes download.

- Licence • Installation • References&Contributions

CalcHEP code for UNIX: • version 2.5.4 (July 10 , 2009) • version 2.5.5 (version for testing)

Models:

- MSSM(04.08.2006) • NMSSM • CPVMSSM(04.08.2006) • LeptoQuarks

Universal Extra Dimension Models: • 5DSM • 6DSM SUSY models for CompHEP • By A.Semenov

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Relative packages on Web:

Packages for model generation: • LanHEP • FeynRules

RGE and spectrum calculation: • SuSpect • Isajet • SoftSUSY • SPheno • CPsuperH • NMHDecay

Particle widths in MSSM: • SDECAY • HDECAY

Parton showers: • PYTHIA

Email contact: **calchep@googlegroups.com**

Quick start:
practical notes on the installation

- **Download code, read manual and compile**
  http://theory.npi.msu.su/~pukhov/calchep.html
  - **tar -zxvf calchep_2.*x.x*.tgz**
  - **cd calchep_2.*x.x***
  - **make**

  the currrent version is 2.*x.x* = 2.*5.4*
- **Create work directory**
  - **From calchep_2.*x.x* directory:**

  ./mkUsrDir *../calc_work*
- **Supported operating system**
  - **Linux, IRIX, IRIX64, HP-UX, OSF1, SunOS, Darwin, CYGWIN**

  (see *getFlags* file)

Starting CalcHEP

- **cd ../calc_work**

- **Files:**

bin -> .... /calchep_2.x.x/bin
calchep
calchep_batch
calchep.ini
models/
results/
tmp/

- **Start:**

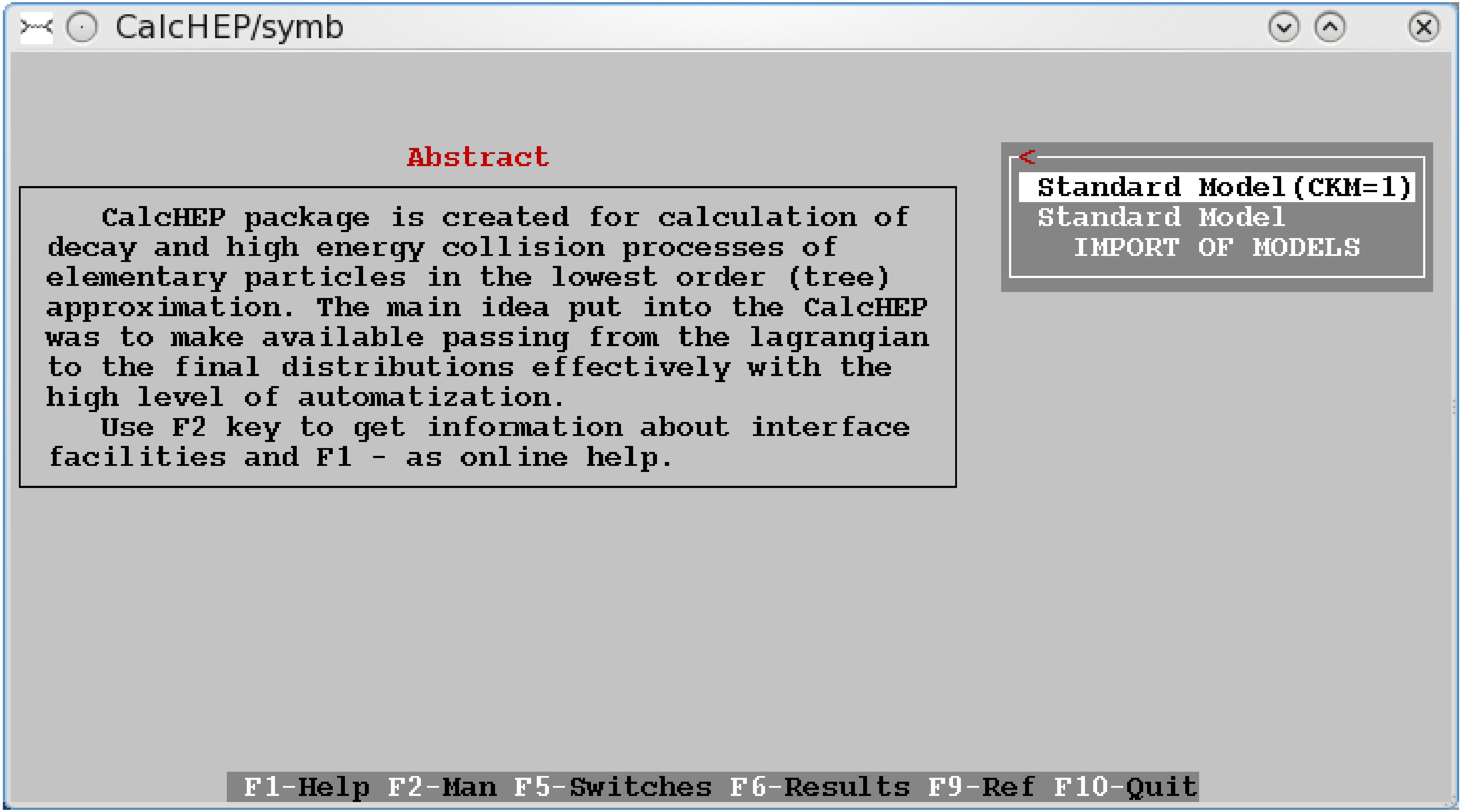
./calchep

Starting CalcHEP

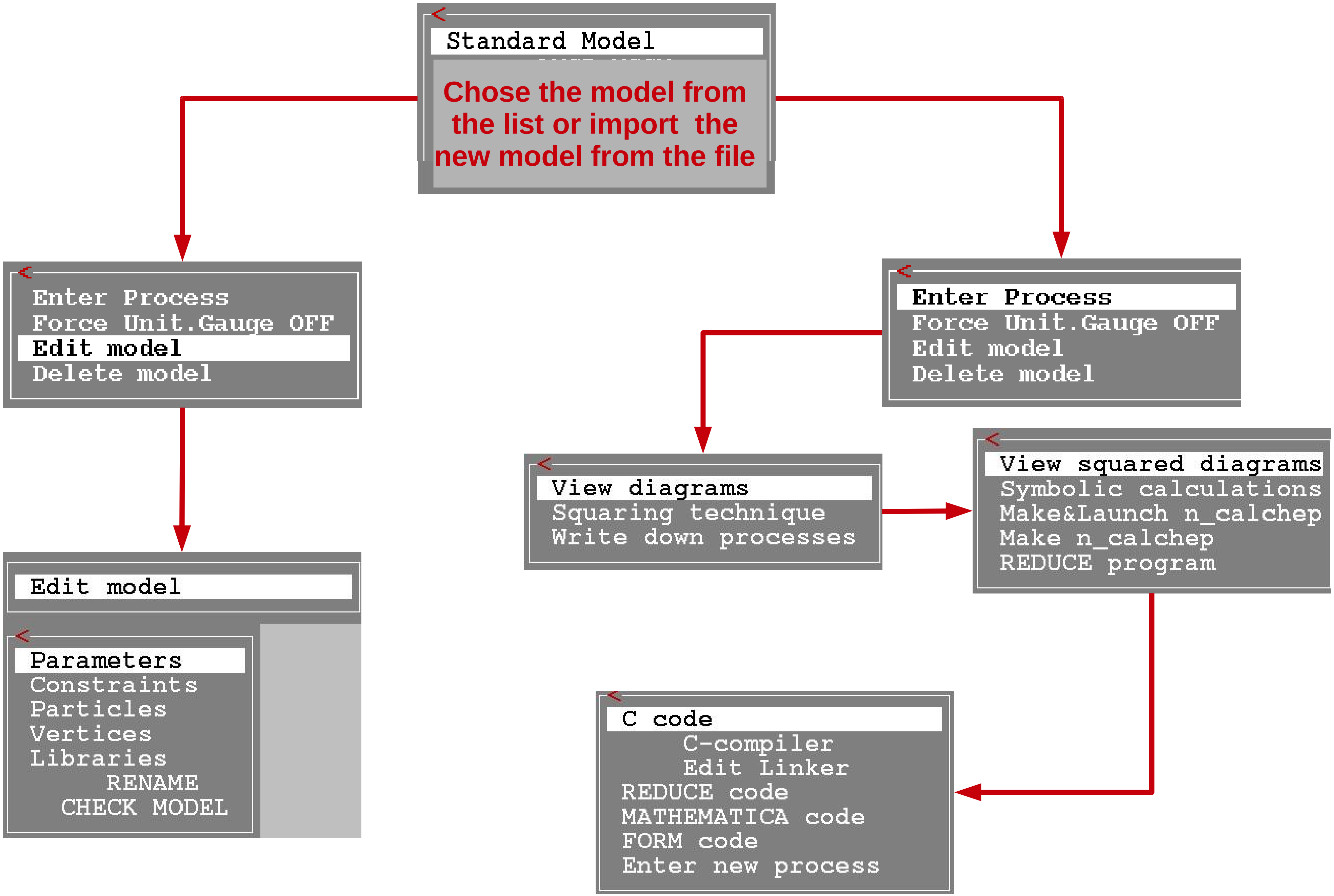
CalcHEP/symb

```
    CalcHEP - a package for Calculation in High Energy Physics
            Version 2.5.4: Last correction July 12,2009


  Main author: Alexander Pukhov(Skobeltsyn Institute of Nuclear Physics,Moscow)
  Batch mode : Neil Chistensen (Michigan State University)
  PYTHIA interface and testing:Alexander Belyaev(University of Southampton)

  For contacts:                email: <pukhov@lapp.in2p3.fr>
                               http://theory.sinp.msu.ru/~pukhov/calchep.html


  The BSMs for CalcHEP were developed in collaboration with:
        G.Belanger,A.Belyaev,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 and Contributions

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

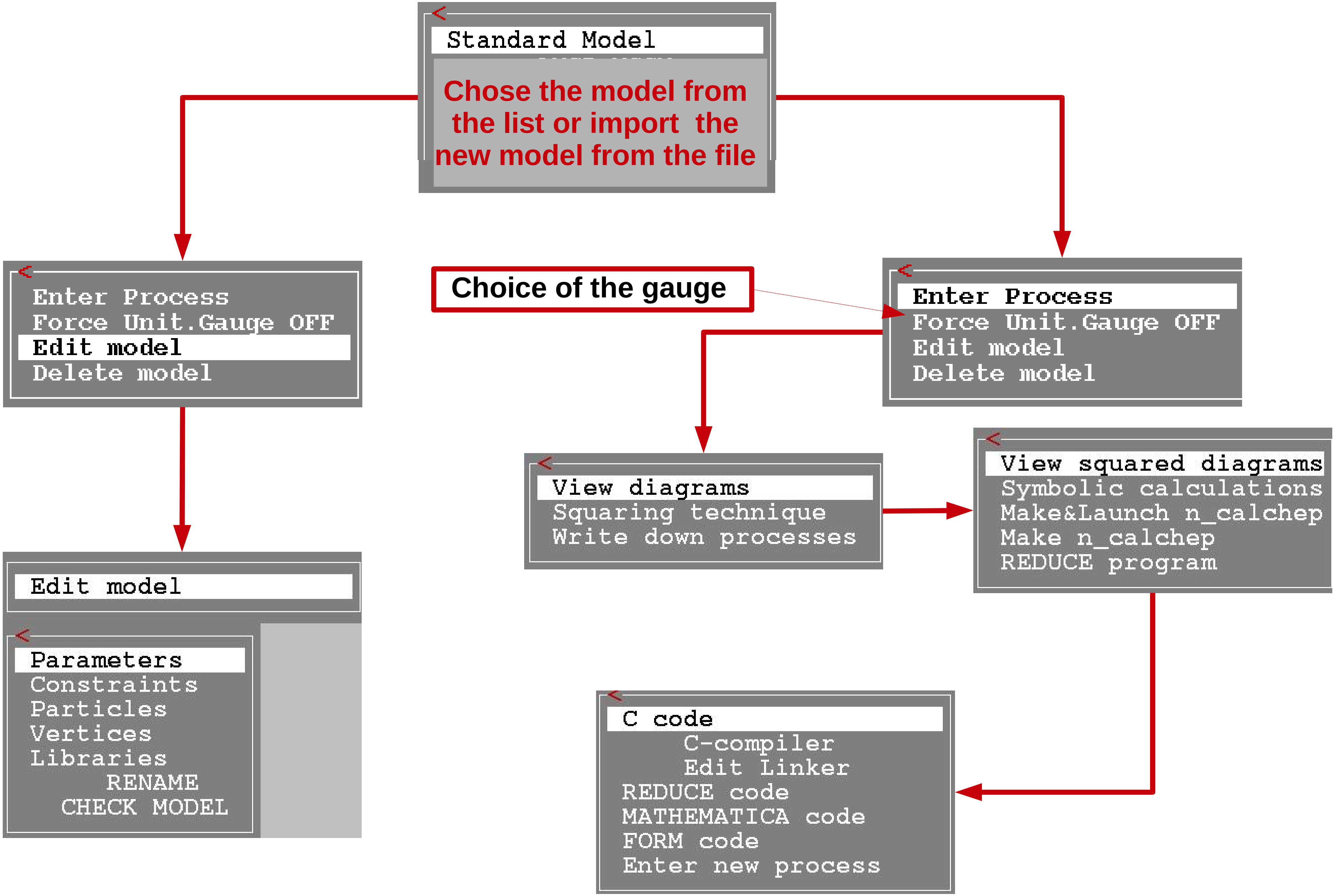
Starting CalcHEP



CalcHEP menu structure: symbolic part

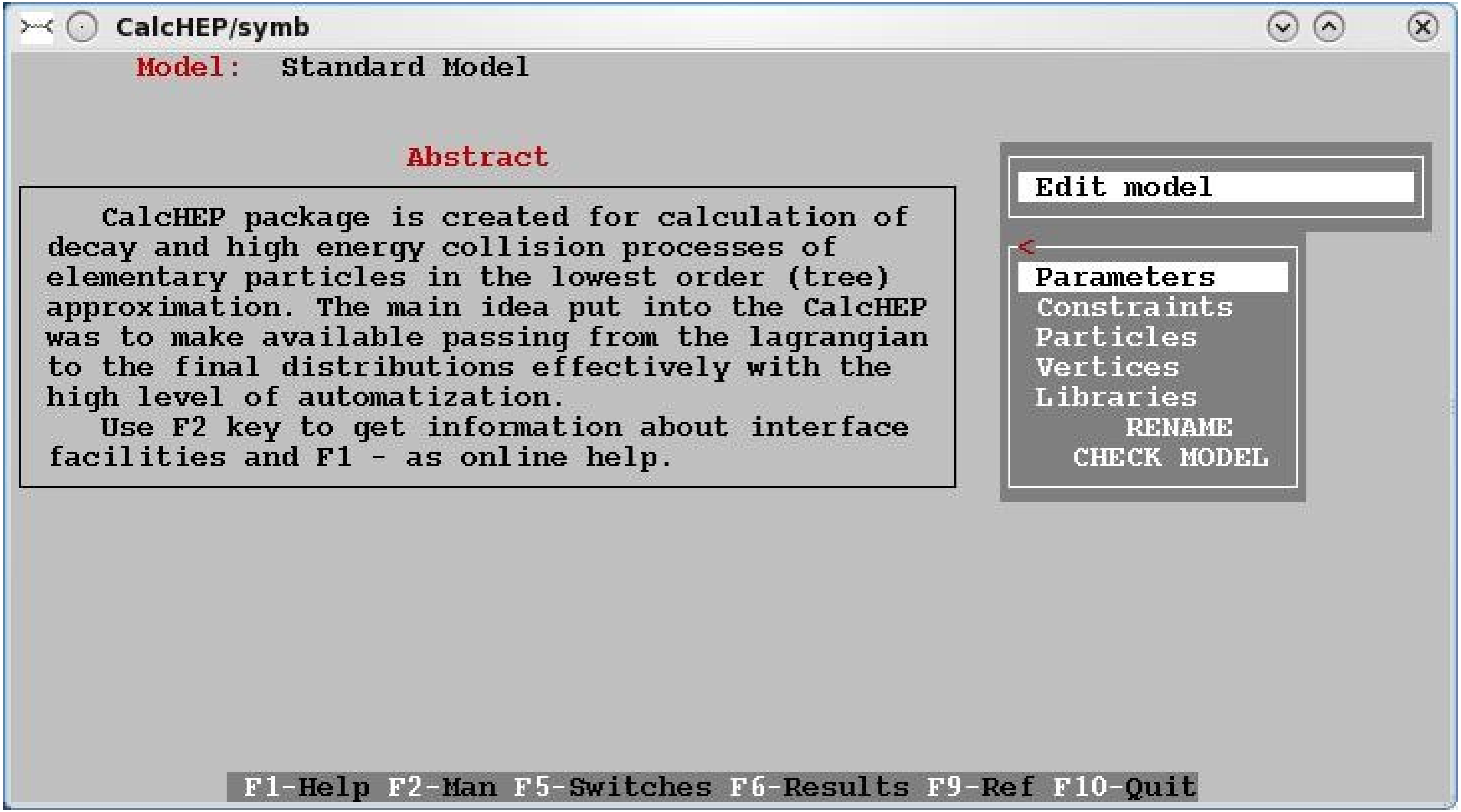


CalcHEP menu structure: symbolic part



Model Structure

Parameters **Constraints**
Particles **Vertices**



Particles: prtcl*xx*.mdl (spins 0,1/2,1,3/2,2)

CalcHEP/symb

Particles

Clr-Del-Size-Read-ErrMes

Full name	A	A+	number	2*spin	mass	width	color	aux	>LaTex(A)<	>LaTeX(A+) <
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^-	\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^-	\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	Ms	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: prtcl*xx*.mdl

CalcHEP/symb

Particles

Clr-Del-Size-Read-ErrMes

Full name	A	A+	number	2*spin	mass	width	color	aux	>LaTex(A)<	>LaTeX(A+)
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^-	\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^-	\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	Ms	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`

F1-F2-Xgoto-Ygoto-Find-Write

Independent parameters: vars*xx*.mdl

CalcHEP/symb

Parameters 1

Clr Del Size Read ErrMes

Name	Value	> Comment
alfEMZ	0.0078180608	MS-BAR electromagnetic alpha(MZ)
alfSMZ	0.1172	Srtong alpha(MZ) for running mass calculation
Q	100	scale for running mass calculation
GG	1.238	Running Strong coupling. The given value doesn't matter.
SW	0.481	MS-BAR sine of the electroweak mixing angle
s12	0.221	Parameter of C-K-M matrix (PDG96)
s23	0.041	Parameter of C-K-M matrix (PDG96)
s13	0.0035	Parameter of C-K-M matrix (PDG96)
Mm	0.1057	muon mass
Ml	1.777	tau-lepton mass
McMc	1.2	Mc(Mc)
Ms	0	s-quark mass (pole mass, PDG96)
MbMb	4.25	Mb(Mb)
Mtp	175	t-quark pole mass
MZ	91.187	Z-boson mass
Mh	120	higgs mass
wt	1.59	t-quark width (tree level 1->2x)
wZ	2.49444	Z-boson width (tree level 1->2x)
wW	2.08895	W-boson width (tree level 1->2x)

F1 F2 Xgoto Ygoto Find Write

Dependent parameters(constraints): func*xx*.mdl

```
CalcHEP/symb
                              Constraints
Clr-Del-Size-Read-ErrMes
 Name    |> Expression
EE       |sqrt(16*atan(1.)*alfEMZ)      % electromagnetic constant
CW       |sqrt(1-SW^ 2)                 % cos of the Weinberg angle
MW       |MZ*CW                         % W-boson  mass
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
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
qcdOk    |initQCD(alfSMZ,McMc,MbMb,Mtp)
 Mb      |MbEff(Q)*one(qcdOk)
 Mt      |MtEff(Q)*one(qcdOk)
 Mc      |McEff(Q)*one(qcdOk)

F1-F2-Xgoto-Ygoto-Find-Write
```

Dependent parameters(constraints): func*xx*.mdl

- **MSSM case**

```
CalcHEP/symb
                         Constraints
Clr Del Size Read ErrMes
  Name  |> Expression
 smOk   |saveSM(MbMb,Mtp,SW,alfSMZ,alfEMZ,MZ,Ml)*saveSLHA(1)
mssmOk  |suspectEwsbMSSMc(smOk,tb,MG1,MG2,MG3,Am,Al,At,Ab,MH3,mu,Ml2,Ml3,Mr2,Mr3,Mq2,Mq
%mssmOk|isajetEwsbMSSMc(smOk,tb,MG1,MG2,MG3,Am,Al,At,Ab,MH3,mu,Ml2,Ml3,Mr2,Mr3,Mq2,Mq3
%mssmOk|softSusyEwsbMSSMc(smOk,tb,MG1,MG2,MG3,Am,Al,At,Ab,MH3,mu,Ml2,Ml3,Mr2,Mr3,Mq2,M
%mssmOk|sphenoEwsbMSSMc(smOk,tb,MG1,MG2,MG3,Am,Al,At,Ab,MH3,mu,Ml2,Ml3,Mr2,Mr3,Mq2,Mq3
*drho   |deltarho(mssmOk)
*gmuon  |gmuon(mssmOk)
*bsgnlo|bsgnlo(mssmOk)
*bsmumu|bsmumu(mssmOk)
*LEPlim|masslimits(mssmOk)
 Mb     |MbEff(Q)*one(smOk)
 Mt     |MtEff(Q)*one(smOk)
*SC     |sqrt(alphaQCD(Q)/12.566371)*one(smOk)
 Mh     |Mh(mssmOk)
 MHH    |MHH(mssmOk)
 MHc    |MHc(mssmOk)
 alpha  |alpha(mssmOk)
 MNE1   |MNE1(mssmOk)
 MNE2   |MNE2(mssmOk)
 MNE3   |MNE3(mssmOk)
 MNE4   |MNE4(mssmOk)
 MC1    |MC1(mssmOk)
 MC2    |MC2(mssmOk)
 MSG    |MSG(mssmOk)
 MSne   |MSne(mssmOk)
```

Feynman rules: lgrng*xx*.mdl

CalcHEP/symb

Vertices

Clr-Del-Size-Read-ErrMes

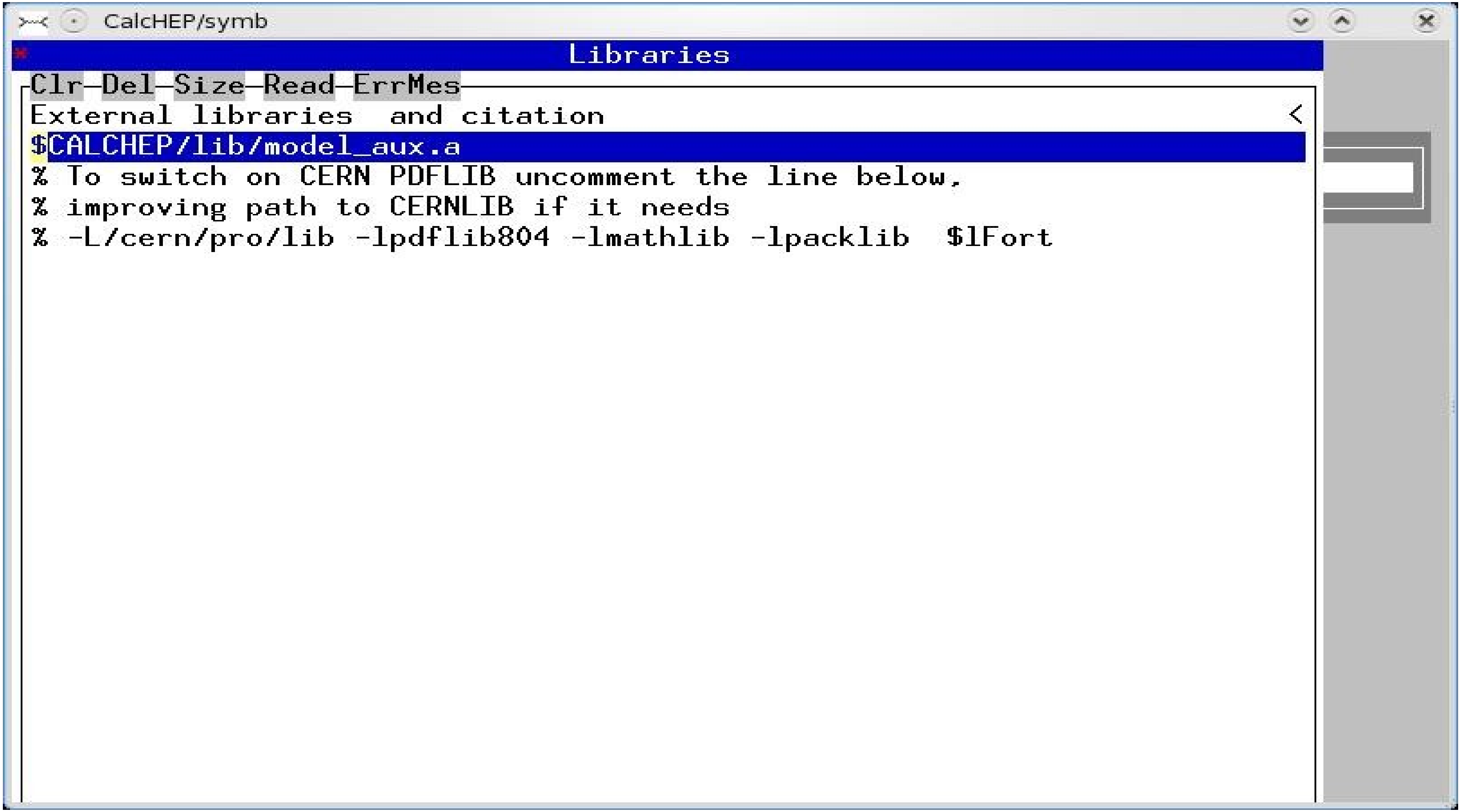
A1	A2	A3	A4	> Factor <|	> Lorentz part
h	W+	W-		EE*MW/SW	m2.m3
h	Z	Z		EE/(SW*CW^ 2)*MW	m2.m3
h	h	h		-(3/2)*EE*Mh^ 2/(MW*SW)	1
h	h	h	h	(-3/4)*(EE*Mh/(MW*SW))^ 2	1
h	h	Z	Z	(1/2)*(EE/(SW*CW))^ 2	m3.m4
h	h	W+	W-	(1/2)*(EE/SW)^ 2	m3.m4
M	m	h		-EE*Mm/(2*MW*SW)	1
L	l	h		-EE*Ml /(2*MW*SW)	1
C	c	h		-EE*Mc/(2*MW*SW)	1
S	s	h		-EE*Ms/(2*MW*SW)	1
B	b	h		-EE*Mb/(2*MW*SW)	1
T	t	h		-EE*Mt /(2*MW*SW)	1
E	e	A		-EE	G(m3)
M	m	A		-EE	G(m3)
L	l	A		-EE	G(m3)
Ne	e	W+		EE/(2*Sqrt2*SW)	G(m3)*(1-G5)
Nm	m	W+		EE/(2*Sqrt2*SW)	G(m3)*(1-G5)
Nl	l	W+		EE/(2*Sqrt2*SW)	G(m3)*(1-G5)
E	ne	W-		EE/(2*Sqrt2*SW)	G(m3)*(1-G5)
M	nm	W-		EE/(2*Sqrt2*SW)	G(m3)*(1-G5)
L	nl	W-		EE/(2*Sqrt2*SW)	G(m3)*(1-G5)

F1-F2-Xgoto-Ygoto-Find-Write

Models created/available for CalcHEP

- **SM + extensions**
  - SM
  - B-L symmetric Z' with heavy Majorana neutrinos
  - SM + Z'
  - general 2 Higgs doublet model
  - 4th generation
  - Excited fermions
  - Model with contact interactions
  - Standard Model + anomalous gauge boson couplings
  - Model of strongly int EW sector
    (5 & 6 dim operators involving Sigma field)
- **SUSY**
  - constraint MSSM
  - general MSSM, with 124 free parameters
  - NMSSM
  - RPVMSSM
  - left-right symmetric MSSM
  - MSSM with CP violation
  - E6MSSM
- **Extra dimensions**
  - 5D UED with 2KK layers
  - 6D UED with 2KK layers
  - ADD = ADD
  - RS = Randall Sundrum
- **Leptoquarks**
  - Complete LQ model
    SU(3)xSU(1)xU(1) vector&scalar
- **Technicolor & Higgsless**
  - Minimal walking technicolor
  - TC with DM
  - 3-site model
  - Hidden Local symmetry model
  - 4SM = general 4-site model
- **Little Higgs**
  - Littlest higss model with T-parity
  - LHT + T-parity violation
- **Here goes your request!**

External libraries: extlib*xx*.mdl



Principle KEYS for CalcHEP's GUI

Enter menu selection (forward)

Exit menu selection (back)

Help! (details on the menu choice)

Details of symbolic session

- *The syntax for the input is:* **P1[,P2] -> P3,P4, [,...,[N*x]]**
  ‘P1’,..., ‘P4’ *are particle names,* **‘N’** *is the number of particles*
- *Polarization for massless particles:* **P1%, P2% -> P3,P4, ...**

- *hadron/composite particle scattering*

  'p,p->W+,b,B'

  unknown particle are assumed to be composite:

  'p' *consists of* **u,U,d,D,s,S,c,C,b,B,G**
- *wild cards/names for outgoing particles* **'H -> 2*x'**
- *intermediate particles can be non-trivially excluded*

  'W+ > 2, A>1, Z>3'
- *particle width can be calculated 'on-fly'*

  '!wtop' *, i.e.* **'!'** *symbol should be used in the prt table*
- *particles spin*

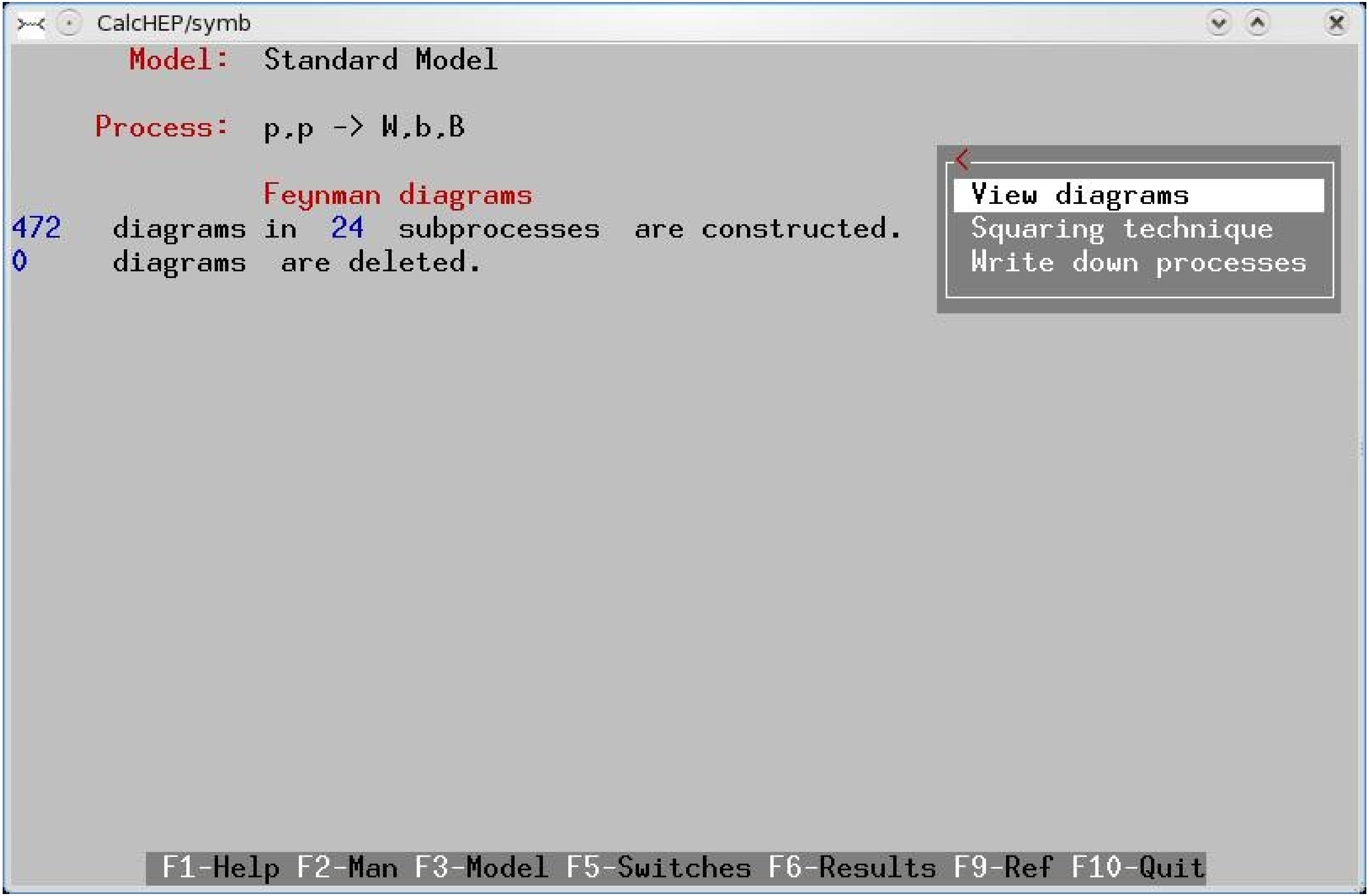
  0, 1/2, 1, 3/2, 2

  0, 1 , 2, 3 , 4

symbolic session: entering a process

```
CalcHEP/symb
      Model:  Standard Model

              List of particles (antiparticles)

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

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

symbolic session: constructing diagrams



symbolic session: list of sub-processes

CalcHEP/symb

Model: Standard Model

Process: p,p -> W,b,B

Feynman diagrams

472 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.

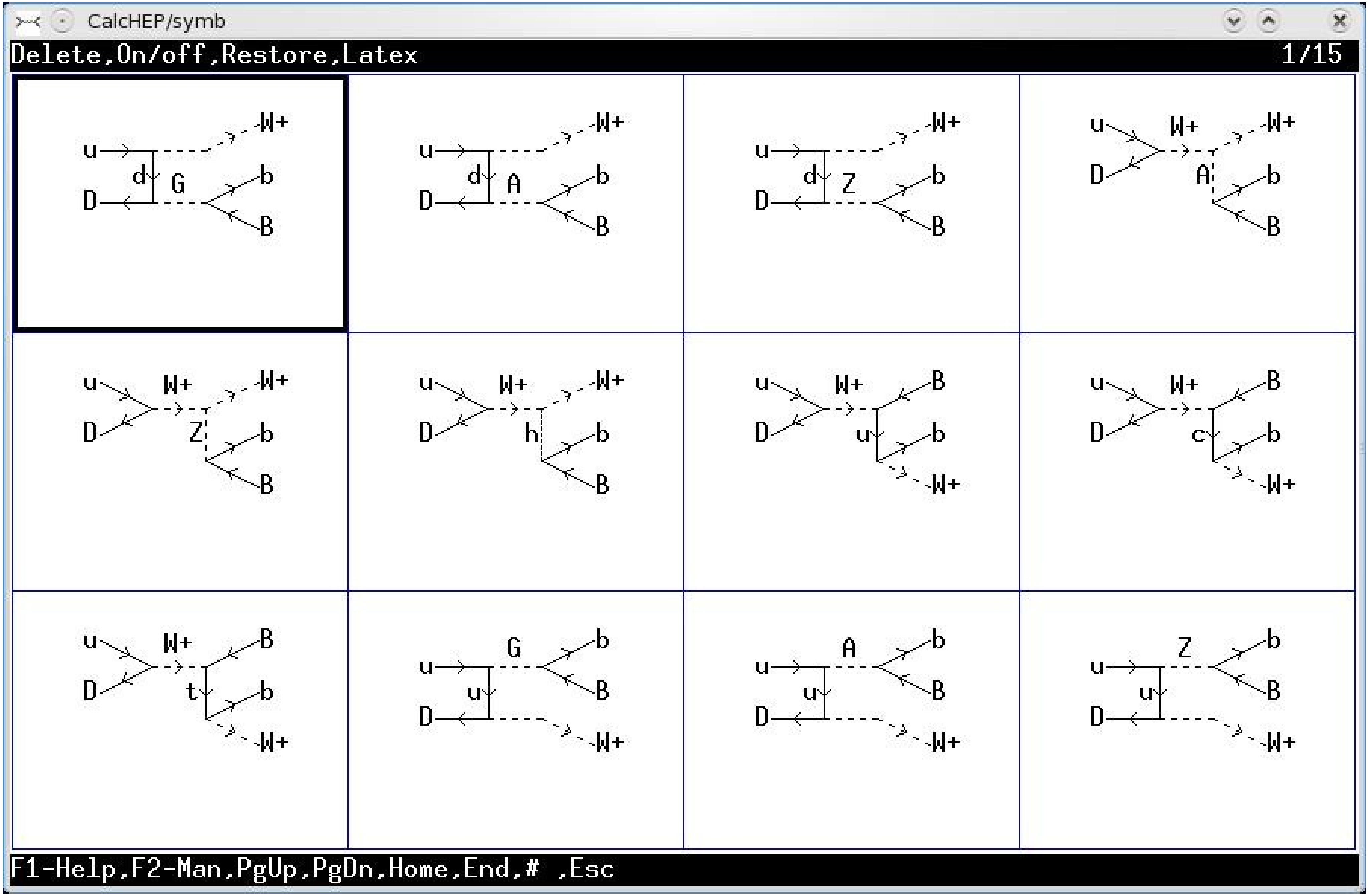
View diagrams

NN	Subprocess	Del	Rest
1	u,D -> W+,b,B	0	15
2	u,S -> W+,b,B	0	16
3	u,B -> W+,b,B	0	26
4	U,d -> W-,b,B	0	15
5	U,s -> W-,b,B	0	16
6	U,b -> W-,b,B	0	26
7	d,U -> W-,b,B	0	15
8	d,C -> W-,b,B	0	16
9	D,u -> W+,b,B	0	15
10	D,c -> W+,b,B	0	16
11	s,U -> W-,b,B	0	16

PgDn

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

symbolic session: diagrams



symbolic session: list of squared diagrams

CalcHEP/symb

Model: Standard Model

Process: p,p -> W,b,B

Feynman diagrams

472 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.

Squared diagrams

5208 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.
0 diagrams are calculated.

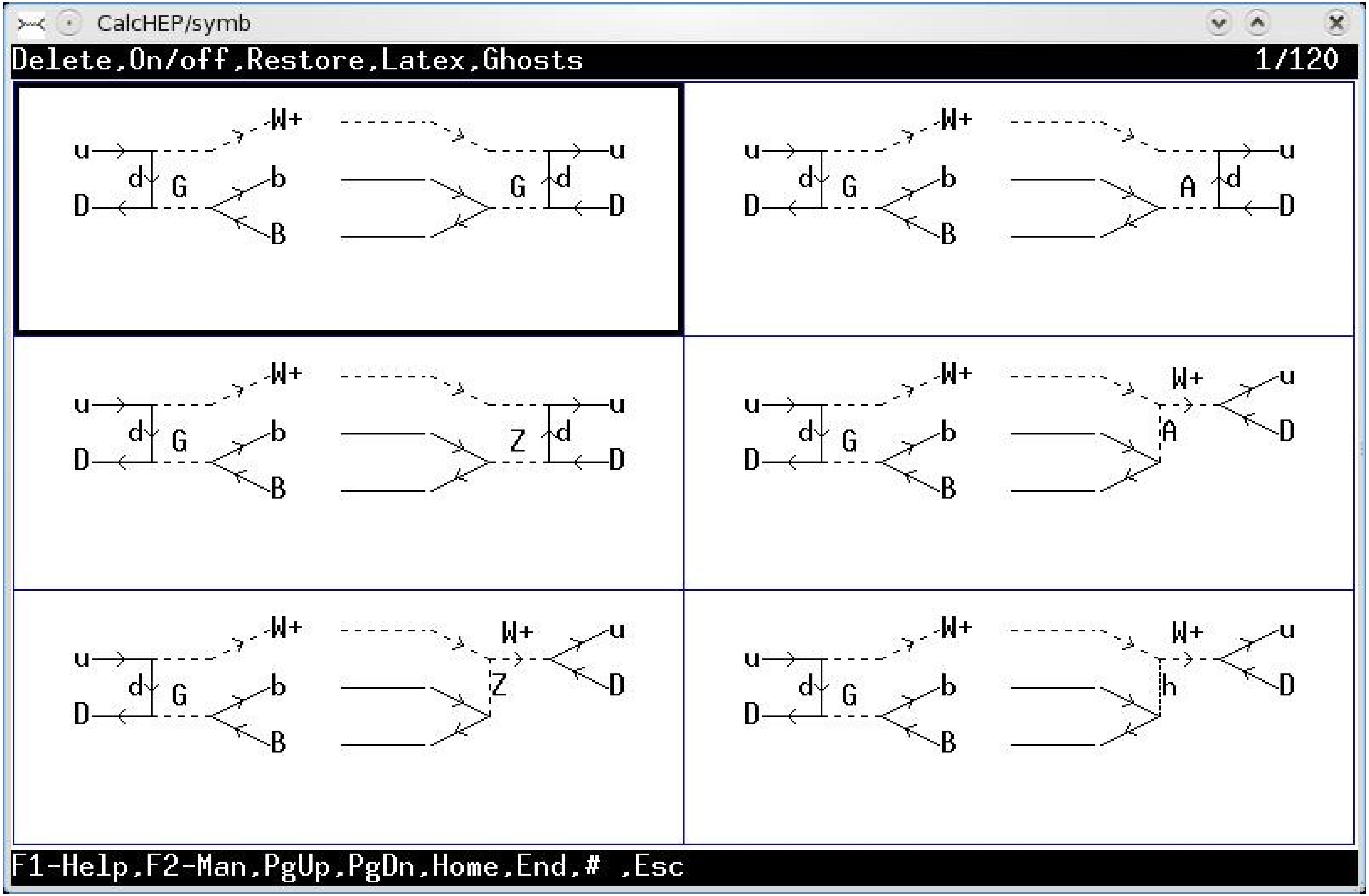
View squared diagrams

NN	Subprocess	Del	Calc	Rest
1	u,D->W+,b,B	0	0	120
2	u,S->W+,b,B	0	0	136
3	u,B->W+,b,B	0	0	351
4	U,d->W-,b,B	0	0	120
5	U,s->W-,b,B	0	0	136
6	U,b->W-,b,B	0	0	351
7	d,U->W-,b,B	0	0	120
8	d,C->W-,b,B	0	0	136
9	D,u->W+,b,B	0	0	120

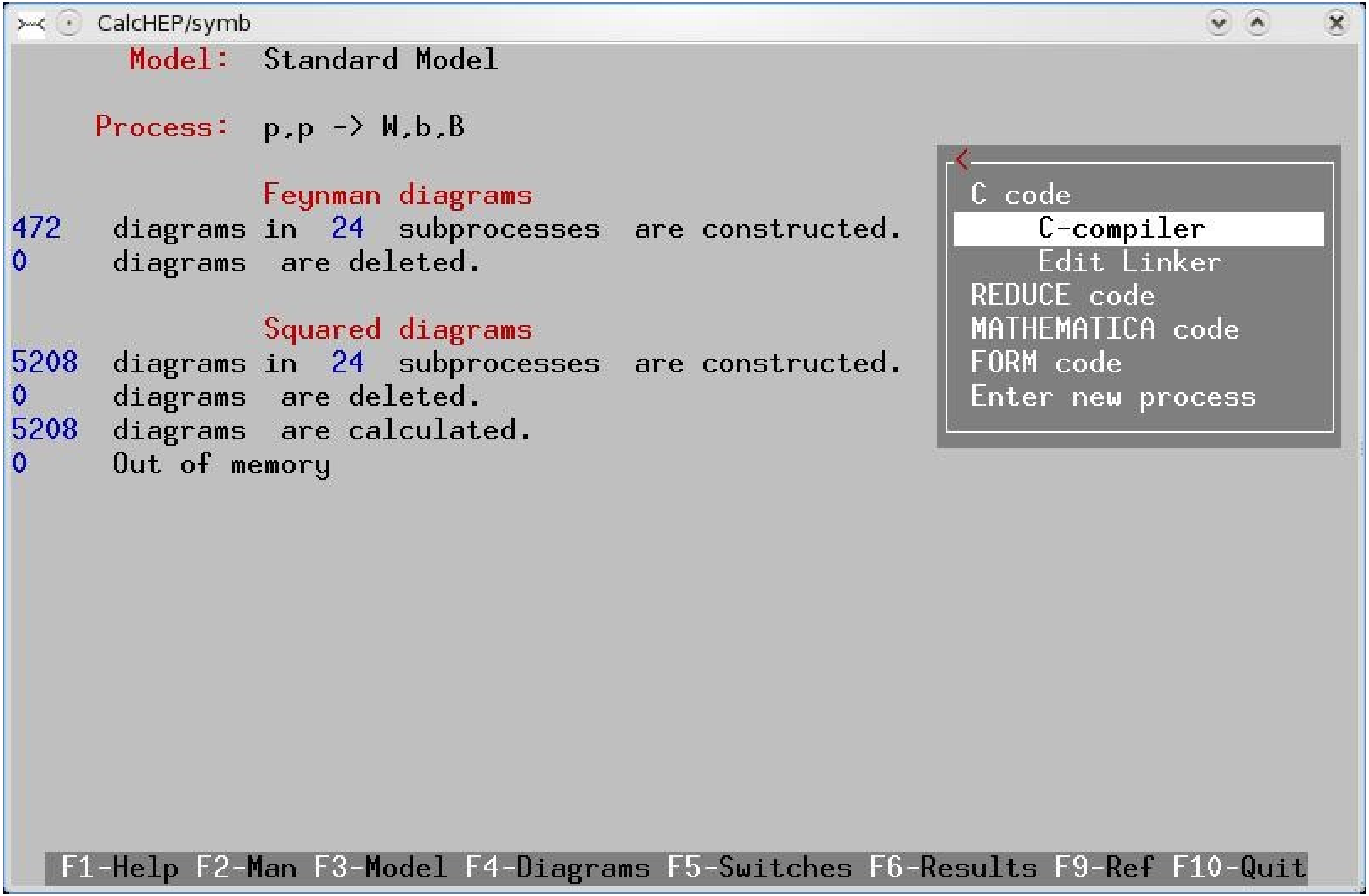
PgDn

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

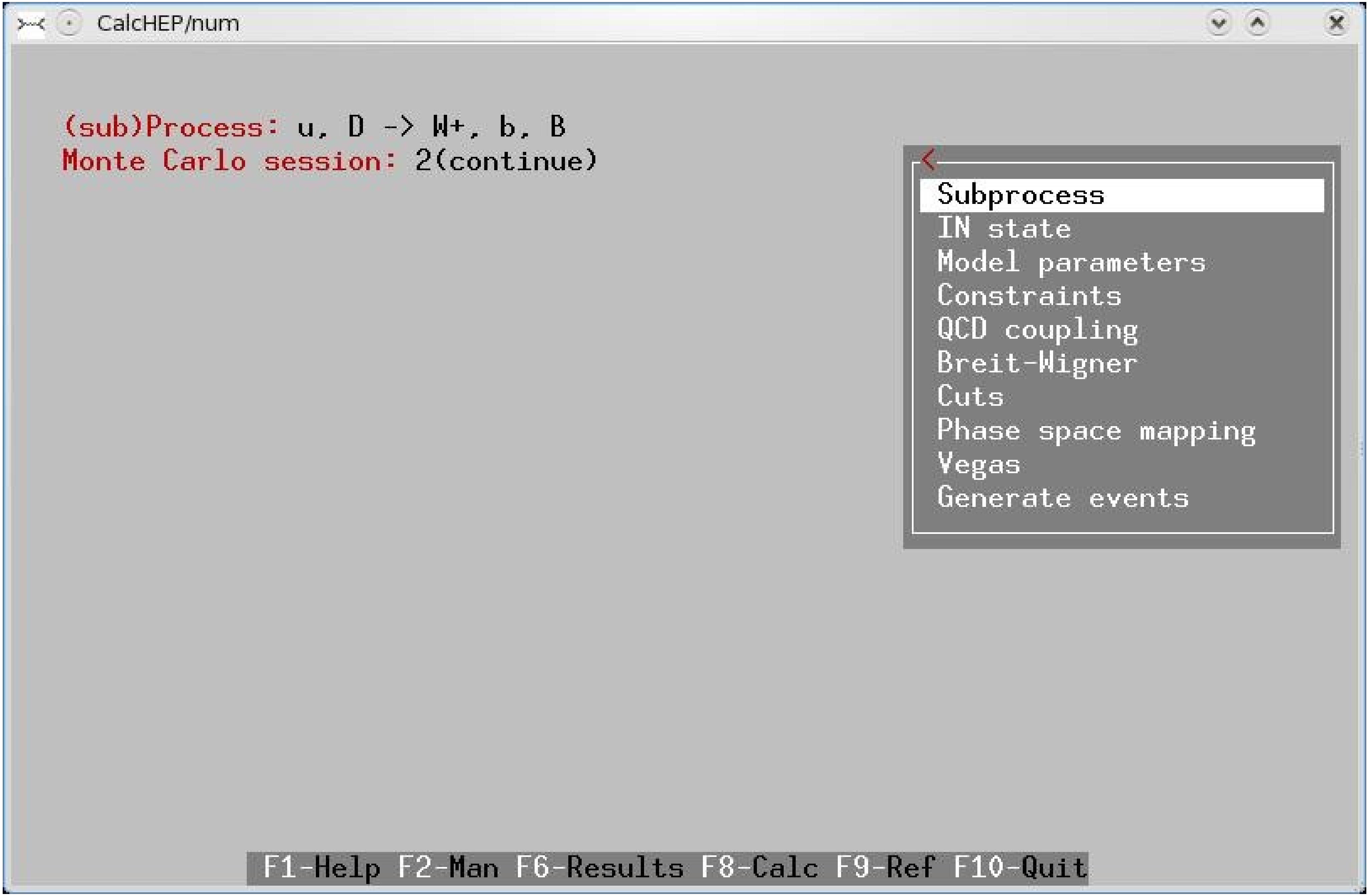
symbolic session: list of squared diagrams



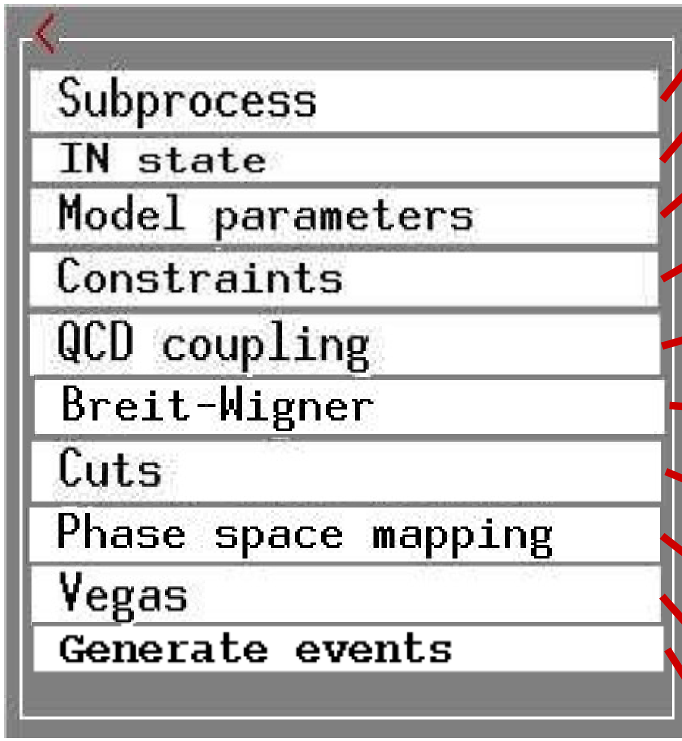
symbolic session: ME² calculation



numerical session: main menu

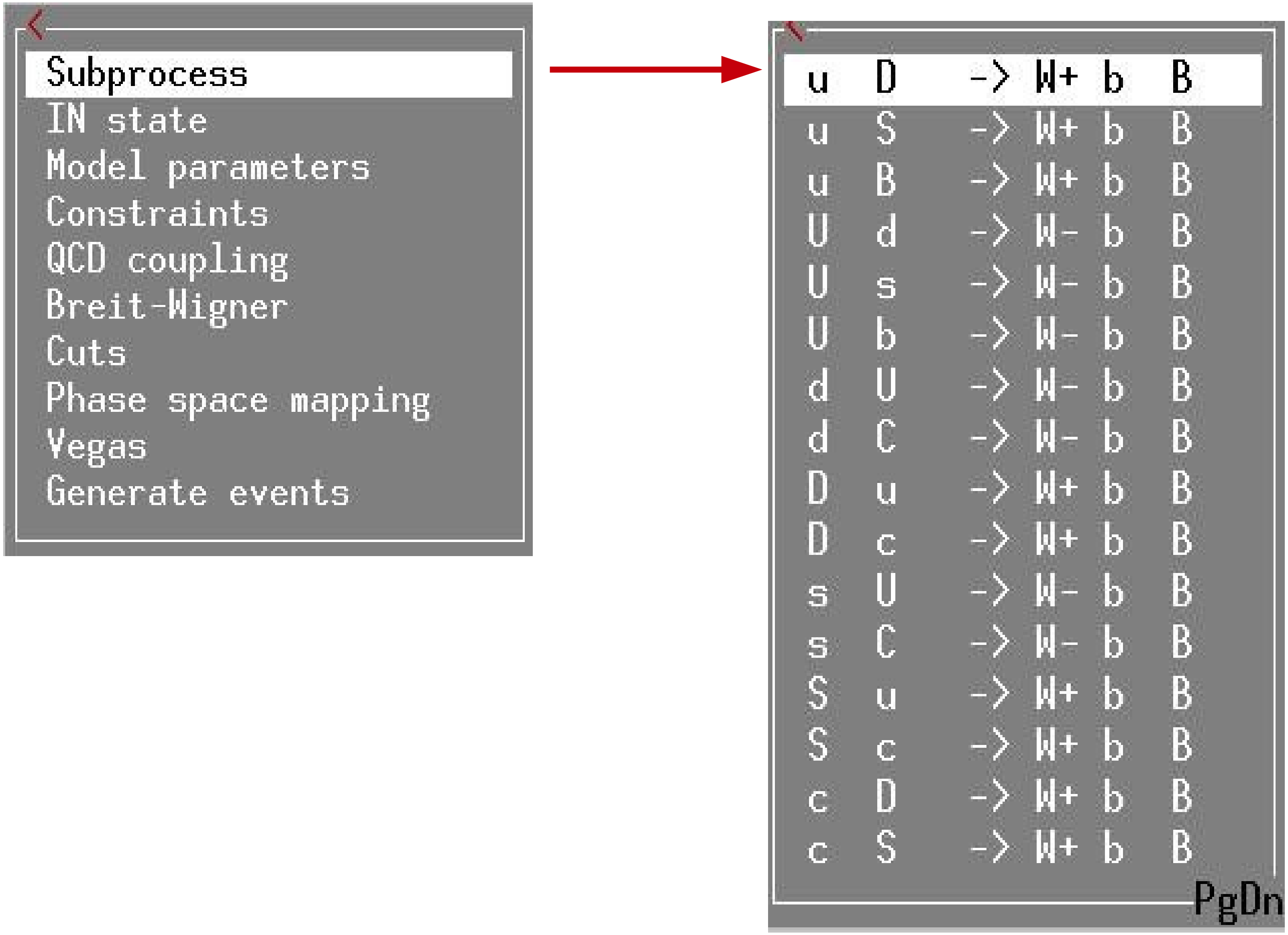


CalcHEP menu structure: numerical part

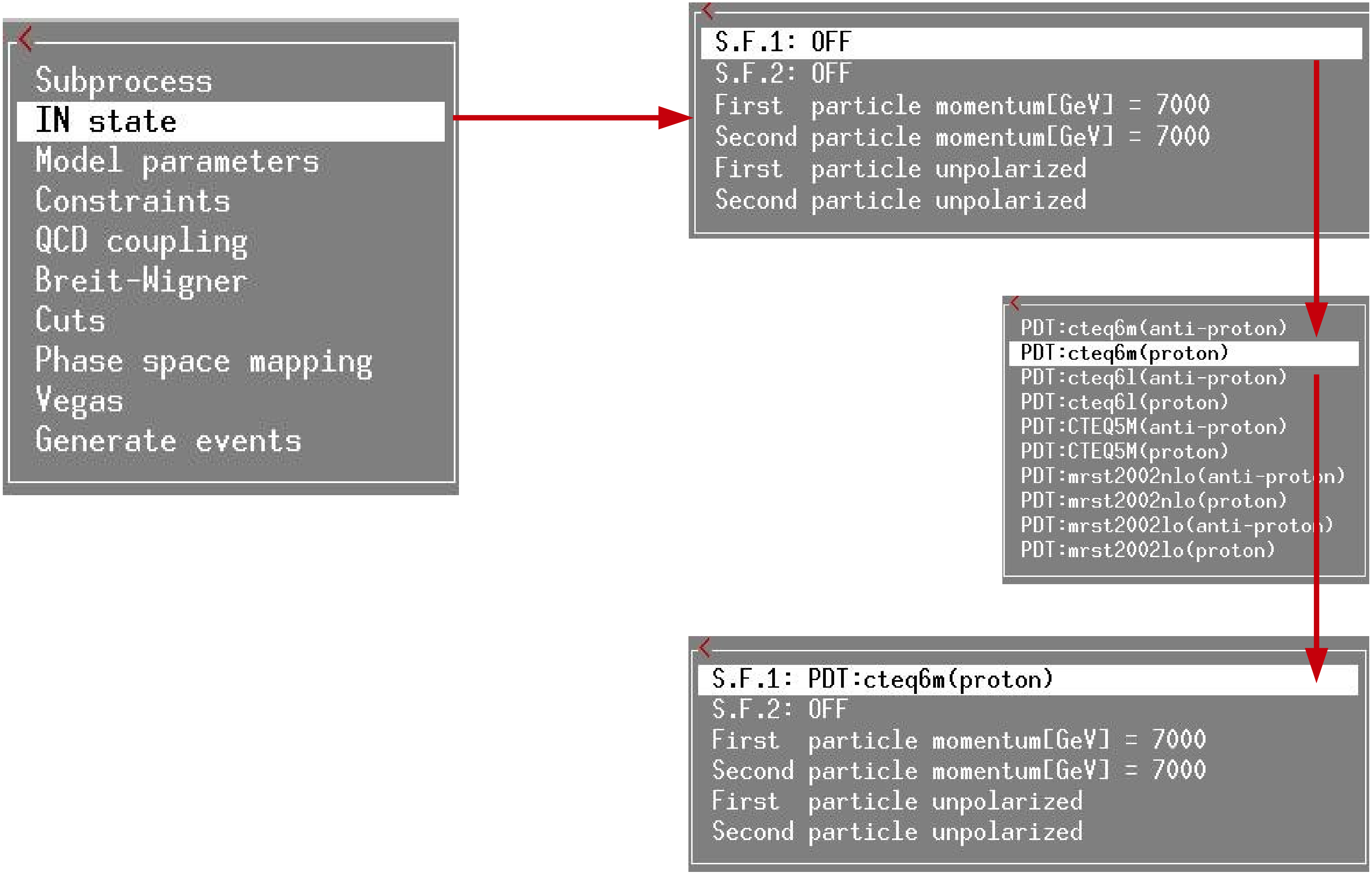


- Choice of the subprocess
- Set of the initial state: momenta, PDF, polarization
- Input of the numerical values of the independent parameters
- Check/evaluation of the dependent parameters
- Check/evaluation of QCD coupling, set up of the QCD scale
- Control of the s- and t-channel resonanses: resonance width, gauge-ivariant resonace treatment
- Set up kinematical cuts, incuding possibility of non-trivial definition of the user-deifned cuts
- Phase-space “smearing” of the “problematic” phase space region with sharp$|M|^2$ behaviour
- Set up VEGAS integration parameters, setup 1- and 2-d kinematical distributions
- Setup parameters for the event generation and generate events

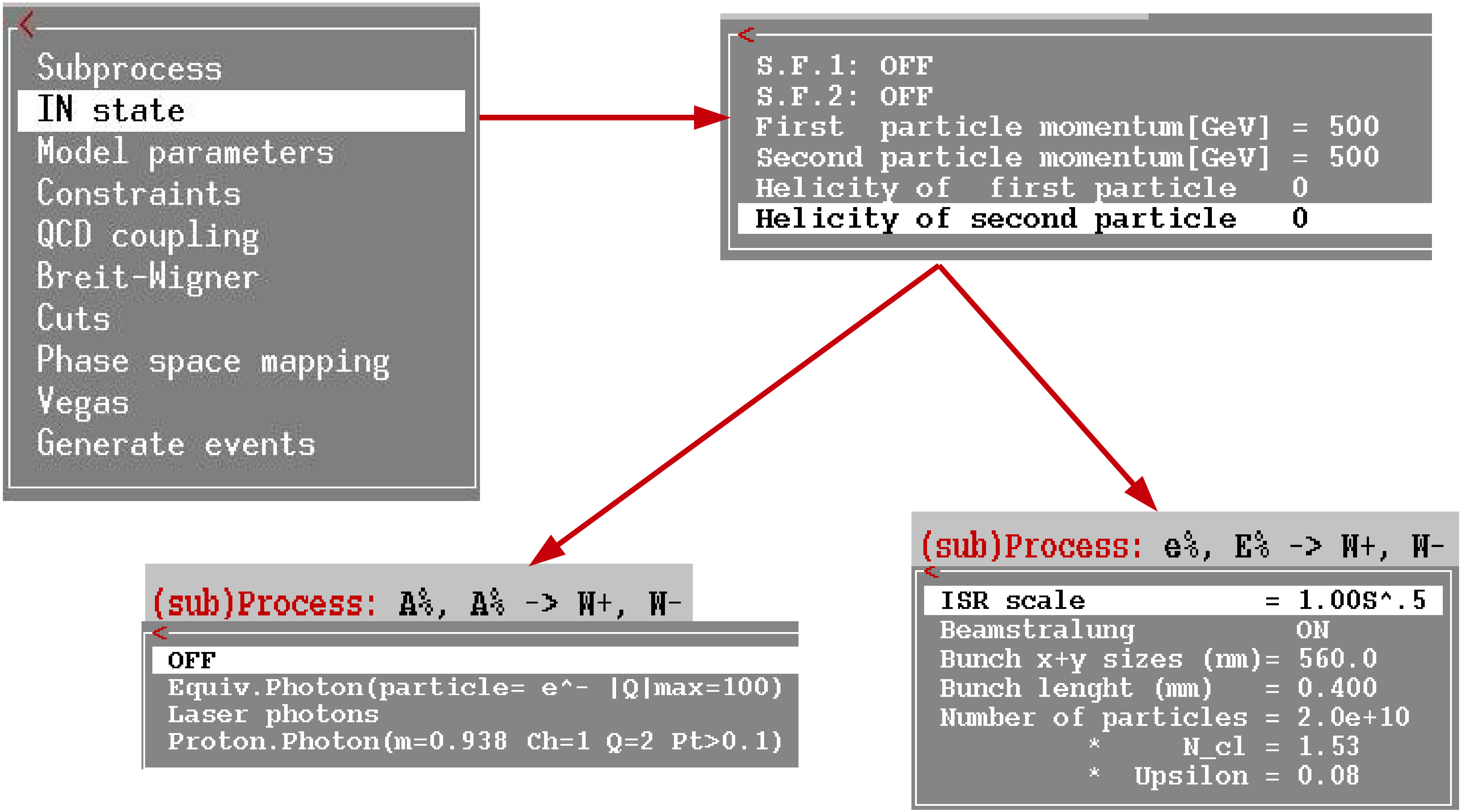
subprocess menu



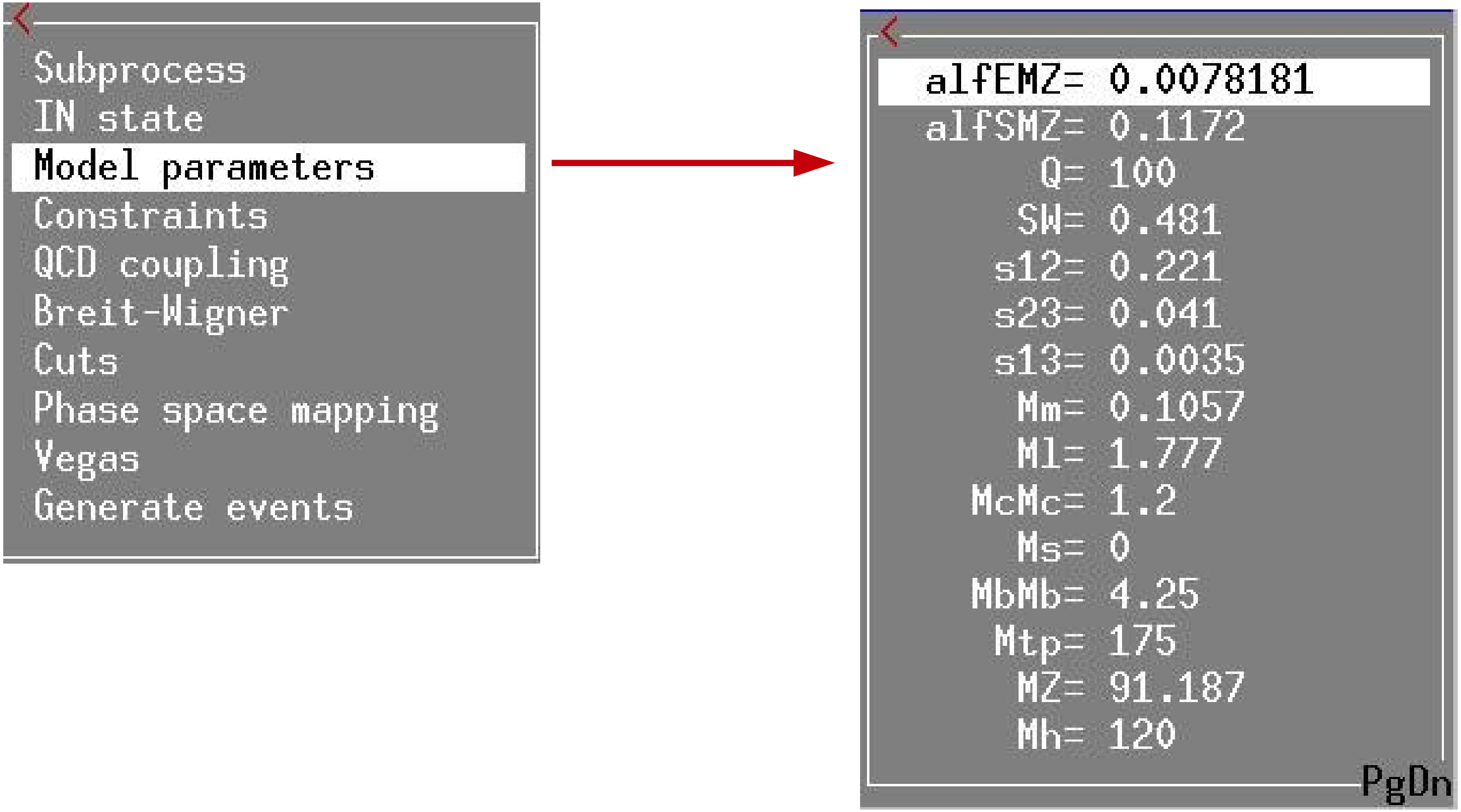
control of the initial states and PDFs: LHC case



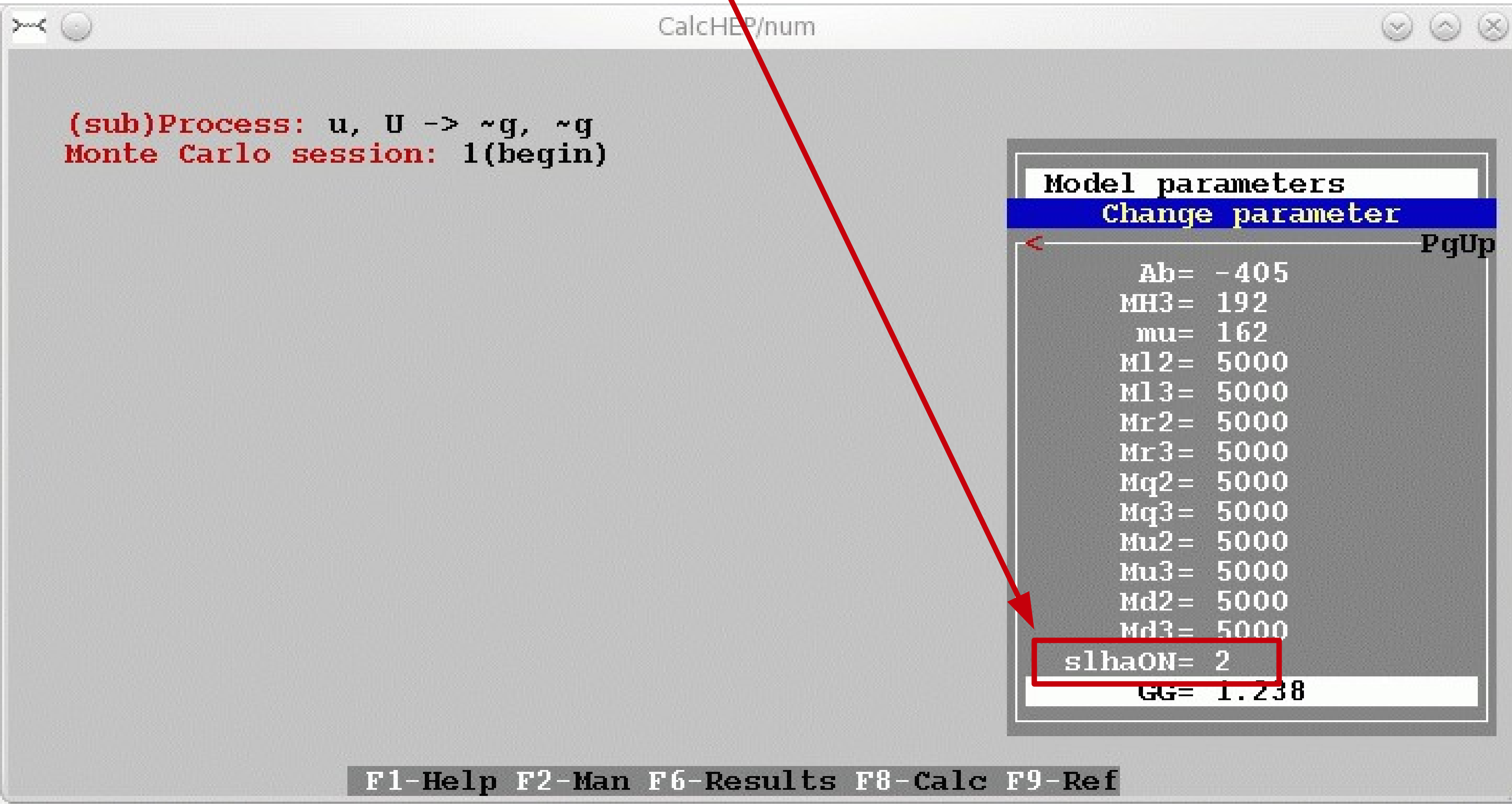
control of the initial states and PDFs: ILC case



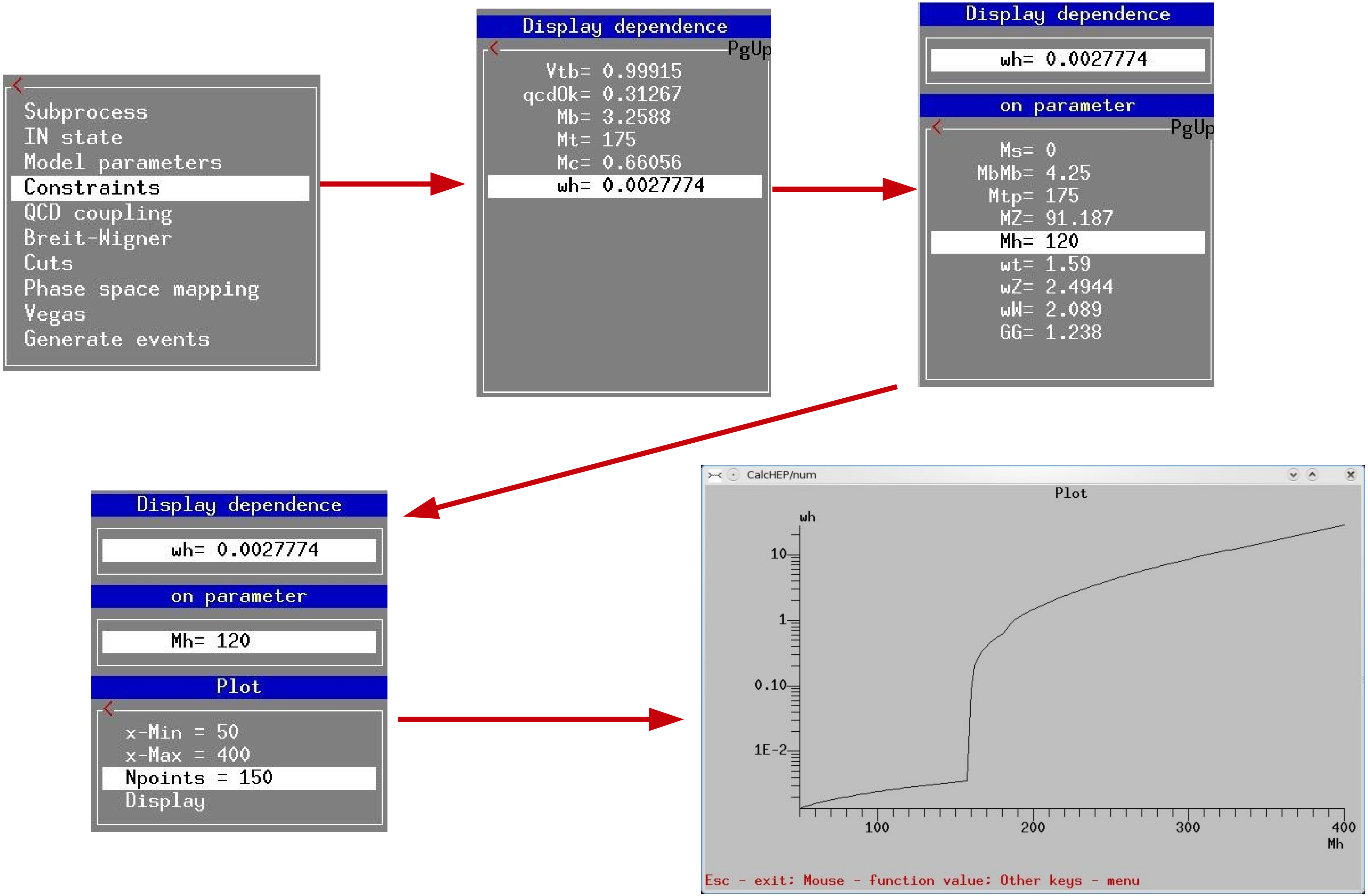
model parameters



Option to read-write LHA file (MSSM case)



dependent parameters



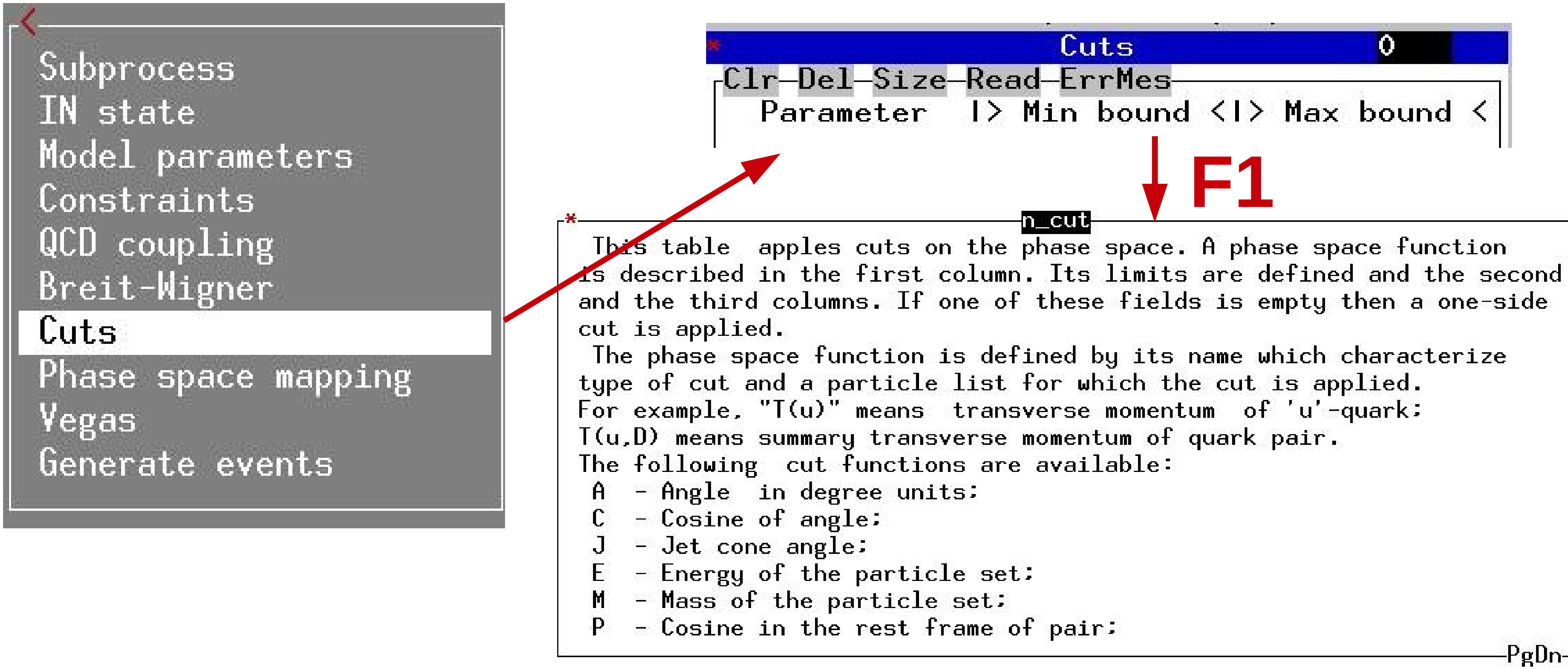
QCD coupling and the scale

```
Subprocess
IN state
Model parameters
Constraints
QCD coupling
Breit-Wigner
Cuts
Phase space mapping
Vegas
Generate events
```

→

```
          QCD alpha
parton dist. alpha !ON
alpha(MZ)=   0.1172
nf =         5
order=       NLO
mb(mb)=      4.200
Mtop(pole)= 175.00
Q[Gev] = M12
Alpha(Q) plot
```

setting kinematical cuts



setting kinematical cuts

Subprocess
IN state
Model parameters
Constraints
QCD coupling
Breit-Wigner
Cuts
Phase space mapping
Vegas
Generate events

Cuts 0
Clr Del Size Read ErrMes
Parameter |> Min bound <|> Max bound <

F1

n_cut

This table applies cuts on the phase space. A phase space function is described in the first column. Its limits are defined and 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 characterize 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;

PgDn

Cuts 5
Clr Del Size Read ErrMes

Parameter	Min bound	Max bound
T(b)	20	
T(B)	20	
N(b)	-5	5
N(B)	-5	5
J(b,B)	0.5	

integration over the phase space

Subprocess
IN state
Model parameters
Constraints
QCD coupling
Breit-Wigner
Cuts
Phase space mapping
Vegas
Generate events

Vegas

nSess_1 = 5
nCalls_1 = 100000
nSess_2 = 5
nCalls_2 = 100000
Set Distributions
*Start integration
Display Distributions
Clear statistic
Freeze grid OFF
Clear grid

Distributions

Clr-Del-Size-Read-ErrMes

Parameter_1	Min_1	Max_1	Parameter_2	Min_2	Max_2
T(b)	0	200			
T(B)	0	200			
N(b)	-5	5			
N(B)	-5	5			
M(b,B)	0	500			
M(W+,b)	0	500			
T(b)	0	500	M(b,B)	0	500

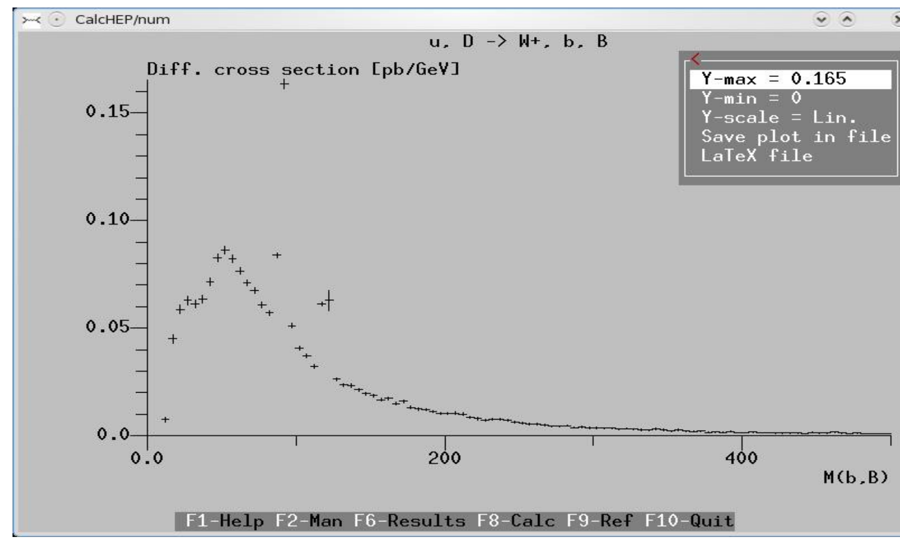
Vegas

nSess_1 = 5
nCalls_1 = 100000
nSess_2 = 5
nCalls_2 = 100000
Set Distributions
***Start integration**
Display Distributions
Clear statistic
Freeze grid OFF
Clear grid

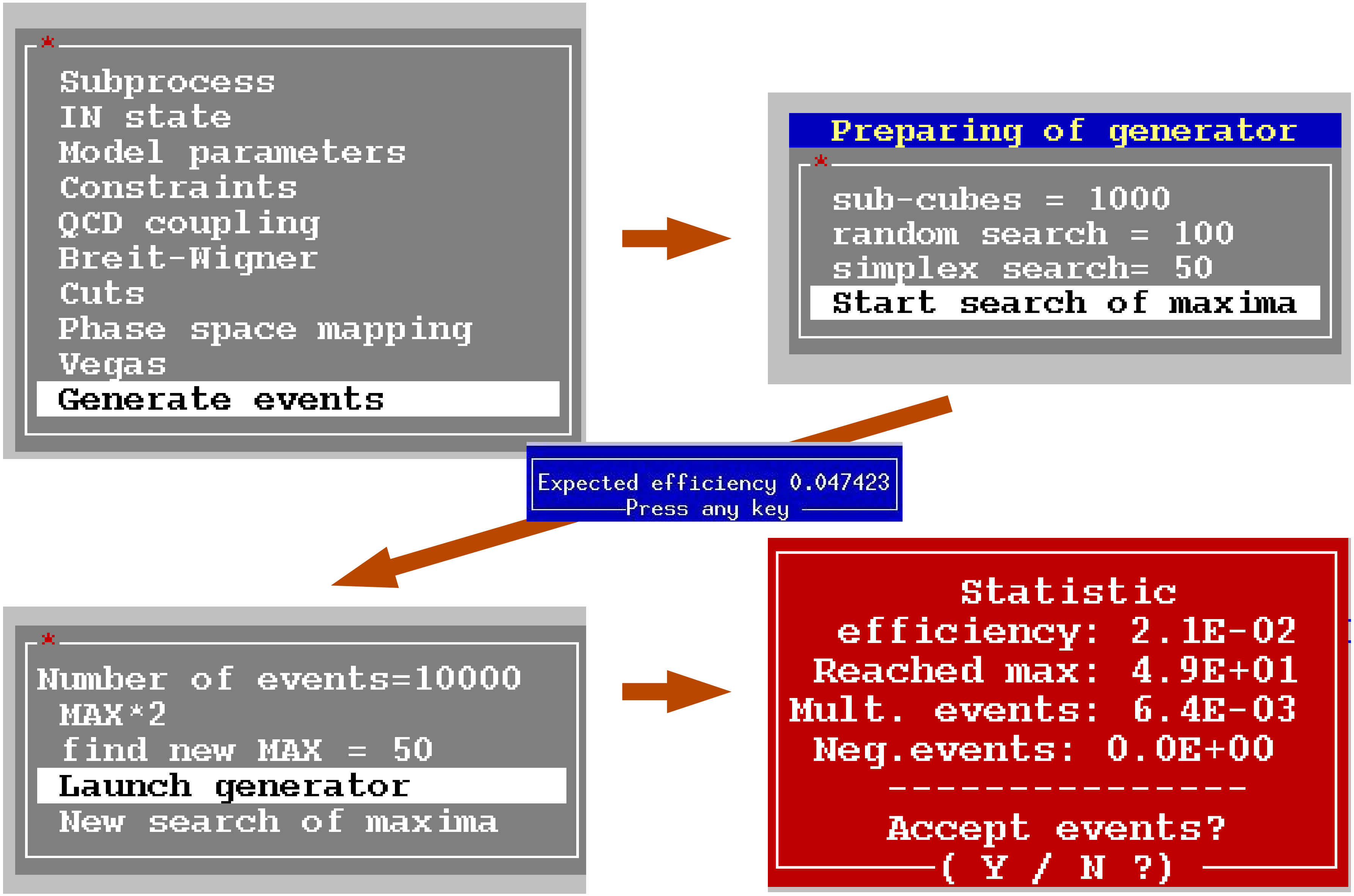
(sub)Process: u, D -> W+, b, B
Monte Carlo session: 2(continue)

#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	9.6945E+00	1.05E+00
5	9.7032E+00	7.68E-01
< >	9.7095E+00	3.74E-01

nSess_1 = 5
nCalls_1 = 100000
nSess_2 = 5
nCalls_2 = 100000
Set Distributions
*Start integration
Display Distributions
Clear statistic
Freeze grid OFF
Clear grid



generation of events



running subproc_cycle for SM model

```
../bin/subproc_cycle 0 0
#Subprocess 1 ( u, D -> W+, b, B ) Cross section = 9.6364E+00 , 0 events
#Subprocess 2 ( u, S -> W+, b, B ) Cross section = 4.0808E-01 , 0 events
#Subprocess 3 ( u, B -> W+, b, B ) Cross section = 2.3490E-04 , 0 events
#Subprocess 4 ( U, d -> W-, b, B ) Cross section = 5.7795E+00 , 0 events
#Subprocess 5 ( U, s -> W-, b, B ) Cross section = 1.0253E-01 , 0 events
#Subprocess 6 ( U, b -> W-, b, B ) Cross section = 4.3181E-05 , 0 events
#Subprocess 7 ( d, U -> W-, b, B ) Cross section = 5.8270E+00 , 0 events
#Subprocess 8 ( d, C -> W-, b, B ) Cross section = 2.1421E-01 , 0 events
#Subprocess 9 ( D, u -> W+, b, B ) Cross section = 9.5470E+00 , 0 events
#Subprocess 10 ( D, c -> W+, b, B ) Cross section = 9.1056E-02 , 0 events
#Subprocess 11 ( s, U -> W-, b, B ) Cross section = 1.0383E-01 , 0 events
#Subprocess 12 ( s, C -> W-, b, B ) Cross section = 1.2694E+00 , 0 events
#Subprocess 13 ( S, u -> W+, b, B ) Cross section = 4.1026E-01 , 0 events
#Subprocess 14 ( S, c -> W+, b, B ) Cross section = 1.2333E+00 , 0 events
#Subprocess 15 ( c, D -> W+, b, B ) Cross section = 9.3773E-02 , 0 events
#Subprocess 16 ( c, S -> W+, b, B ) Cross section = 1.2480E+00 , 0 events
#Subprocess 17 ( c, B -> W+, b, B ) Cross section = 3.4475E-03 , 0 events
#Subprocess 18 ( C, d -> W-, b, B ) Cross section = 2.1469E-01 , 0 events
#Subprocess 19 ( C, s -> W-, b, B ) Cross section = 1.2651E+00 , 0 events
#Subprocess 20 ( C, b -> W-, b, B ) Cross section = 3.4542E-03 , 0 events
#Subprocess 21 ( b, U -> W-, b, B ) Cross section = 4.3722E-05 , 0 events
#Subprocess 22 ( b, C -> W-, b, B ) Cross section = 3.3992E-03 , 0 events
#Subprocess 23 ( B, u -> W+, b, B ) Cross section = 2.3111E-04 , 0 events
#Subprocess 24 ( B, c -> W+, b, B ) Cross section = 3.4543E-03 , 0 events
Sum of distributions is stored in file distr_7_30
Total Cross Section 37.45843711 [pb]
see details in prt_7 - prt_30 files
```

Accessing 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 *qnumbers – PYTHIA input with new prt definitions*
  - 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
............................................
............................................
```

A few words about LanHEP package

Andrei Semenov: V3.0, arXiv:0805.0555

http://theory.sinp.msu.ru/~semenov/lanhep.html

The program for Feynman rules generation in momentum space

QCD as an example

Gauge term $L_{YM} = -\frac{1}{4} F^{a\mu\nu} F^a_{\mu\nu}, \quad F^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g_s f^{abc} G^b_\mu G^c_\nu$

Quark kinetic term $L_F = \bar{q}_i \gamma^\mu \partial_\mu q_i + g_s \lambda^a_{ij} \bar{q}_i \gamma^\mu q_j G^c_\mu,$

GF term and FP ghost term $\mathcal{L}_{GF} = -\frac{1}{2} (\partial_\mu G^\mu_a)^2 + i g_s f^{abc} \bar{c}^a G^b_\mu \partial^\mu c^c,$

```
model QCD/2.
parameter gg=1.117:'Strong coupling'.
spinor q/Q:(quark, mass mq=0.01, color c3).
vector G/G:(gluon, color c8, gauge).
let F^mu^nu^a = deriv^nu*G^mu^a - deriv^mu*G^nu^a -
         gg*f_SU3^a^b^c*G^mu^b*G^nu^c.
lterm -F**2/4-(deriv*G)**2/2.
lterm Q*(i*gamma*deriv+mq)*q.
lterm i*gg*f_SU3*ccghost(G)*G*deriv*ghost(G).
lterm gg*Q*gamma*lambda*G*q.
```

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Andrei Semenov: V3.0, arXiv:0805.0555

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Gauge term $$L_{YM} = -\frac{1}{4} F^{a\mu\nu} F^a_{\mu\nu}, \quad F^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g_s f^{abc} G^b_\mu G^c_\nu$$

Quark kinetic term $$L_F = \bar{q}_i \gamma^\mu \partial_\mu q_i + g_s \lambda^a_{ij} \bar{q}_i \gamma^\mu q_j G^c_\mu,$$

GF term and FP ghost term $$\mathcal{L}_{GF} = -\frac{1}{2} (\partial_\mu G^\mu_a)^2 + i g_s f^{abc} \bar{c}^a G^b_\mu \partial^\mu c^c,$$

QCD Feynman rules generated by LanHEP in LaTeX format

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

Features of LanHEP

- it reads Lagrangian written in the form close to one used in publications and transforms it into momenta space
- it writes Feynman rules in the form of four tables in CompHEP format as well as tables in LaTeX format
- LanHEP expands expression and combines similar terms user can define the substitution rules, it allows to define multiplets, and their components
- it can check whether the set of introduced vertices satisfies the electric charge conservation law
- many more features: see manual(!) – using superpotential formalism, check for BRST invariance, two-component notation for fermions, spins 3/2,2, ...

LanHEP installation

- ***http://theory.sinp.msu.ru/~semenov/lanhep.html***

tar -zxvf lhep*xxx*.tar.gz

cd lhep*xxx*

make

make clean

Running LanHEP

- ***../lhep stand.mdl***

File sm_tex processed, 0 sec.

File stand.mdl processed, 1 sec.

Future plans

➧ *Effective FR derivation for ExD models*

recent news from Andrei!

```
model uedqwd/3.

parameter ee = 0.3133: 'Electric charge', R=le-4.

vector A/A:photon, A1/A1:(photon1, mass Ma1=1000), ....

scalar s1/s1:(phot5^1, mass Ma51=1000), ....

spinor e:(electron, mass me=2000.511),
       e1l:(electron1, mass me1=1000.0511),
       e1r:(electron1, mass me1=1000.0511), ....

transform A -> A*cos(0) + (A1*cos(1) + A2*cos(2))*Sqrt2, ....

.............................................................

let        A5 = (s1*sin(1) + s2*sin(2))*Sqrt2.

ued_5th deriv5->1/R, A->(s1*sin(1) + s2*sin(2))*Sqrt2.

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

CheckHerm.
CheckMasses.
```

CalcHEP batch interface:
results from CalcHEP in one shot!

- calchep_batch batch_file

```
calchep_batch batch_file
Progress information can be found in the html directory.
Simply open the following link in your browser:
file:///home/belyaev/proj/intro_to_hep_tools/calc_work_2.5.4/html/index.html
```

Main Features

- Batch file
- Process library
- Runs
- Combines decays
- Parallelization
- HTML progress

batch_file

```
Model:         Standard Model(CKM=1)
Model changed: False
Gauge:         Feynman
```

```
Process:    p,p->W,b,B
Decay:      W->ll,nn

Composite:  p=u,U,d,D,s,S,c,C,b,B,G
Composite:  W=W+,W-
Composite:  ll=e,E,m,M,l,L
Composite:  nn=ne,Ne,nm,Nm,nl,Nl
```

CalcHEP batch interface: results from CalcHEP in one shot!

file:///home/belyaev/proj/intro_to_hep_tools/calc_work_2.5.4/html/index.html

Home
Symbolic Results
Numerical Results
Events Library
Process Library
Help

Thank you for using CalcHEP!
Please cite arXiv:0000.0000

CalcHEP Batch Details

Standard Model(CKM=1)

Done!

	Finished	Time(hr)
Symbolic	14/14	0.00
σ	1/1	0.03
Events	1/1	0.05

CalcHEP batch interface: results from CalcHEP in one shot!

file:///home/belyaev/proj/intro_to_hep_tools/calc_work_2.5.4/html/index.html

Symbolic Sessions

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Process Library
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Please cite arXiv:0000.0000

Standard Model(CKM=1)

Processes	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+->E,ne	✓		
W+->M,nm	✓		
W+->L,nl	✓		
W-->e,Ne	✓		
W-->m,Nm	✓		
W-->l,Nl	✓		
Widths	✓		

CalcHEP batch interface: results from CalcHEP in one shot!

file:///home/belyaev/proj/intro_to_hep_tools/calc_work_2.5.4/html/index.html

Home
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Thank you for using CalcHEP!
Please cite arXiv:0000.0000

Numerical Sessions

Standard Model(CKM=1)

Done!

Runs	σ (fb)	Running	Finished	Time (hr)	N events
Single	12350	0/15	15/15	0.14	50000
				0.14	

CalcHEP batch interface:
results from CalcHEP in one shot!

file:///home/belyaev/proj/intro_to_hep_tools/calc_work_2.5.4/html/index.html

Standard Model(CKM=1)

Done!

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Thank you for using CalcHEP!
Please cite arXiv:0000.0000

Processes	σ (fb)	PID	Time (hr)	N events	Details	
u,D->W+,b,B	10047	27115	0.02	14910/14910	prt_1	session.dat
U,d->W-,b,B	5636.4	27125	0.01	8364/8364	prt_1	session.dat
d,U->W-,b,B	5567.9	27129	0.01	8263/8263	prt_1	session.dat
D,u->W+,b,B	9850.2	27145	0.02	14618/14618	prt_1	session.dat
s,C->W-,b,B	1609.9	27366	0.01	2389/2389	prt_1	session.dat
S,c->W+,b,B	1359.9	27370	0.01	2018/2018	prt_1	session.dat
c,S->W+,b,B	1374.5	27563	0.01	2039/2039	prt_1	session.dat
C,s->W-,b,B	1614.8	27581	0.01	2396/2396	prt_1	session.dat
Total	37061			54997/54997		

Decays	Γ (GeV)	PID	Time (hr)	N events	Details	
W+->E,ne	0.22339	27583	0.01	255000/254999	prt_1	session.dat
W+->M,nm	0.22339	27586	0.01	255000/254999	prt_1	session.dat
W+->L,nl	0.22323	27891	0.01	255000/254999	prt_1	session.dat
W-->e,Ne	0.22339	27893	0.01	255000/254999	prt_1	session.dat
W-->m,Nm	0.22339	27896	0.01	255000/254999	prt_1	session.dat
W-->l,Nl	0.22323	27905	0.01	255000/254999	prt_1	session.dat

Widths		PID	Time (hr)		Details	
Widths		28254	0.01			session.dat
Total	12350		0.14			

CalcHEP batch interface: results from CalcHEP in one shot!

file:///home/belyaev/proj/intro_to_hep_tools/calc_work_2.5.4/html/index.html

Distributions

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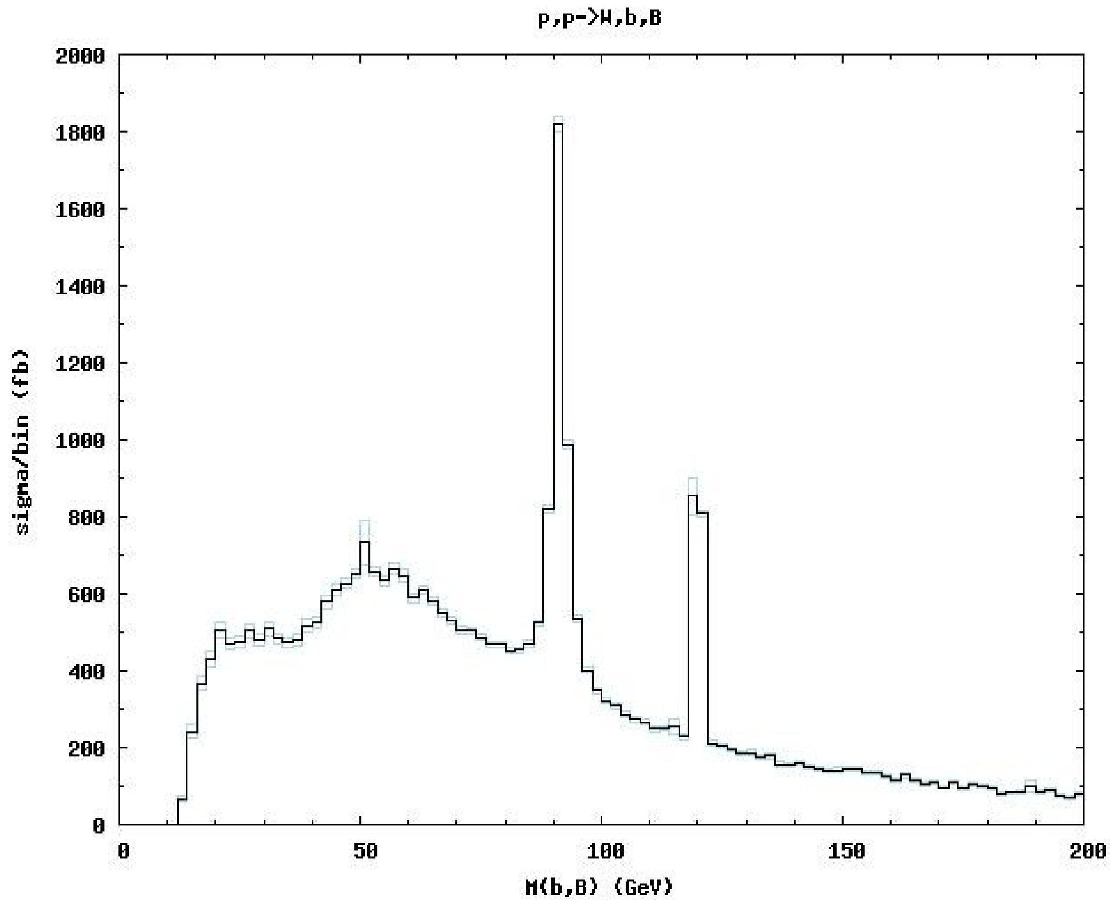
Thank you for using CalcHEP!
Please cite arXiv:0000.0000



p,p->H,b,B

CalcHEP batch interface: results from CalcHEP in one shot!

file:///home/belyaev/proj/intro_to_hep_tools/calc_work_2.5.4/html/index.html

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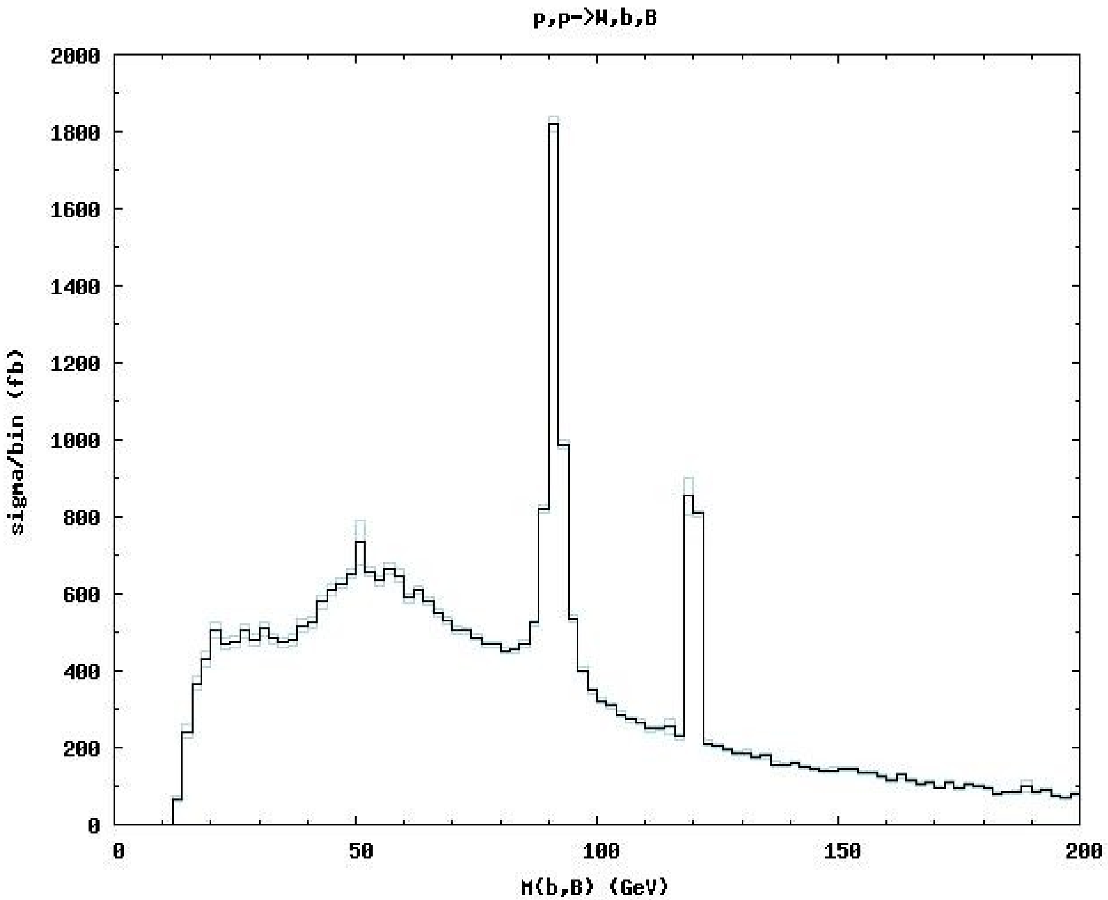


p,p->H,b,B

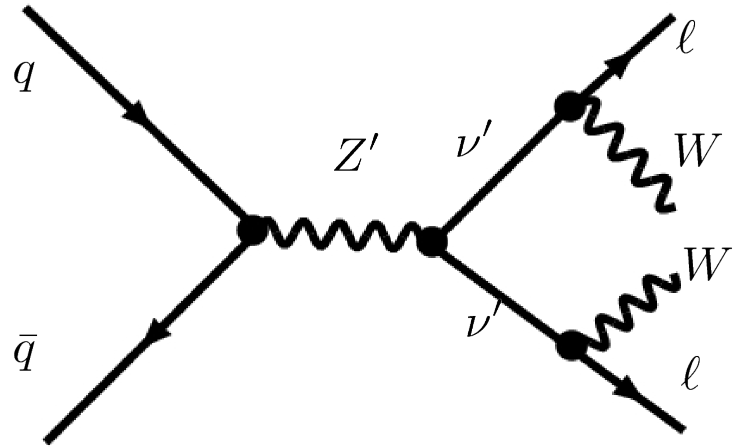
The new version of CalcHEP (dev version) implements all properties of batch interface

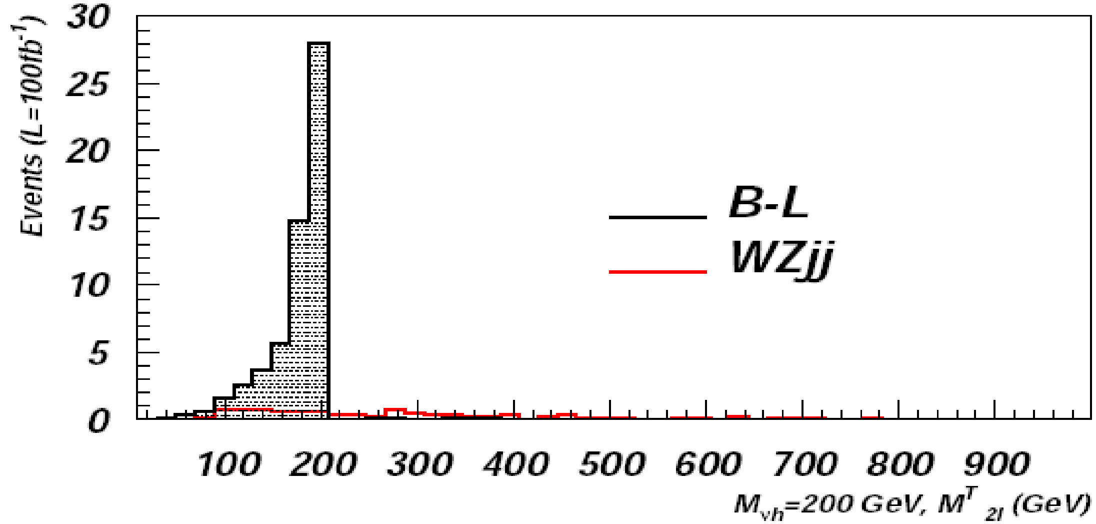
Recent applications: B-L extension of SM

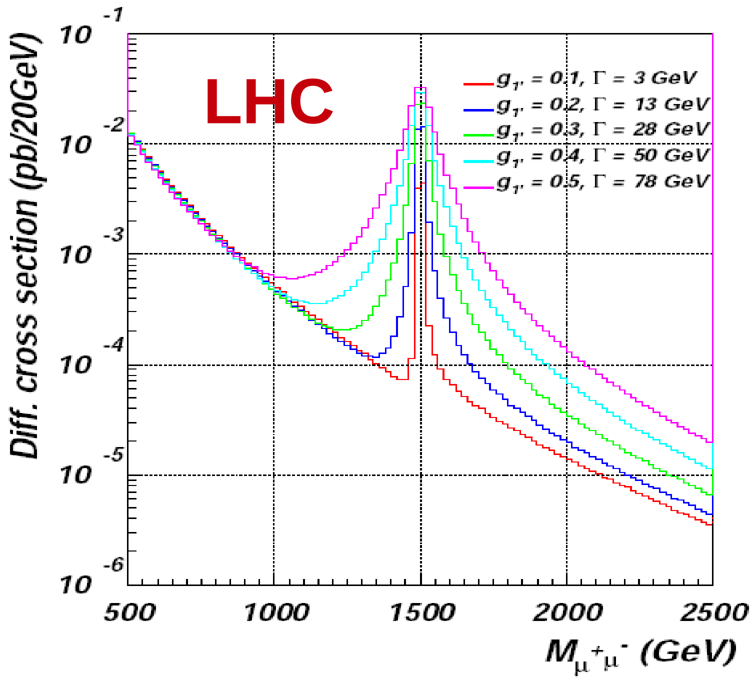
Extra U(1)' : Z', heavy long leaving neutrino

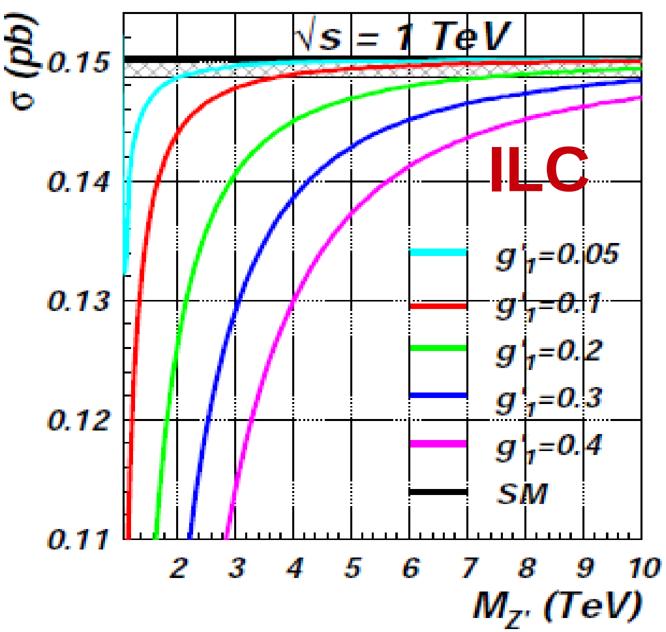
(in collaboration with S. Moretti, L. Basso, M.Pruna, C. Shepherd)

arXiv:0812.4313
arXiv:0903.4777









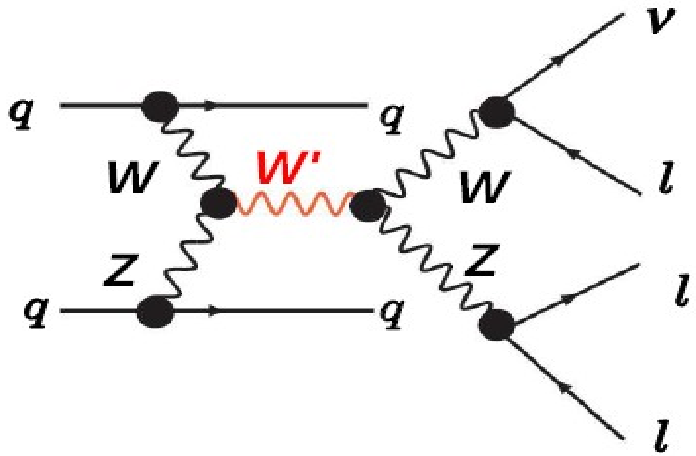
Recent applications:

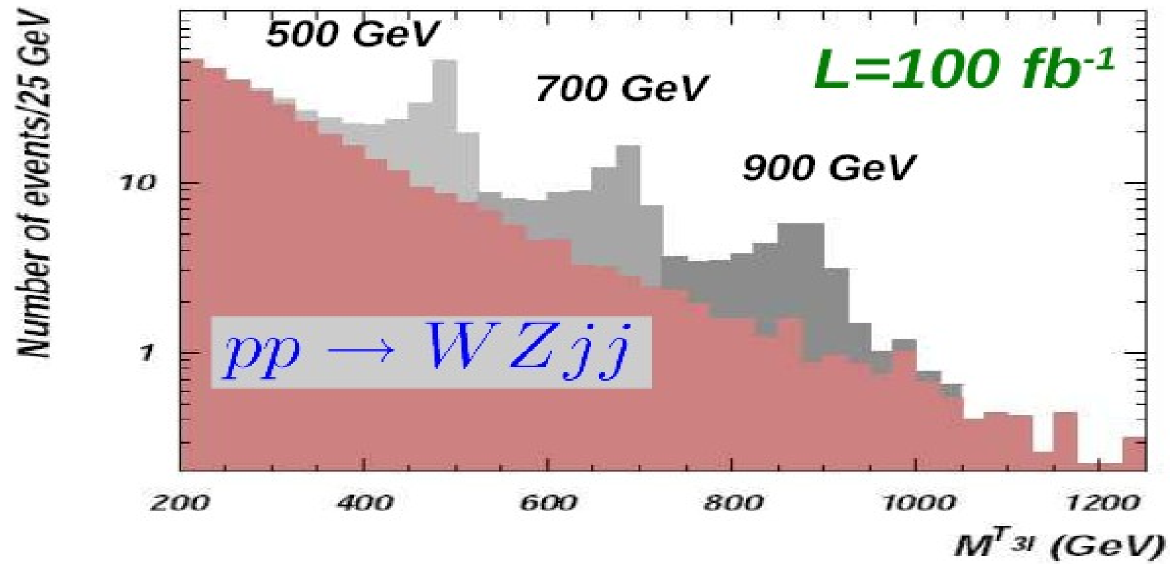
W' 3-lepton signatures from 3-site Higgsless model

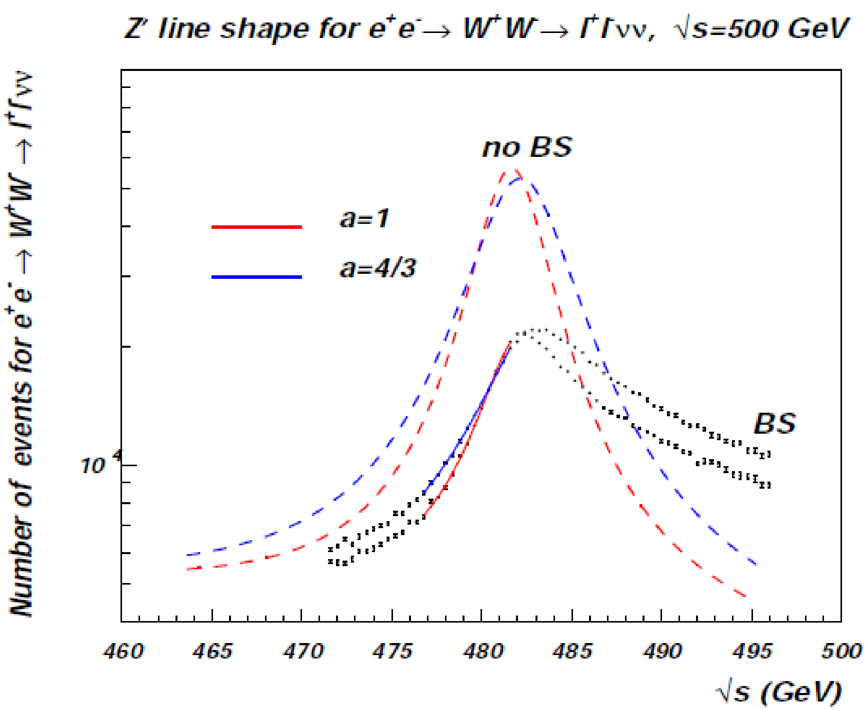
arXiv:0708.2588

LHC reach for WZ->W' process

[AB, Chivukula, Christensen, He, Kuang, Pukhov, Qi, Simmons, Zhang '07]



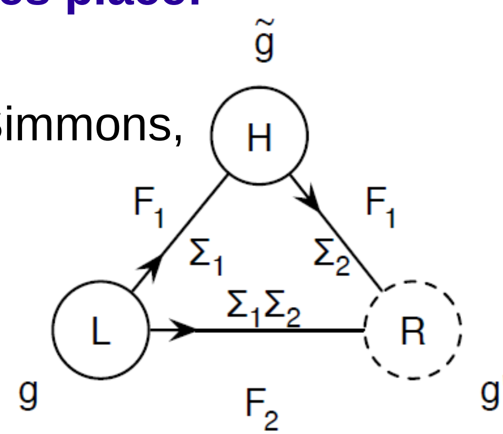




Z' line shape Z' study at ILC:
the Z' width can be measured precisely [2.5%],
So we will be able to understand
which higgsless model takes place!

arXiv:0907.2662
AB, Chivukula, Christensen, Simmons, He, Kurachi, Tanabashi

$$SU(2)_L \times SU(2)_H \times U(1)_R$$



Recent applications:
phenomenology of WalkingTechnicolor models

arXiv:0809.0793

AB, Foadi, Frandsen, Järvinen, Pukhov, Sannino

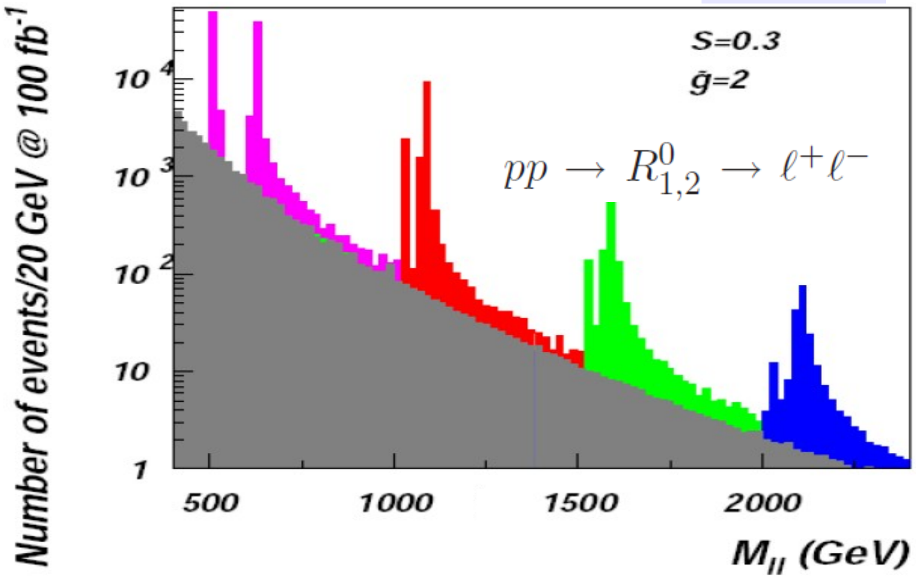
N_c = 3, N_f = 2
in the two-index symmetric
$SU(2)_L$ X $SU(2)_R$ –> $SU(2)_V$
two triplets of heavy mesons

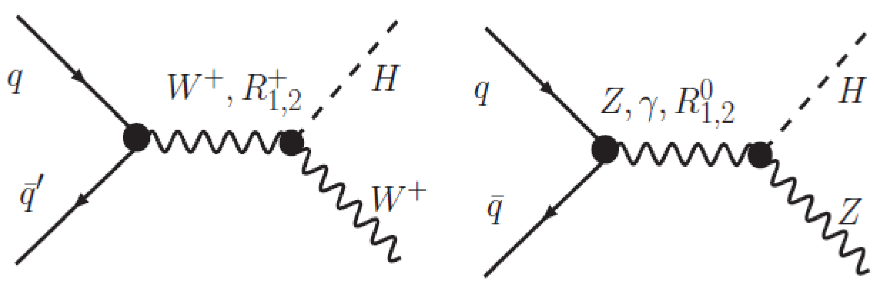
LHC

$R_1^{\pm}(R_2^{\pm})$

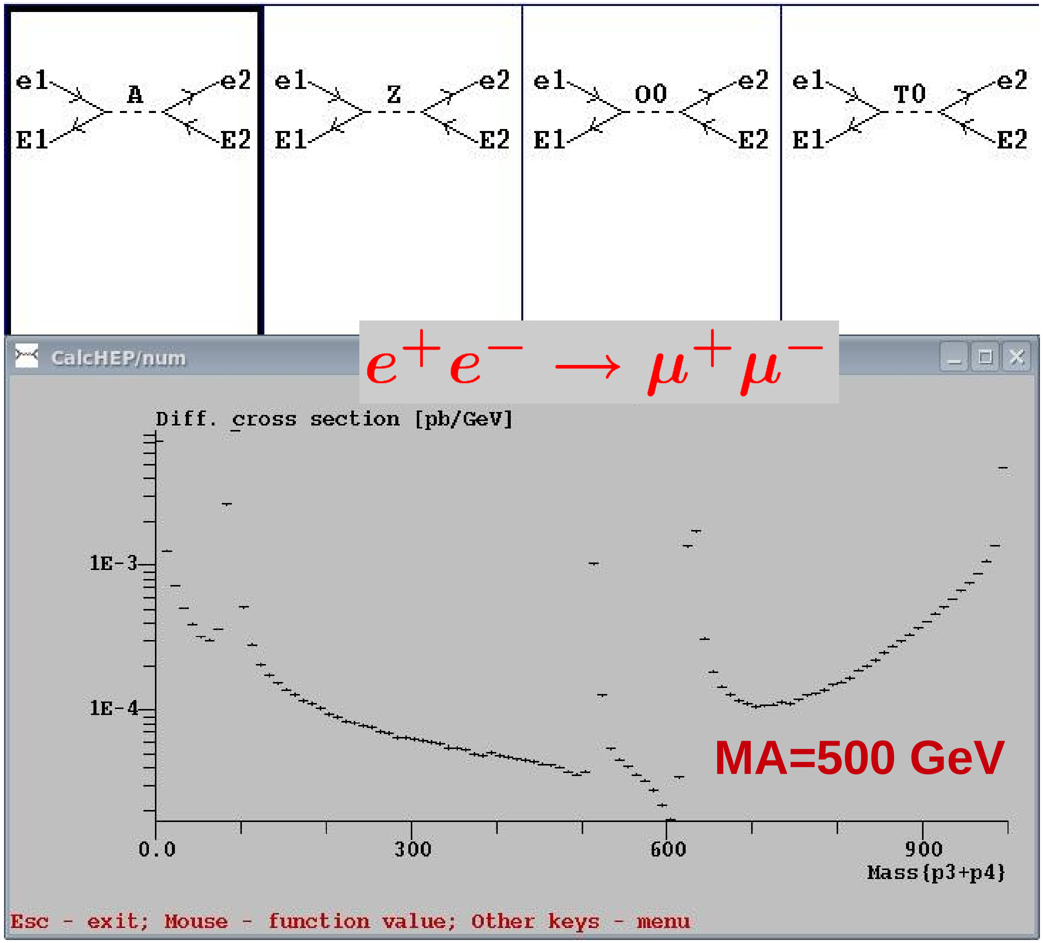
and

$R_1^0(R_2^0)$





ILC@1TeV
(work in progress)



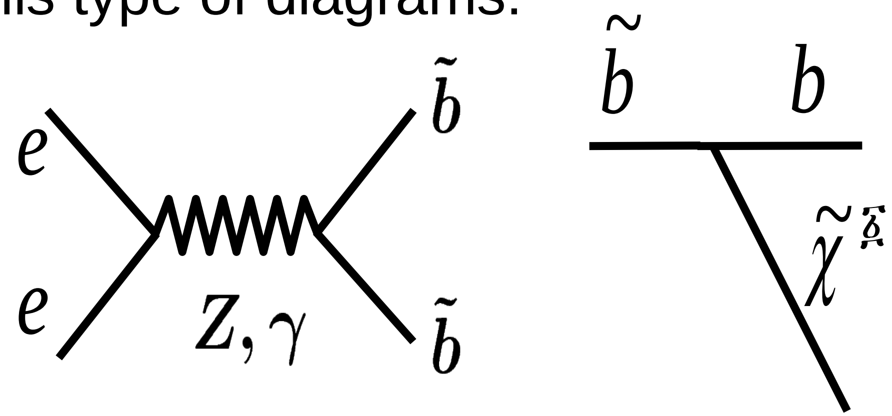
$e^+e^- \to \mu^+\mu^-$

MA=500 GeV

Recent applications:
sbottom coannihilation scenario at ILC

arXiv:0912.2411
AB, Nomerotski, Lastovicka, Medin Pukhov,

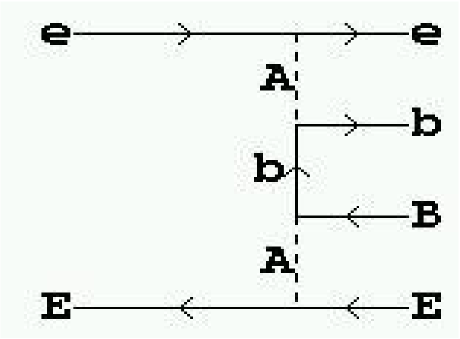
If sbottom and neutralino have a small mass split they can account for co-annihilation in early Universe through this type of diagrams:



the small mass split leads to very soft b-jets and missing p_T.

$$e^+e^- \to e^+e^-b\bar{b}$$

background process



one of 50 diagrams is regularized by non-zero electron mass the minimal $(p_1-p_3)^2$ is non zero and equal to

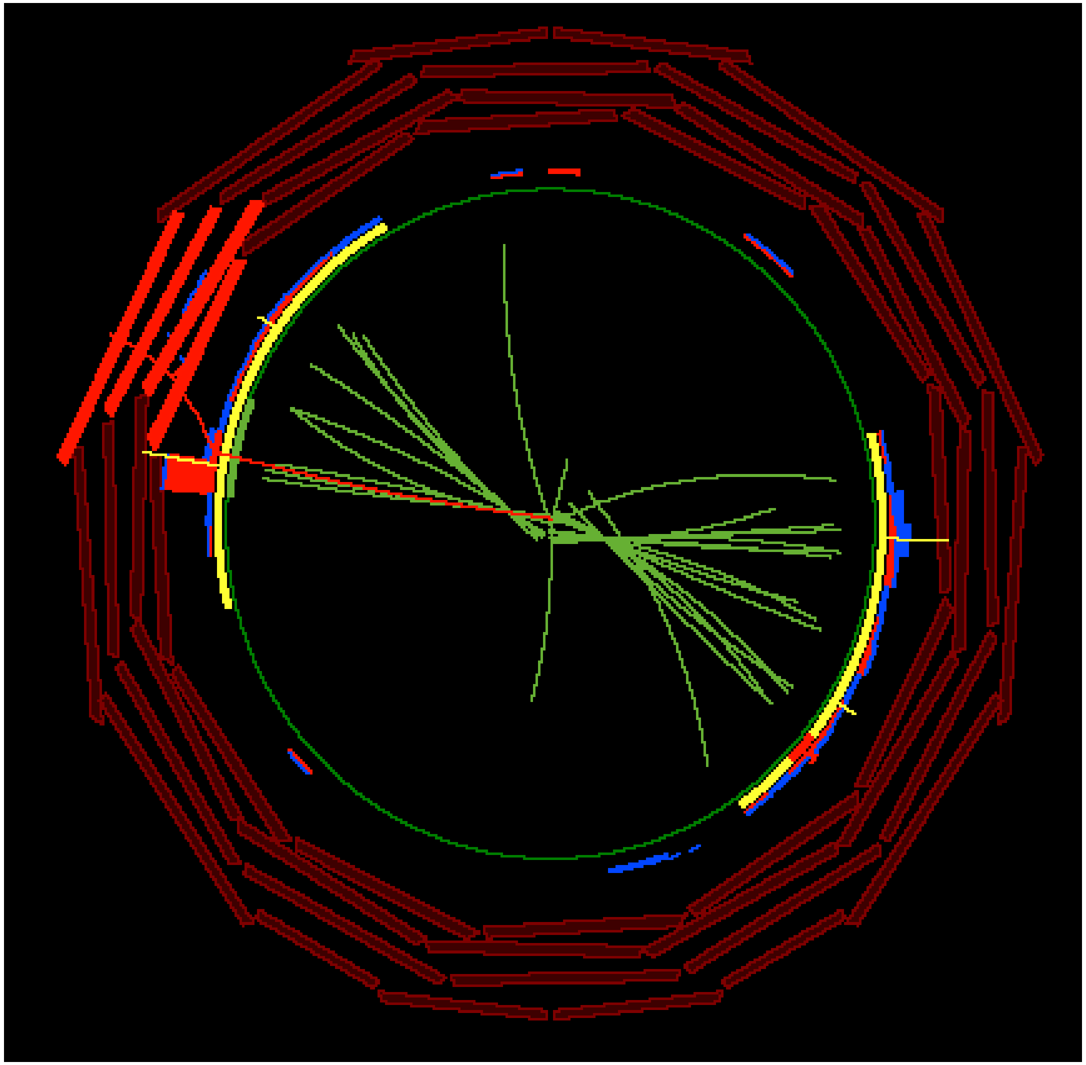
$$-m_e^2 \frac{(E_1 - E_3)^2}{E_1 E_3}$$

numerical cancellations are of the order of $m_e^4/E^4 \sim 10^{-30}$ and one

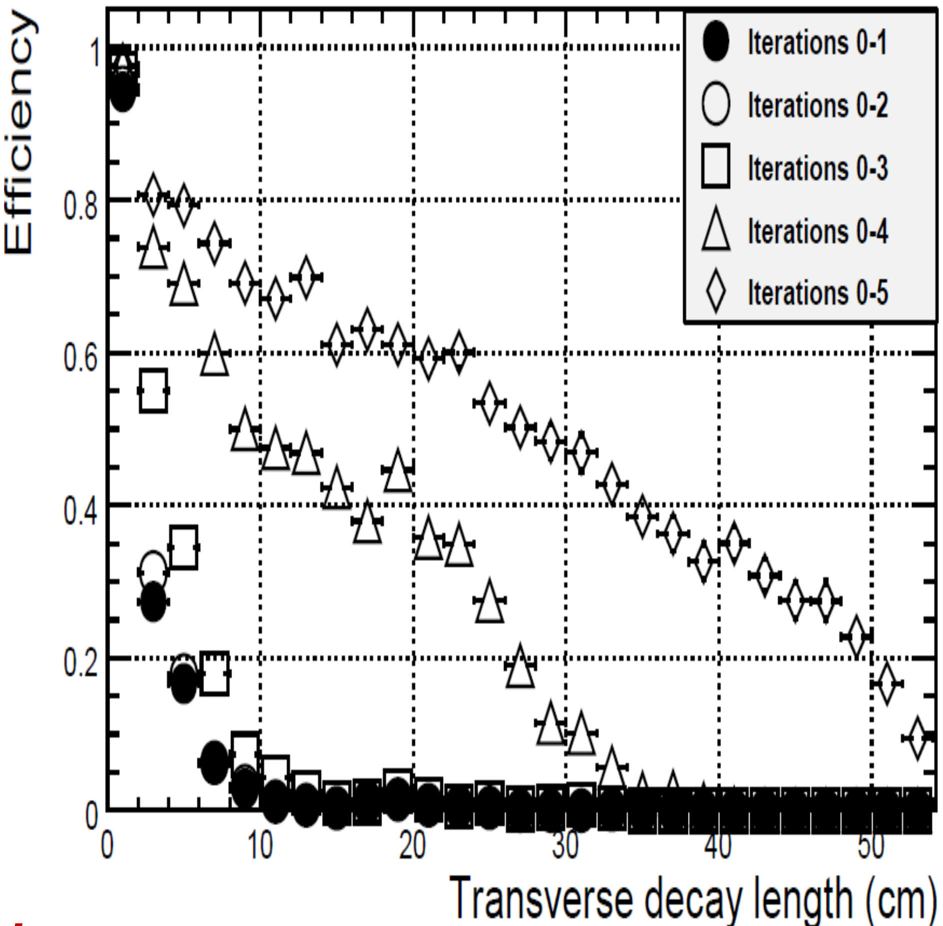
Ongoing project:

Study of long living heavy photons from Little Higgs Model with broken T-parity

In collaboration with Ian Tomalin and Arnaud Gay



Improved tracking efficiency

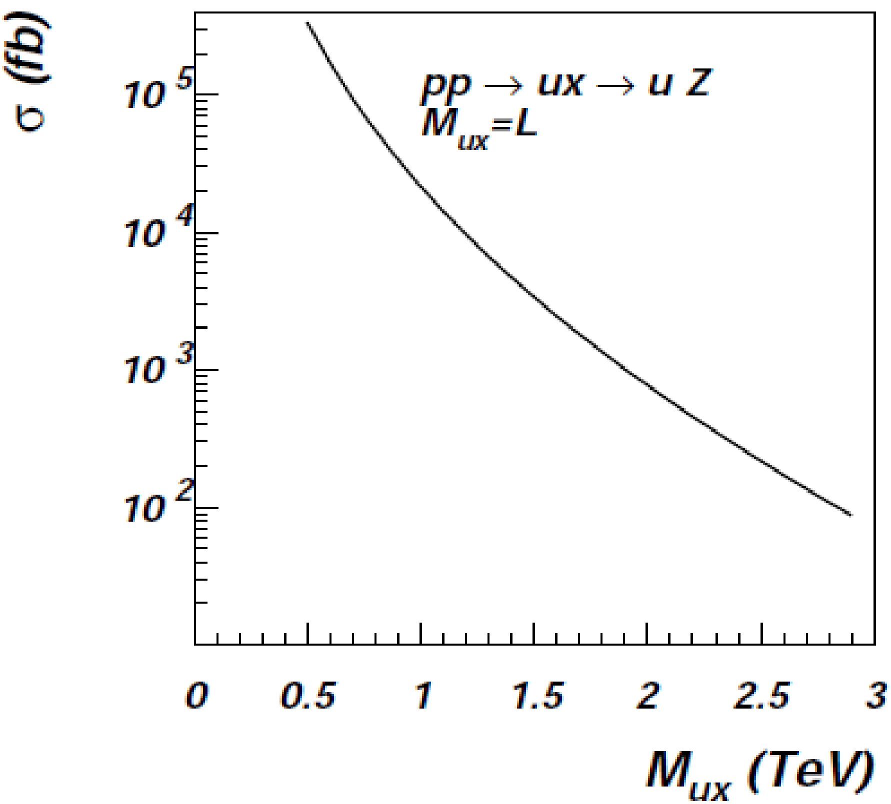


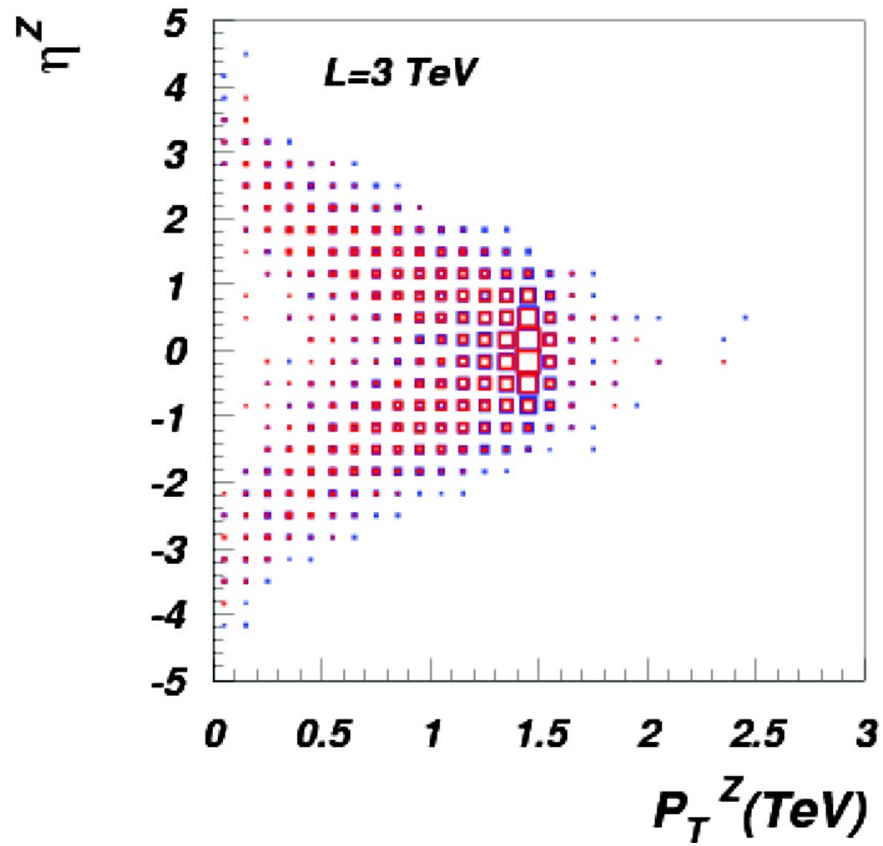
2 displaced vertices from 2 heavy photons decay

Ongoing project:
Boosted Z-bosons

In collaboration with James Jackson and Claire Shepherd-Themistocleous

Benchmark model:* *model with excited fermions with gauge interactions





- ***Motivated by several promising candidates for New Physics such as***
  - *SUSY (cascase squark and gluinos decays)*
  - *Technicolor (W' -> WZ decays)*
- ***Study of multiparticle final states should be performed for efficiency estimation***

Future plans for CalcHEP

- **Include polarization effects into production-decay chain**
- **QCD scale definition (leading diagram)**
- **polarization for massive particles**
- **implementation of jet matching algorithm**

Final remarks

- **Main features of CalcHEP**
  - ***easy model implementation (manual or with LanHEP/FeynRules)***
  - ***will work with* ANY GENERIC MODEL**
  - ***convenient interface***
  - ***batch mode + new gui version with "batch features" is coming***

- **Ready to be used by wide range of HEP community:**

  from model builders to experimentalists!

- **Any of you can start using CalcHEP with BSM models**

  and generate LHE events for LHC NOW!

- **Powerful tool which**

  should not be blindly trusted or blamed !