Collider phenomenology with CalcHEP

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Southampton University & Rutherford Appleton LAB

LC09

e+e- Physics at the TeV Scale and the Dark Matter Connection

Perugia, Italy,

21-24 September, 2009

OUTLINE

location of this talk

http://www.hep.phys.soton.ac.uk/~belyaev/proj/talks/lc09_belyaev.pdf

- **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 beyond the parton level MC generators**
- **Application of CalcHEP for SM and BSM at LHC/LC**

Practical points

- **The WEB page of CalcHEP**
  http://theory.npi.msu.su/~pukhov/calchep.html

- **e-mail for your questions/requests/remarks**
  calchep@googlegroups.com , a.belyaev@soton.ac.uk

- **exercises** **Exercise#xx**

  for those who wants to practice and start using CalcHEP rightaway

Introduction to CalcHEP

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

  (AB and Neil Christensen have joined the project in 2009)

- **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, ...***

Introduction to CalcHEP

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- **Analogous packages** **(matrix element generators)**

  http://www.ippp.dur.ac.uk/montecarlo/BSM/
  http://www-theory.lbl.gov/tools/
  - ***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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- **Tree-level processes**
- **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

Quick start with CalcHEP

practical notes on the installation: download code, read manual, compile

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 12 , 2009) • version 2.6.a (version under development)

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 with CalcHEP: 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)

Exercise#1: Install CalcHEP

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

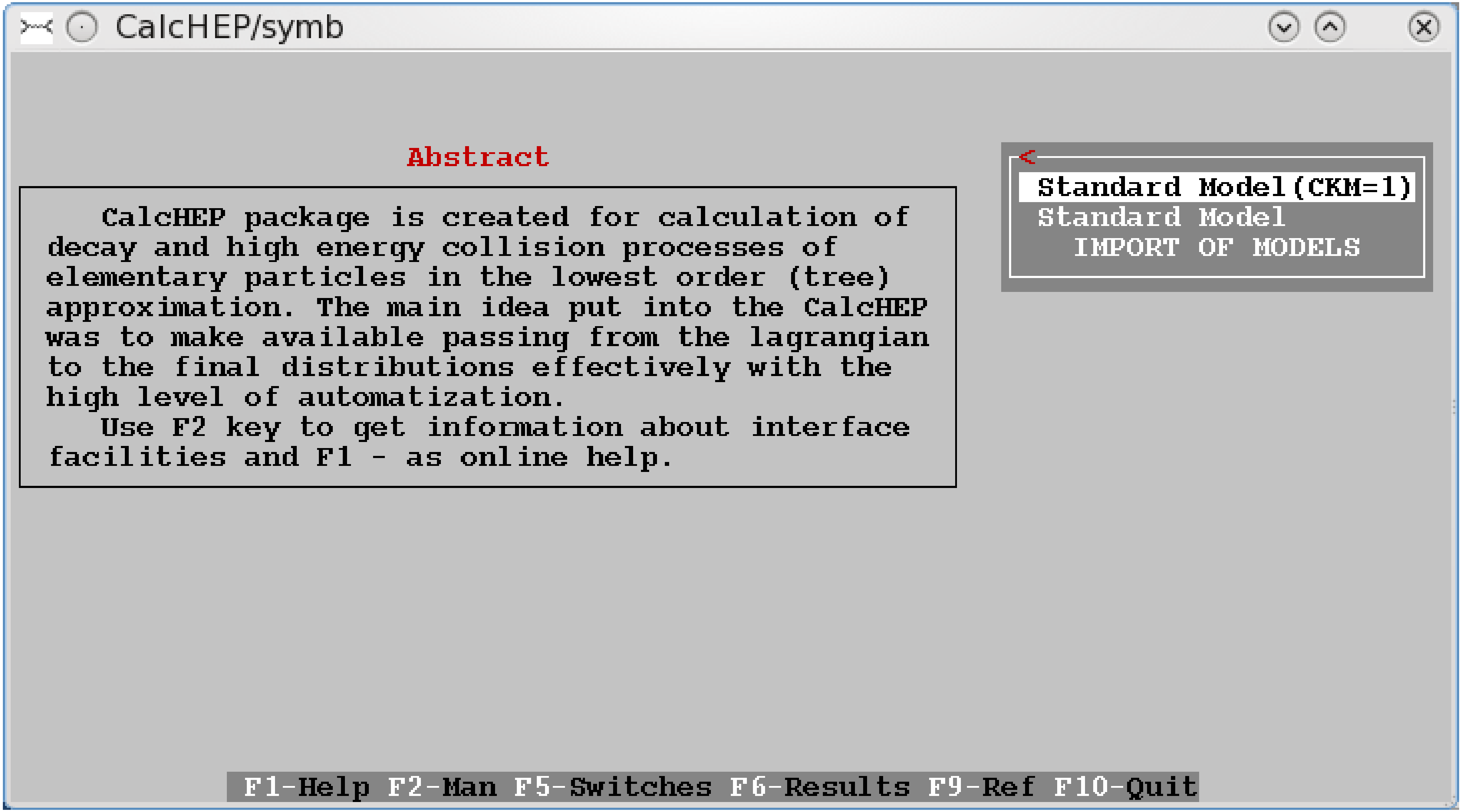
The package contains codes written by:
M.Donckt,V.Edneral,V.Ilyin,D.Kovalenko,A.Kryukov,G.Lepage,A.Semenov

Press F9 or click the box below to get

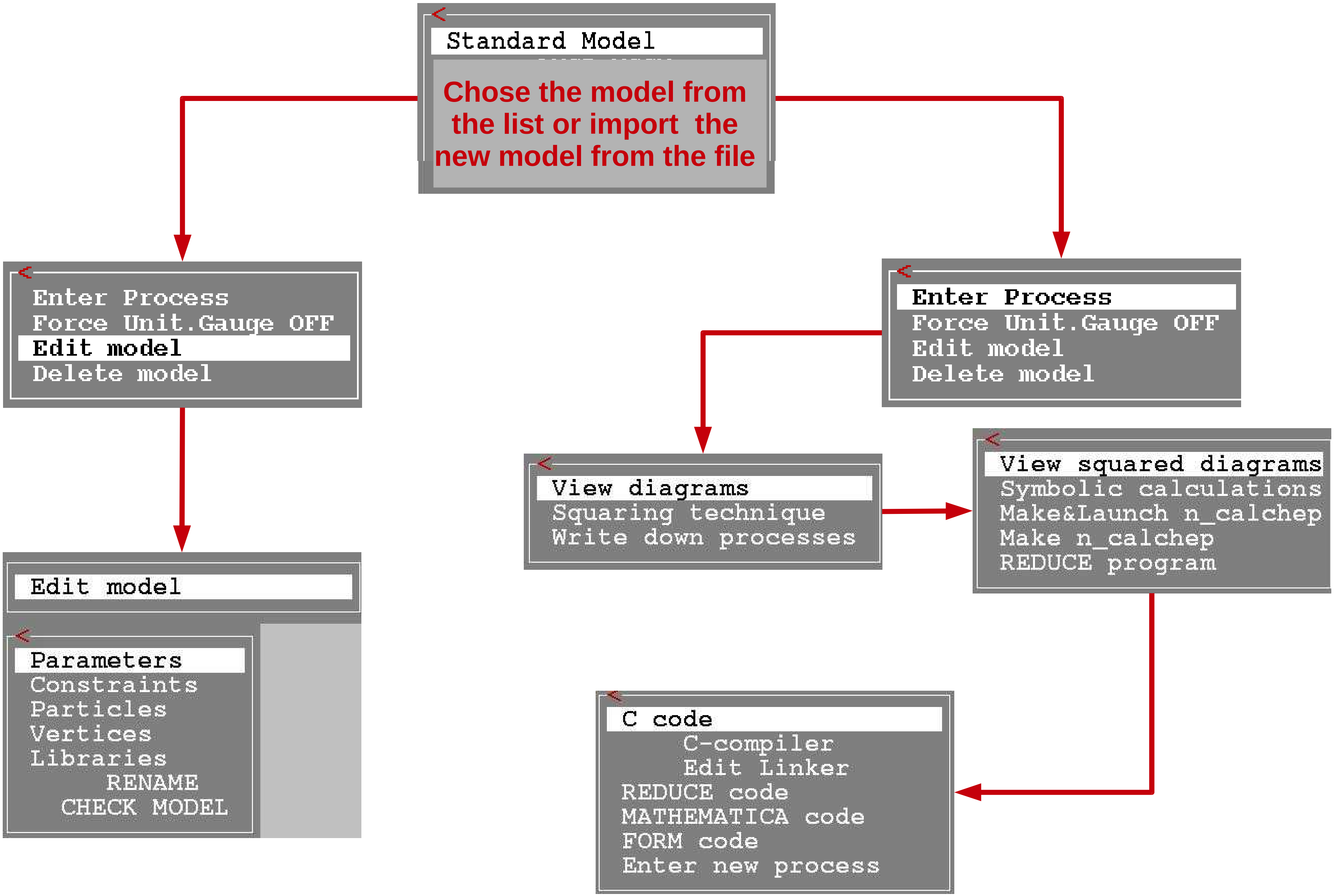
References and Contributions

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

Starting CalcHEP



CalcHEP menu structure: symbolic part



Model: 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}

F1-F2-Xgoto-Ygoto-Find-Write

Model: 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

Model: 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
```

Model: 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
```

Model: lgrng*xx*.mdl

CalcHEP/symb

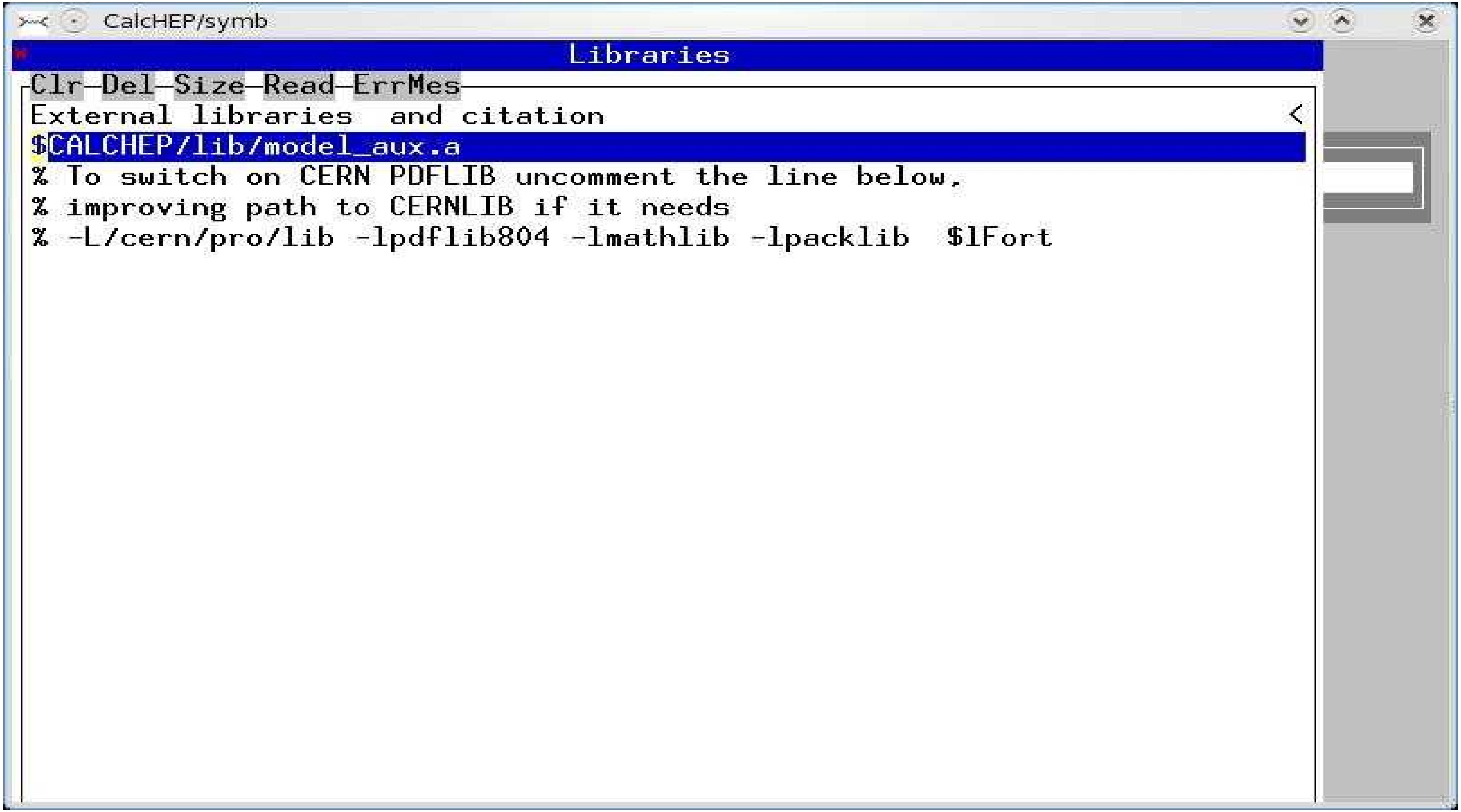
Vertices

Clr-Del-Size-Read-ErrMes

A1	A2	A3	A4	> Factor <|	> Lorentz part
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)
E	e	Z		-EE/(4*SW*CW)	G(m3)*(1-G5)-4*(SW^ 2)*G(m3)
M	m	Z		-EE/(4*SW*CW)	G(m3)*(1-G5)-4*(SW^ 2)*G(m3)
L	l	Z		-EE/(4*SW*CW)	G(m3)*(1-G5)-4*(SW^ 2)*G(m3)
Ne	ne	Z		EE/(4*SW*CW)	G(m3)*(1-G5)

F1-F2-Xgoto-Ygoto-Find-Write

Model: extlib*xx*.mdl



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

Exercise#2
calculate SM Higgs boson Decay width and branching ratios as a function of Higgs boson mass

Principle KEYS for CalcHEP's GUI

Enter menu
selection
(forward)

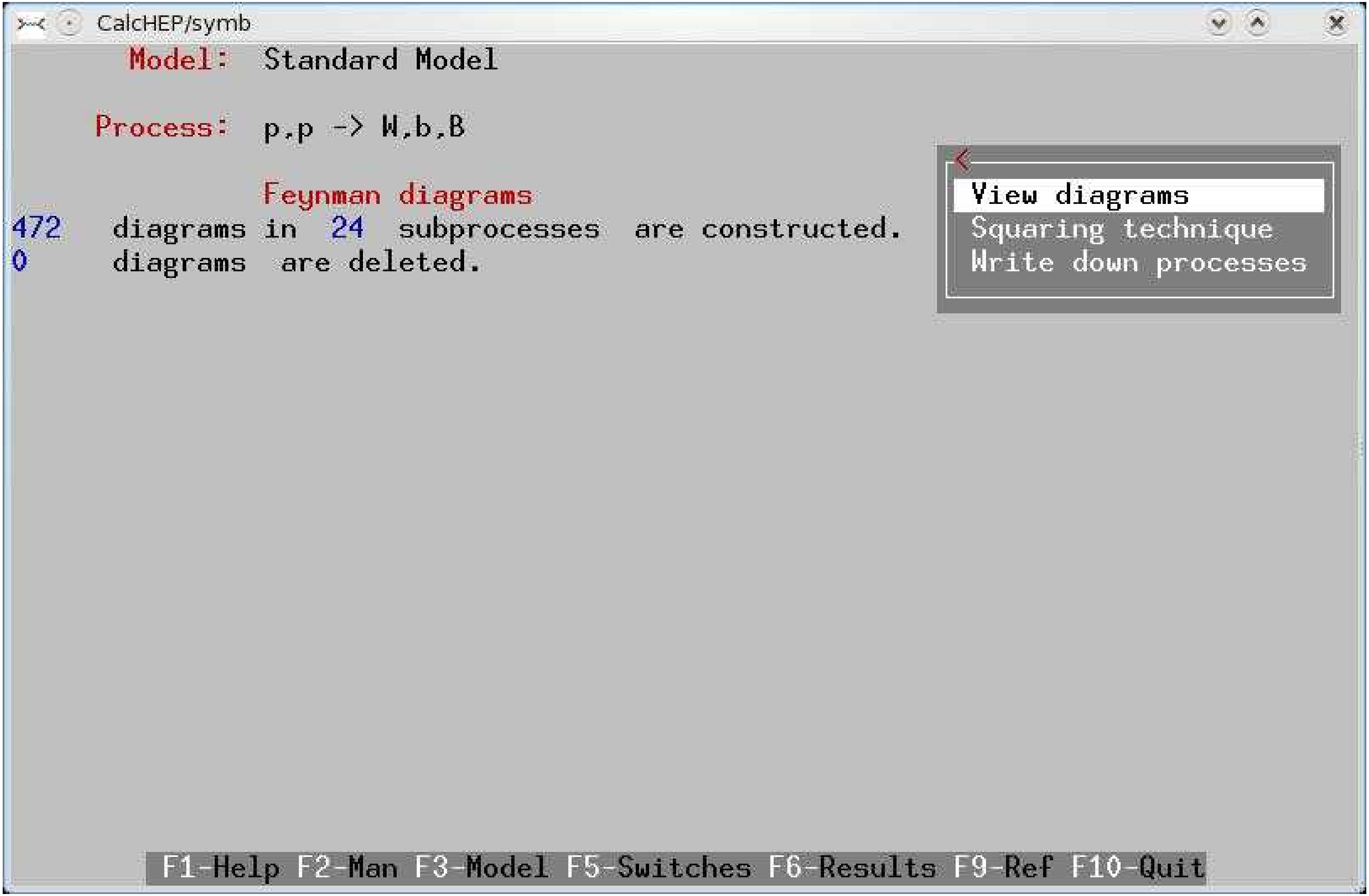
Exit menu
selection
(back)

Help!
(details on the
menu choice)

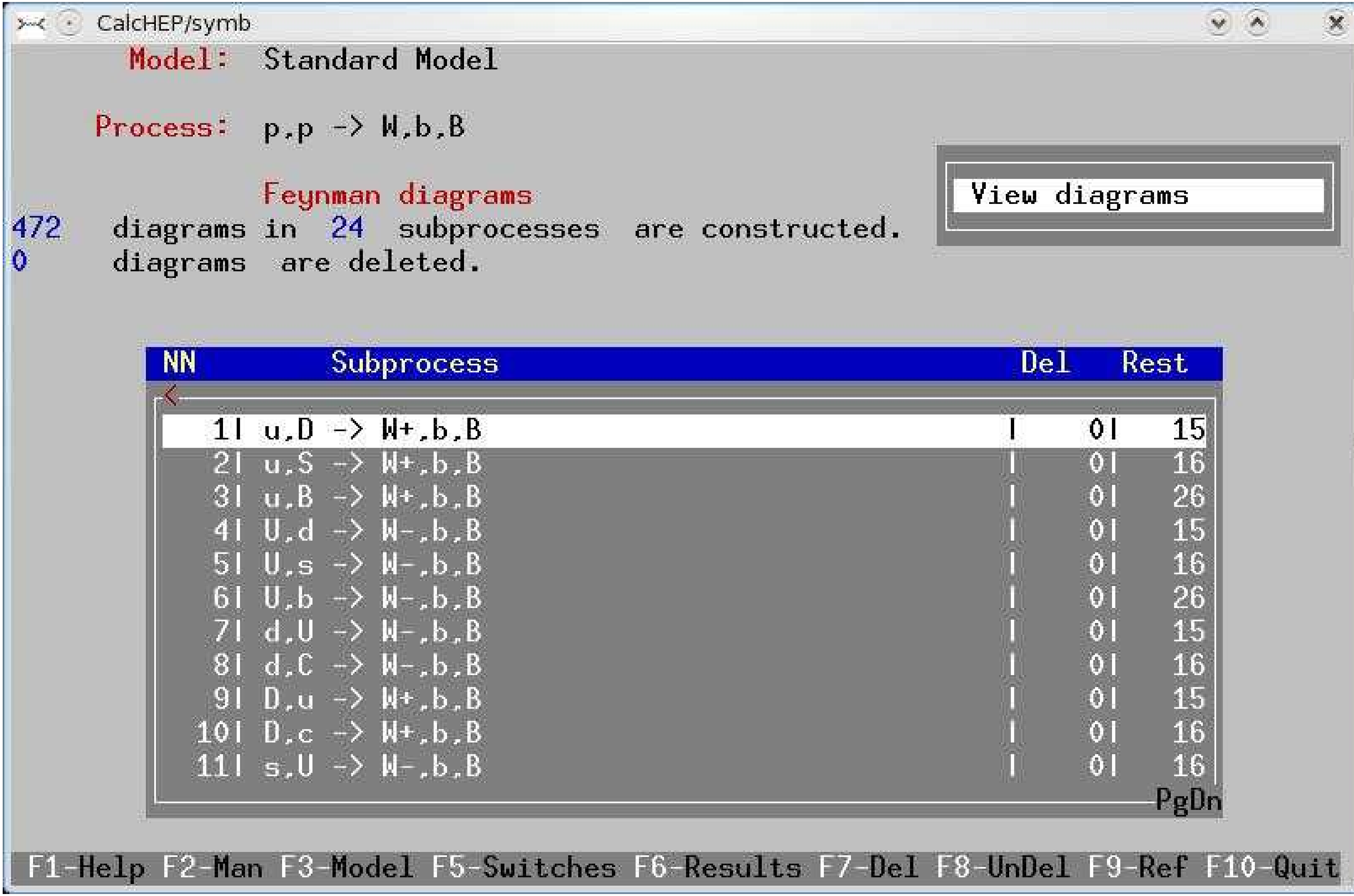
Example of the symbolic calculation

```
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
```

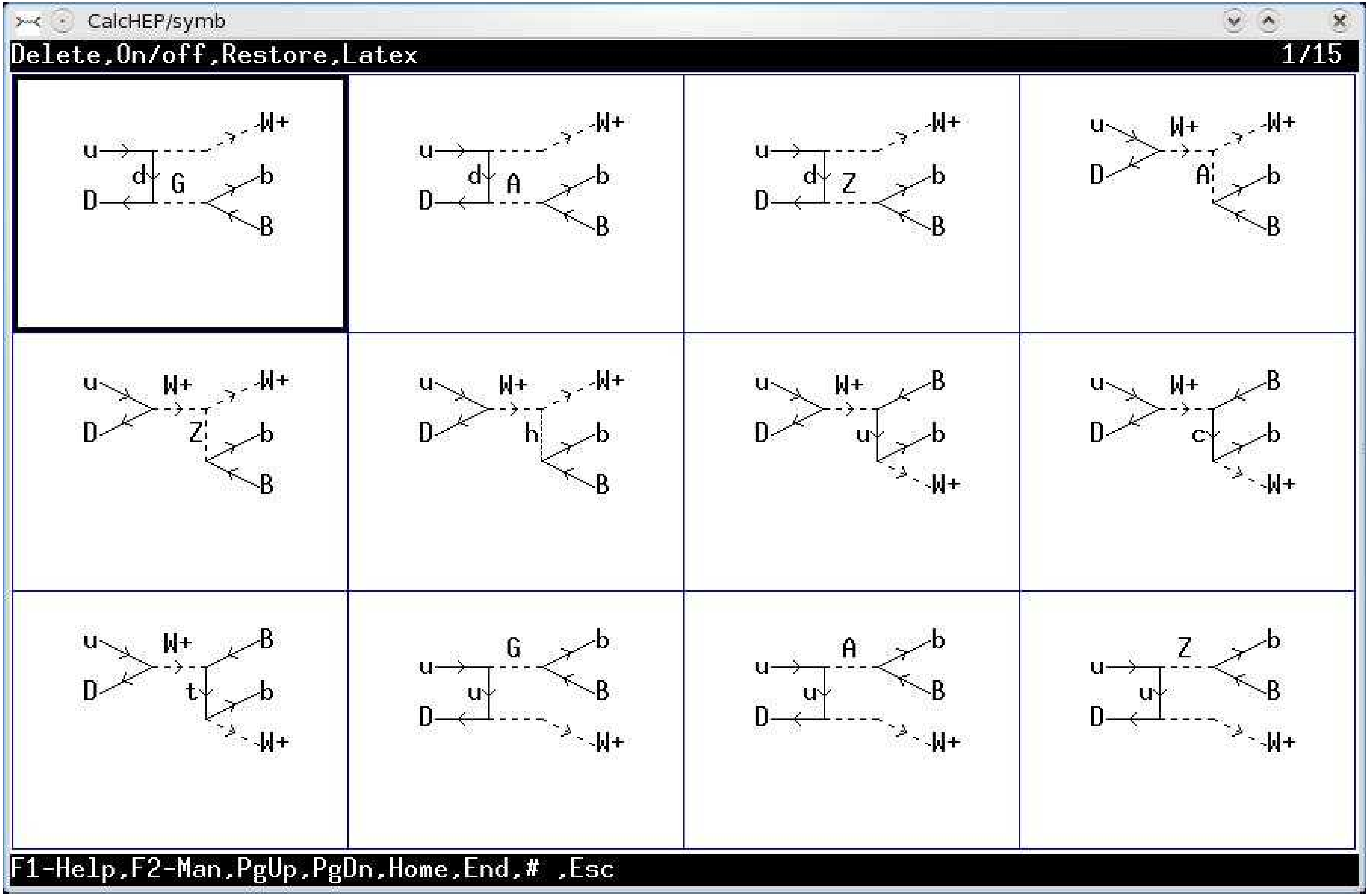
Example of the symbolic calculation



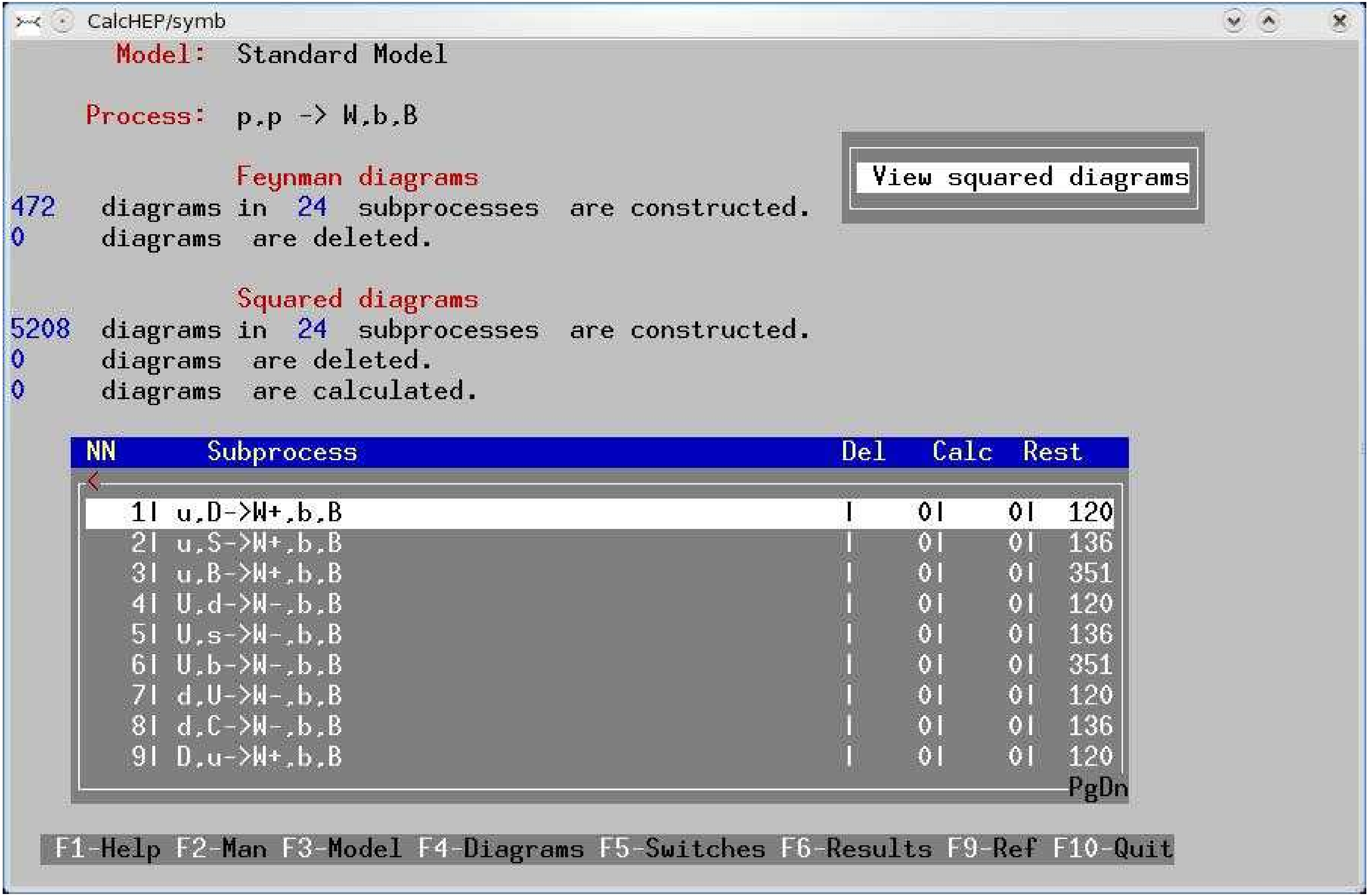
Example of the symbolic calculation



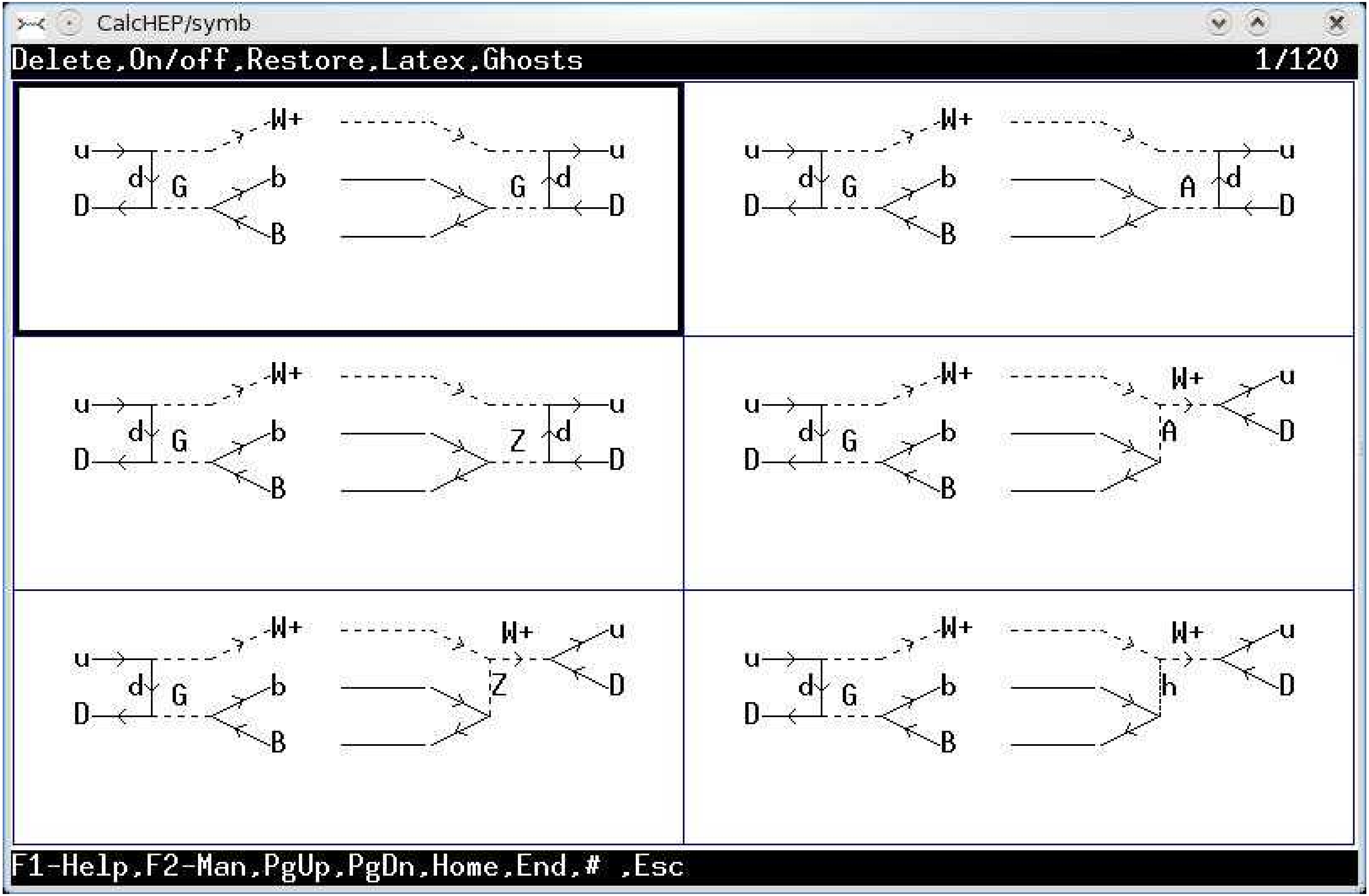
Example of the symbolic calculation



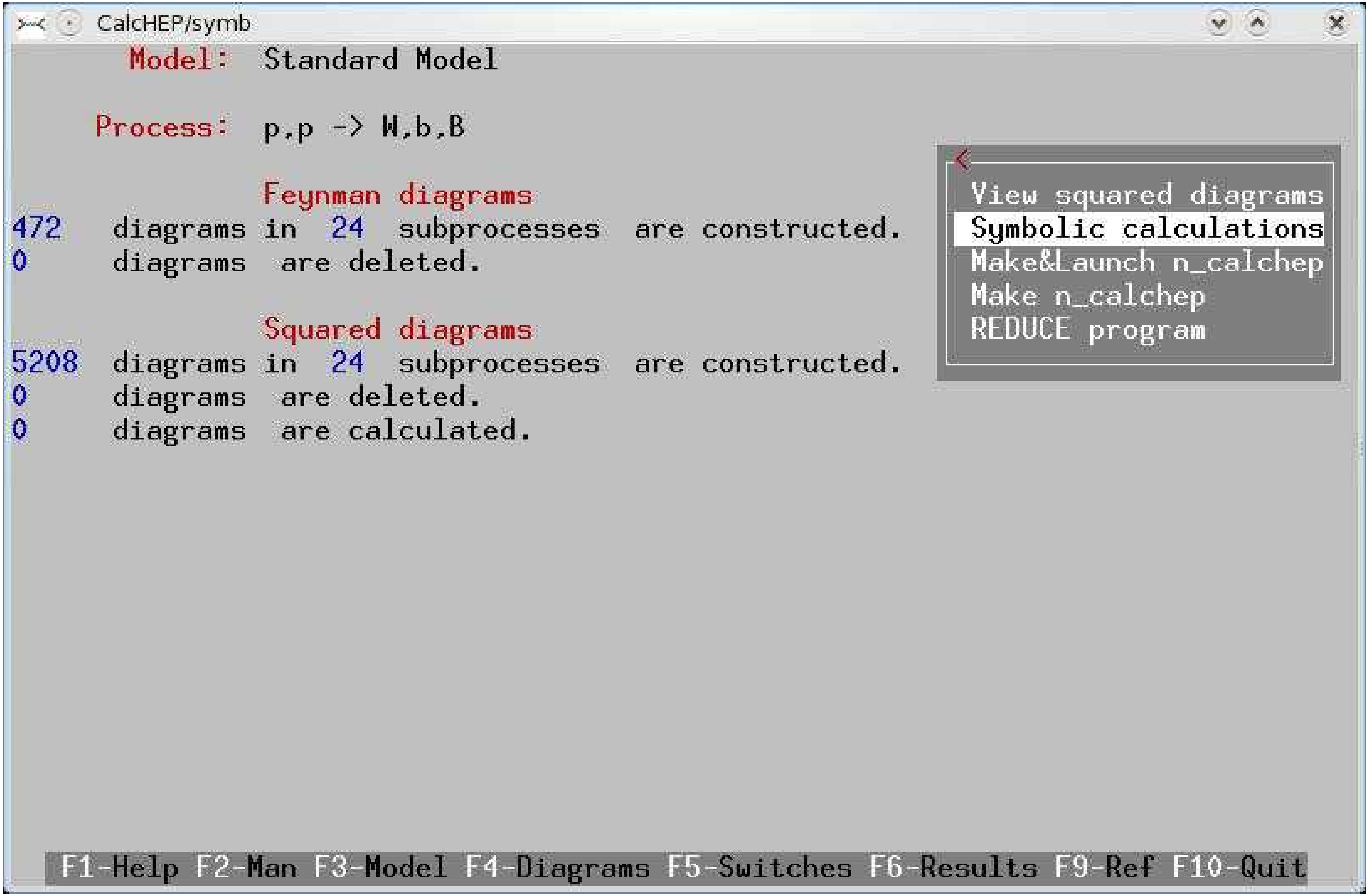
Example of the symbolic calculation



Example of the symbolic calculation



Example of the symbolic calculation



Example of the symbolic calculation

```
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.
5208   diagrams  are calculated.
0      Out of memory

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

```
C code
    C-compiler
    Edit Linker
REDUCE code
MATHEMATICA code
FORM code
Enter new process
```

Example of the symbolic calculation

```
CalcHEP/symb

     Model:  Standard Model

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

             Feynman diagrams
472   diagrams in  24  subprocesses  are constructed.
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C code
     C-compiler
     Edit Linker
REDUCE code
MATHEMATICA code
FORM code
Enter new process

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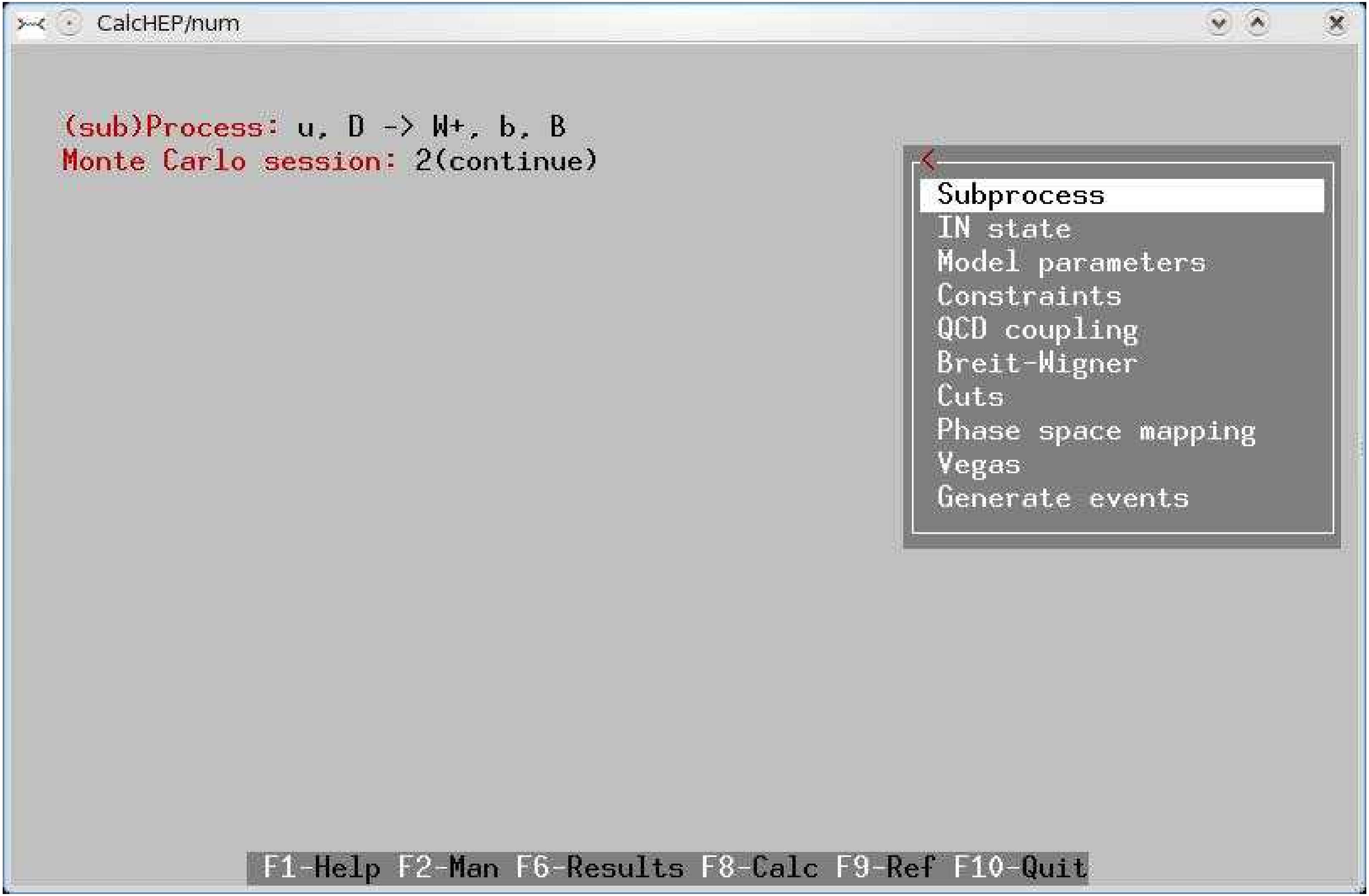

Numerical part of CalcHEP



subprocess menu

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

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

control of the initial states and PDFs: LHC case

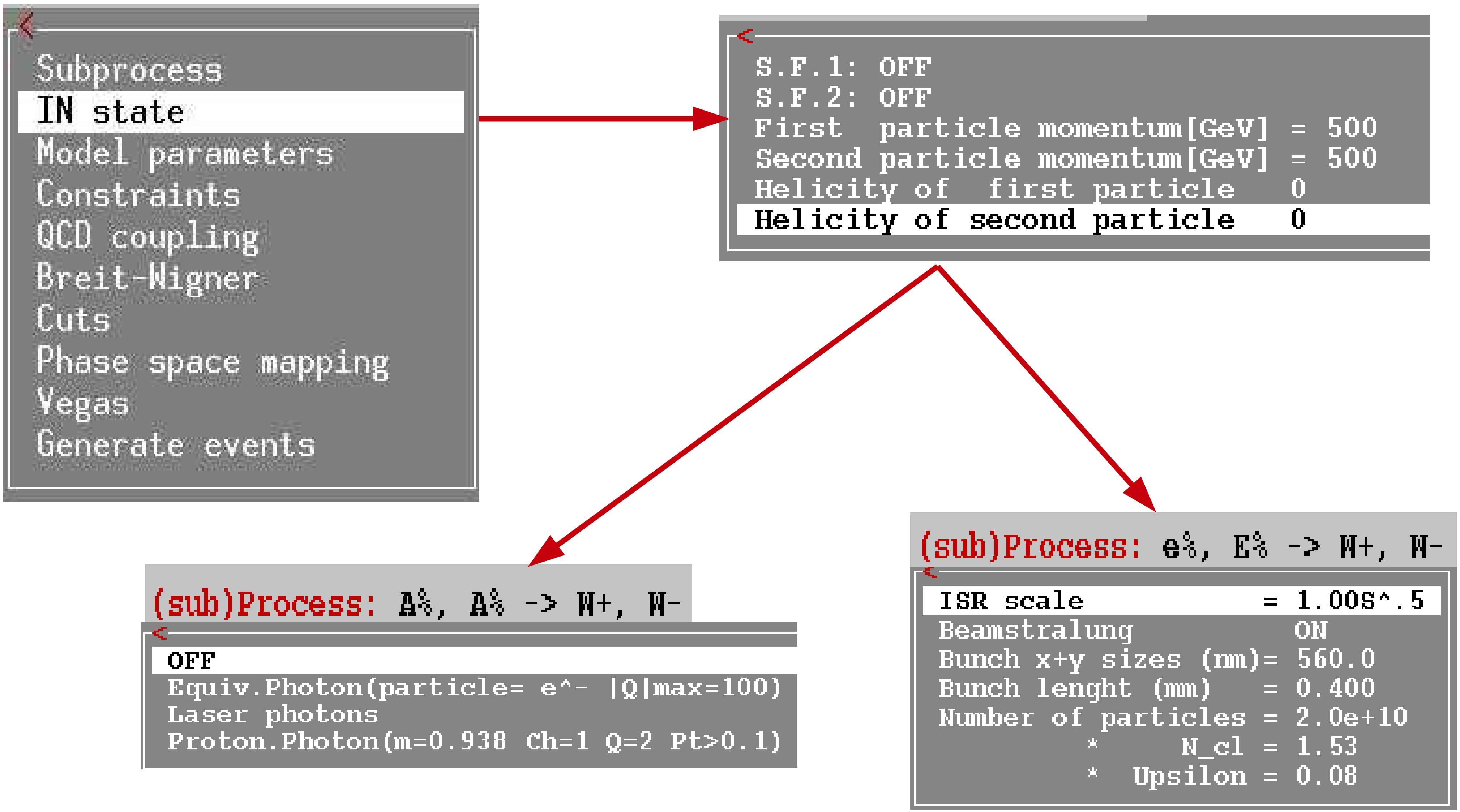
```
Subprocess
IN state
Model parameters
Constraints
QCD coupling
Breit-Wigner
Cuts
Phase space mapping
Vegas
Generate events
```

```
S.F.1: OFF
S.F.2: OFF
First  particle momentum[GeV] = 7000
Second particle momentum[GeV] = 7000
First  particle unpolarized
Second particle unpolarized
```

```
PDT:cteq6m(anti-proton)
PDT:cteq6m(proton)
PDT:cteq6l(anti-proton)
PDT:cteq6l(proton)
PDT:CTEQ5M(anti-proton)
PDT:CTEQ5M(proton)
PDT:mrst2002nlo(anti-proton)
PDT:mrst2002nlo(proton)
PDT:mrst2002lo(anti-proton)
PDT:mrst2002lo(proton)
```

```
S.F.1: PDT:cteq6m(proton)
S.F.2: OFF
First  particle momentum[GeV] = 7000
Second particle momentum[GeV] = 7000
First  particle unpolarized
Second particle unpolarized
```

control of the initial states and PDFs: ILC case

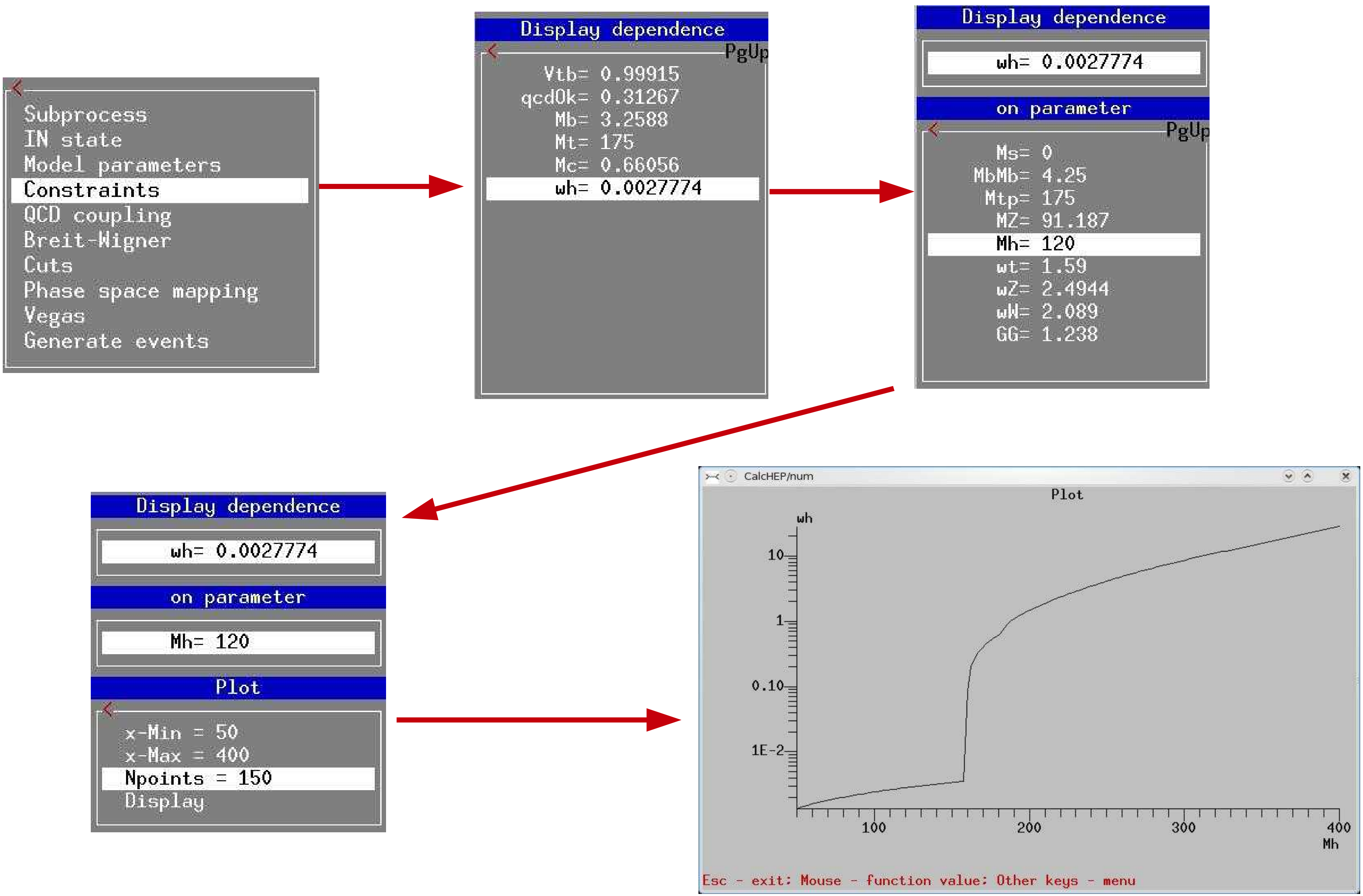


model parameters

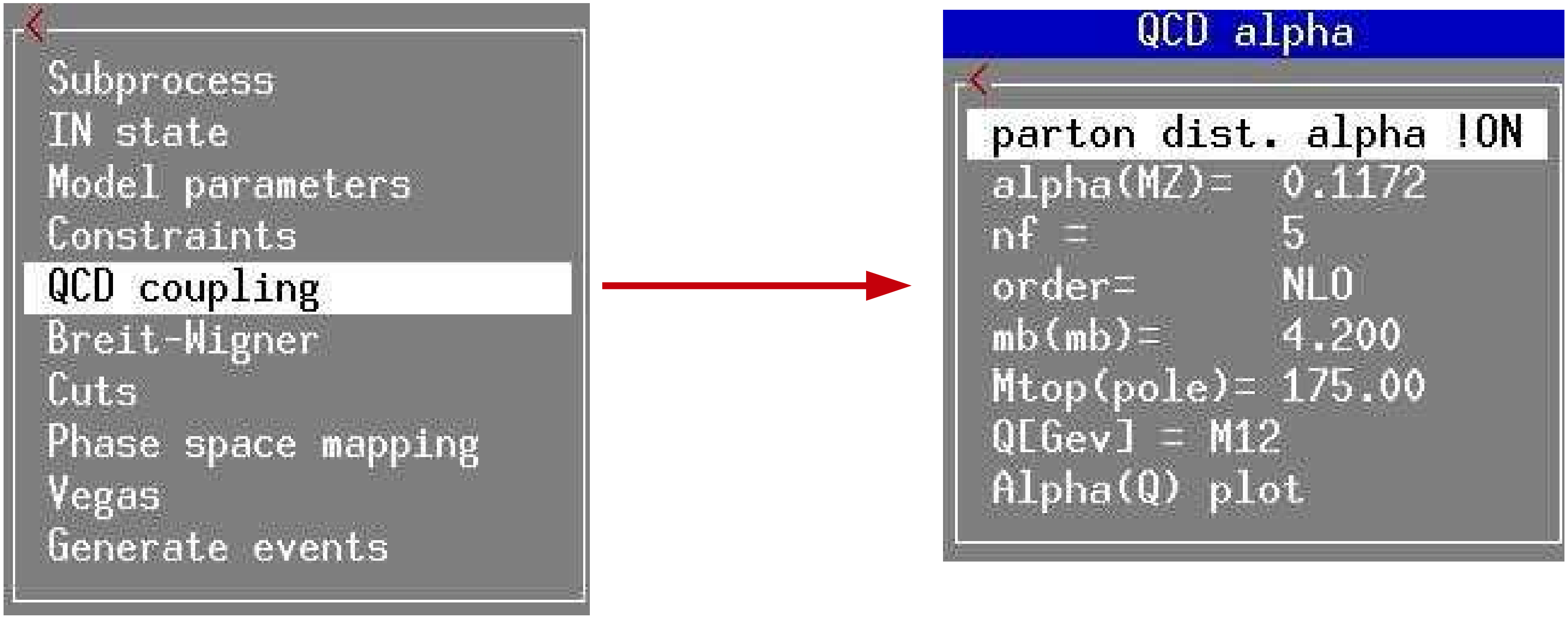
```
Subprocess
IN state
Model parameters
Constraints
QCD coupling
Breit-Wigner
Cuts
Phase space mapping
Vegas
Generate events
```

```
alfEMZ= 0.0078181
alfSMZ= 0.1172
     Q= 100
    SW= 0.481
   s12= 0.221
   s23= 0.041
   s13= 0.0035
    Mm= 0.1057
    Ml= 1.777
  McMc= 1.2
    Ms= 0
  MbMb= 4.25
   Mtp= 175
    MZ= 91.187
    Mh= 120
                PgDn
```

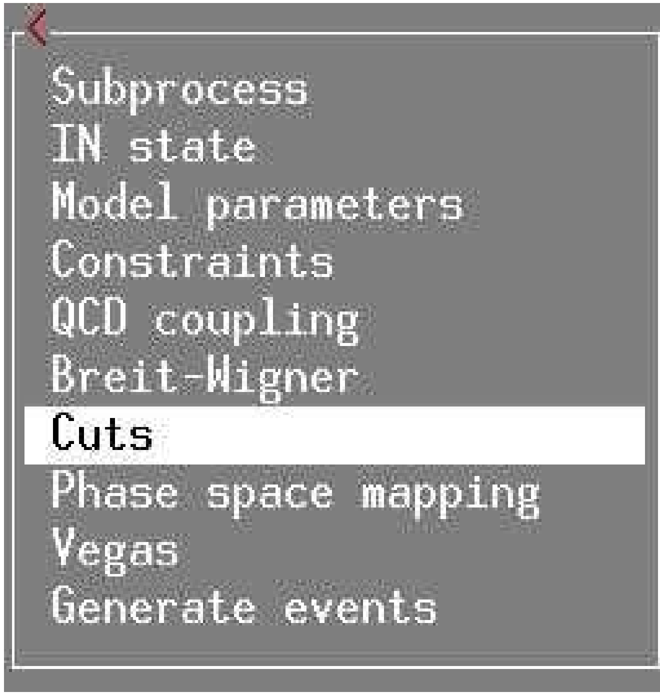
dependent parameters



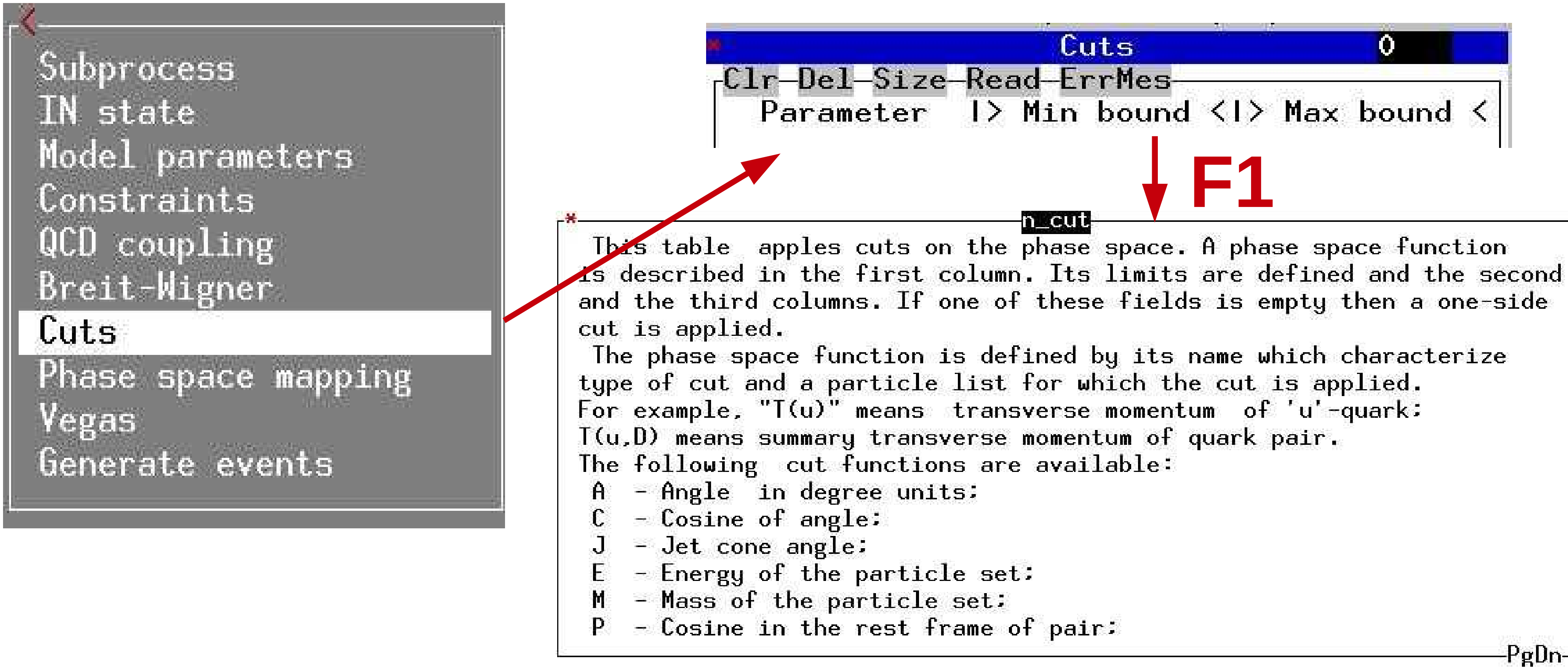
QCD coupling and the scale



setting kinematical cuts



setting kinematical cuts



setting kinematical cuts

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

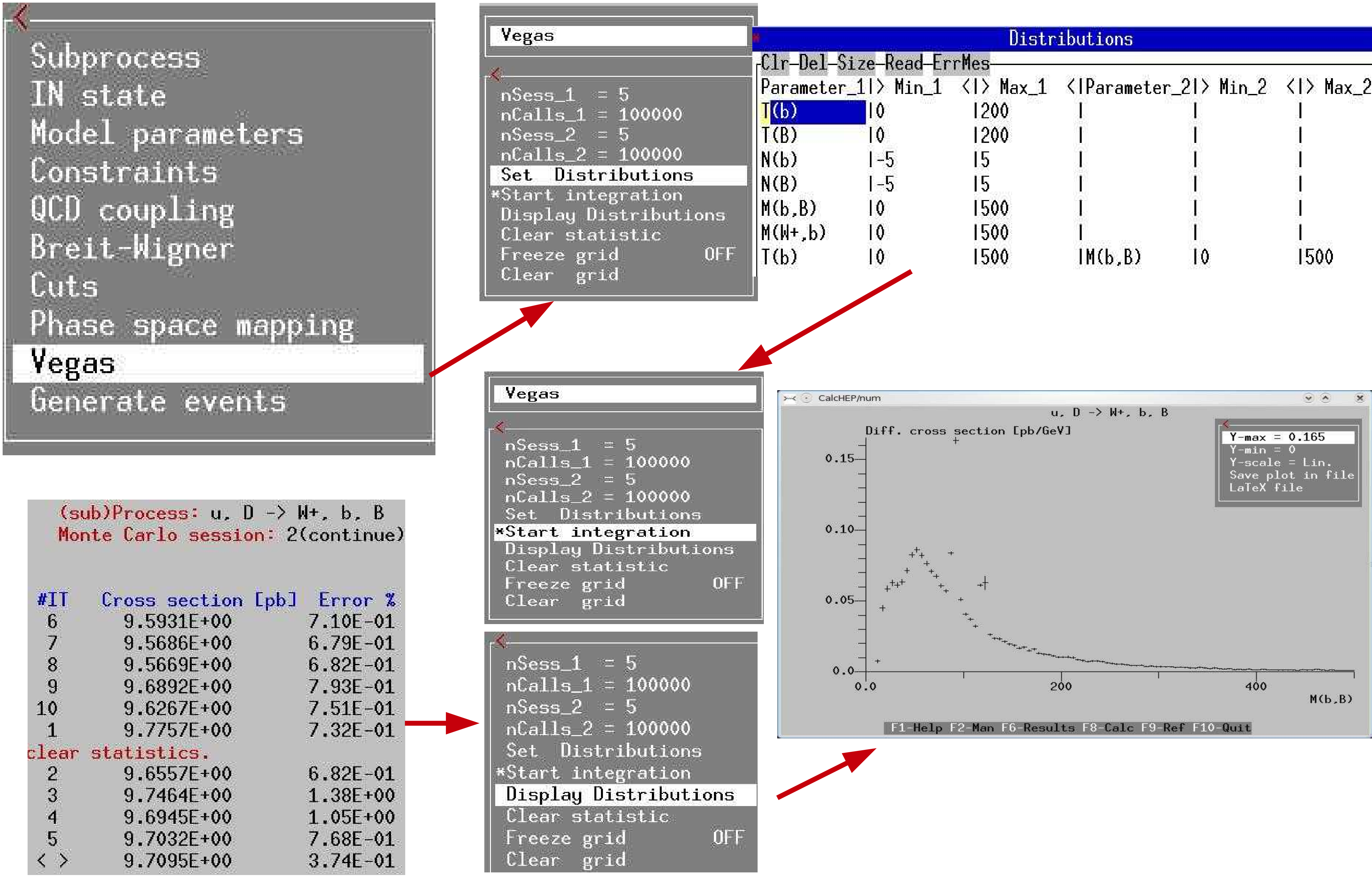
```
                    Cuts                      0
Clr Del Size Read ErrMes
   Parameter    |> Min bound <|> Max bound <
```

F1

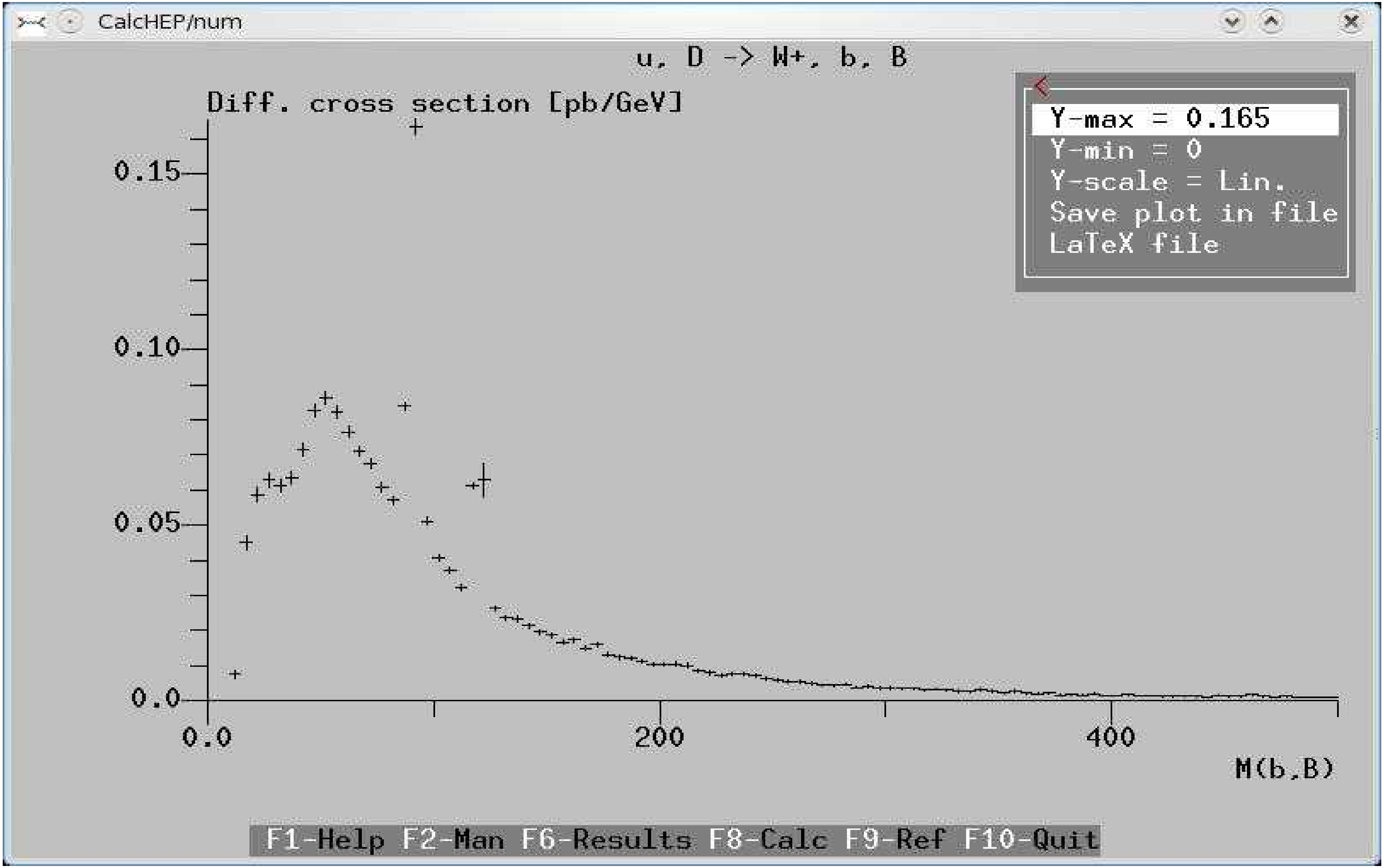
```
n_cut
 This table  apples cuts on the phase space. A phase space function
is described in the first column. Its limits are defined and the second
and the third columns. If one of these fields is empty then a one-side
cut is applied.
 The phase space function is defined by its name which characterize
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         |
```

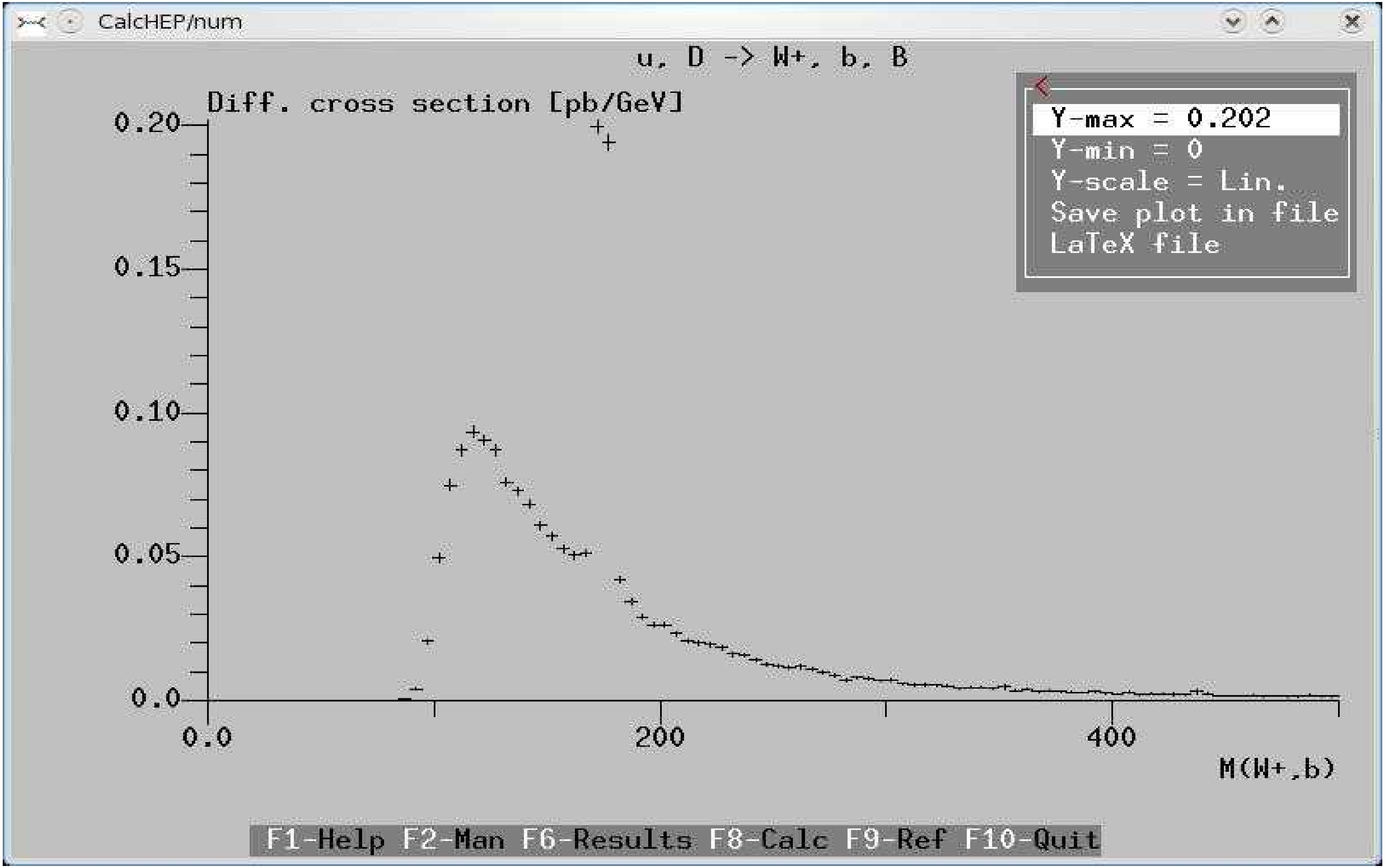
integration over the phase space



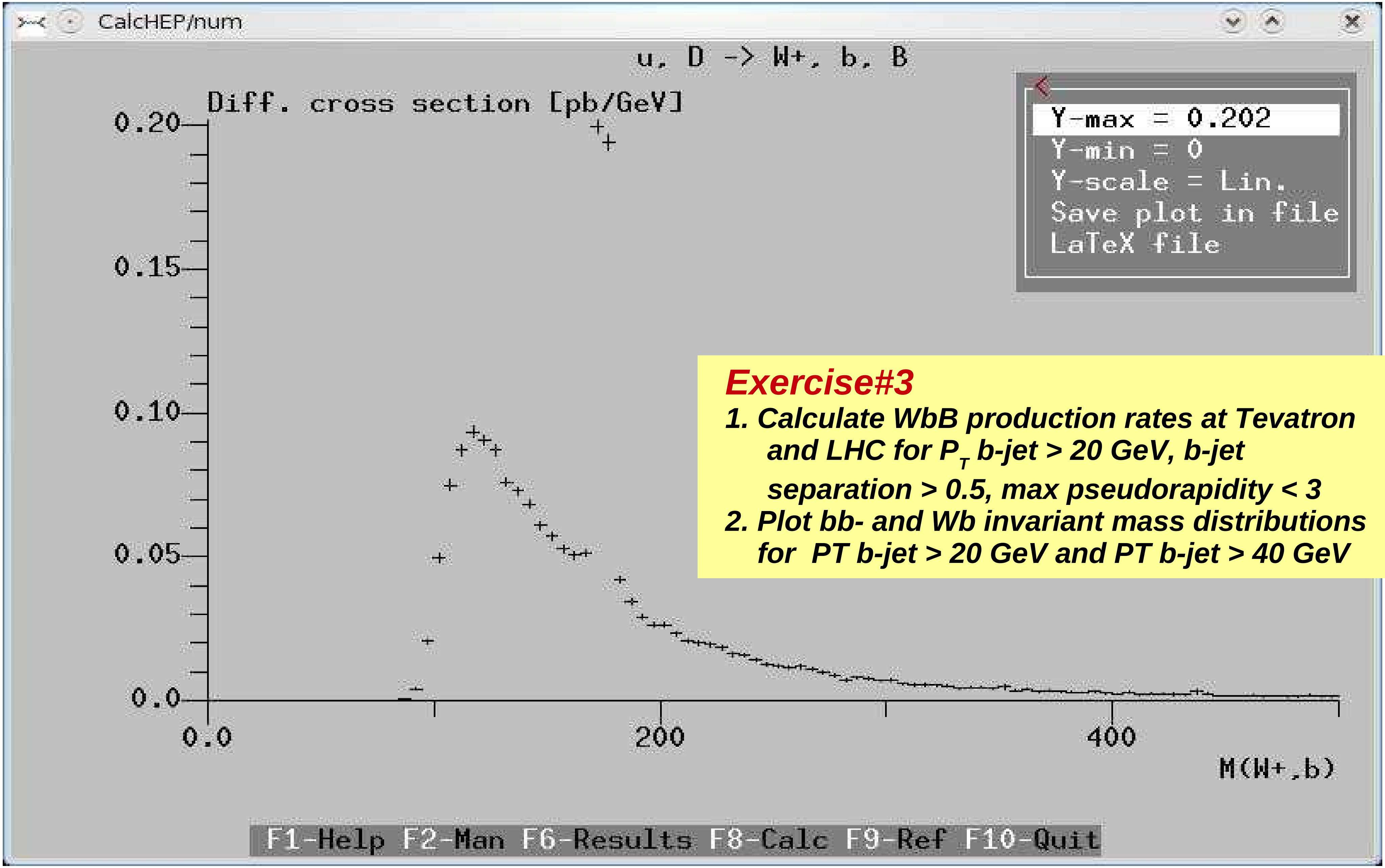
Resulting M_{bb} kinematical distribution



Resulting M_{Wb} kinematical distribution



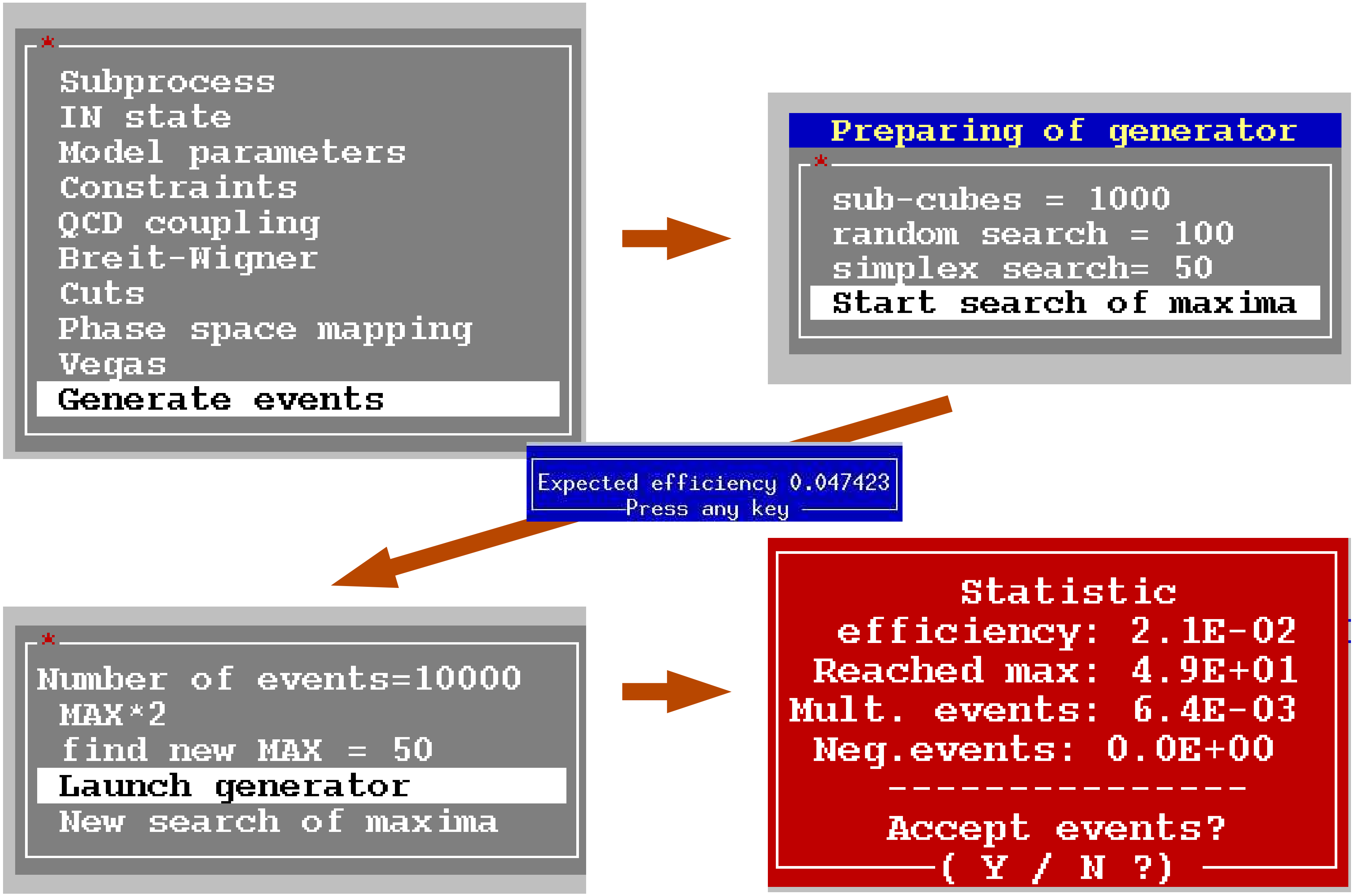
Resulting M_{Wb} kinematical distribution



Exercise#3

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

generation of events



Useful scripts

GUI gives user a full control of details of symbolic/numerical session. Is there automation of calculation involving many sub-processes?

- ***cycle over subprocesses***
  - ***exit from the numerical session***
  - **cd results**
  - **../bin/subproc_cycle** ***lumi nmax***

requires 2 parameters:

1. luminosity

2. max number of events per process

e.g.

../bin/subproc_cycle 1000 100000

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
............................................
............................................
```

Introduction to LanHEP package

- **Andrei Semenov: V3.0, arXiv:0805.0555**

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

This is 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.
```

Introduction to LanHEP package

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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, ...

LanHEP installation

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

tar -zxvf lhep*xxx*.tar.gz

cd lhep*xxx*

make

make clean

> ***Exercise#4***
> *install LanHEP*

Running LanHEP

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

File sm_tex processed, 0 sec.

File stand.mdl processed, 1 sec.

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

- **Yuakawa 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* term from scalar supersymmetric potential**

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

in LanHEP notation will take a form

```
lterm - df(W,H1)*df(Wc,H1c) - ....
```

where Wc should be decleared above as the conjugate superpotential

FF* term can be introduced even in shorter way as

```
lterm - dfdfc(W,H1) - ....
```

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

CalcHEP interface with MC generators via events in Les Houches accord format (LHE)

Specialized Generator

$\Longrightarrow$ Hard Process

↓

Les Houches Interface

↓

HERWIG or PYTHIA

- (Resonance Decays)
- Parton Showers
- Underlying Event
- Hadronization
- Ordinary Decays

↓

Some Specialized Generators:

- AcerMC: $t\bar{t}b\bar{b}, \ldots$
- ALPGEN: $W/Z+ \leq 6j$, $nW + mZ + kH + \leq 3j, \ldots$
- AMEGIC++: generic LO
- CompHEP: generic LO
- GRACE+Bases/Spring: generic LO+ some NLO loops
- GR@PPA: $b\bar{b}b\bar{b}$
- MadCUP: $W/Z+ \leq 3j, t\bar{t}b\bar{b}$
- MadGraph+HELAS: generic LO
- MCFM: NLO $W/Z+ \leq 2j$, $WZ, WH, H+ \leq 1j$
- O'Mega+WHIZARD: generic LO
- VECBOS: $W/Z+ \leq 4j$

Apologies for all unlisted programs

Events generation with CalcHEP

- **format of the event_nn.txt files**

```
#CalcHEP version 2.5.1
#Type 2 -> 3
#Initial_state
  P1_3=7.000000E+03  P2_3=-7.000000E+03
  StrFun1="PDT:cteq6m(proton)" 2212
  StrFun2="PDT:cteq6m(proton)" 2212
#PROCESS   2(u) -5(B) -> 24(W+) 5(b) -5(B)
#MASSES  0.0000000000E+00 3.2588068426E+00 7.9945520808E+01 3.2588068426E+00 3.2
#Cross_section(Width) 2.276199E-04
#Number_of_events          0
#Events        P1_3 [Gev]        P2_3 [Gev]        P3_1 [Gev]        P3_2 [Gev]
       1   1.7923832011E+03 -6.8581781926E+00  1.3284736587E+01  2.9090505045E+0
       1   1.3346128427E+03 -6.4780880073E+01  1.6367502247E+01  2.8018282294E+0
```

- **the idea is to generate events for production and decay process and connect them together into LHE file**

Events generation with CalcHEP

```
~/proj/intro_to_hep_tools/calc_work_2.5.4/pp_wbb_ckm1>
../bin/subproc_cycle 1000 1000
#Subprocess 1 ( u, D -> W+, b, B ) Cross section = 9.7505E+00 , 1000 events
#Subprocess 2 ( U, d -> W-, b, B ) Cross section = 5.5019E+00 , 1000 events
#Subprocess 3 ( d, U -> W-, b, B ) Cross section = 5.5315E+00 , 1000 events
#Subprocess 4 ( D, u -> W+, b, B ) Cross section = 9.7105E+00 , 1000 events
#Subprocess 5 ( s, C -> W-, b, B ) Cross section = 1.5902E+00 , 1000 events
#Subprocess 6 ( S, c -> W+, b, B ) Cross section = 1.3525E+00 , 1000 events
#Subprocess 7 ( c, S -> W+, b, B ) Cross section = 1.3425E+00 , 1000 events
#Subprocess 8 ( C, s -> W-, b, B ) Cross section = 1.5716E+00 , 1000 events
Sum of distributions is stored in file distr_34_41
Total Cross Section 36.3512 [pb]

~/proj/intro_to_hep_tools/calc_work_2.5.4/w_decay>
../bin/subproc_cycle 1000
width(W+)=0.67001
#Subprocess 1 ( W+ -> E, ne ) width=2.2339E-01 Br=0.3334129341 Nevents= 334
#Subprocess 2 ( W+ -> M, nm ) width=2.2339E-01 Br=0.3334129341 Nevents= 334
#Subprocess 3 ( W+ -> L, nl ) width=2.2323E-01 Br=0.3331741317 Nevents= 334
width(W-)=0.67001
#Subprocess 4 ( W- -> e, Ne ) width=2.2339E-01 Br=0.3334129341 Nevents= 334
#Subprocess 5 ( W- -> m, Nm ) width=2.2339E-01 Br=0.3334129341 Nevents= 334
#Subprocess 6 ( W- -> l, Nl ) width=2.2323E-01 Br=0.3331741317 Nevents= 334
```

- Dirs are accessible at

http://www.hep.phys.soton.ac.uk/~belyaev/proj/intro_to_hep_tools/

Events generation with CalcHEP

- **bin/event_mixer nevents event_dirs**

mixes subprocesses and connects scattering and decay events

```
bin/event_mixer 1000 pp_wbb_ckm1 w_decay
total cross section 1.166E+01
Max number of events 3728
```

- **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   1
</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>
```

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

Home
Symbolic Results
Numerical Results
Events Library
Process Library
Help

Thank you for using CalcHEP!
Please cite arXiv:0000.0000

Symbolic Sessions

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
Symbolic Results
Numerical Results
Events Library
Process Library
Help

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 0.14	50000

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!

Home
Symbolic Results
Numerical Results
Events Library
Process Library
Help

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		

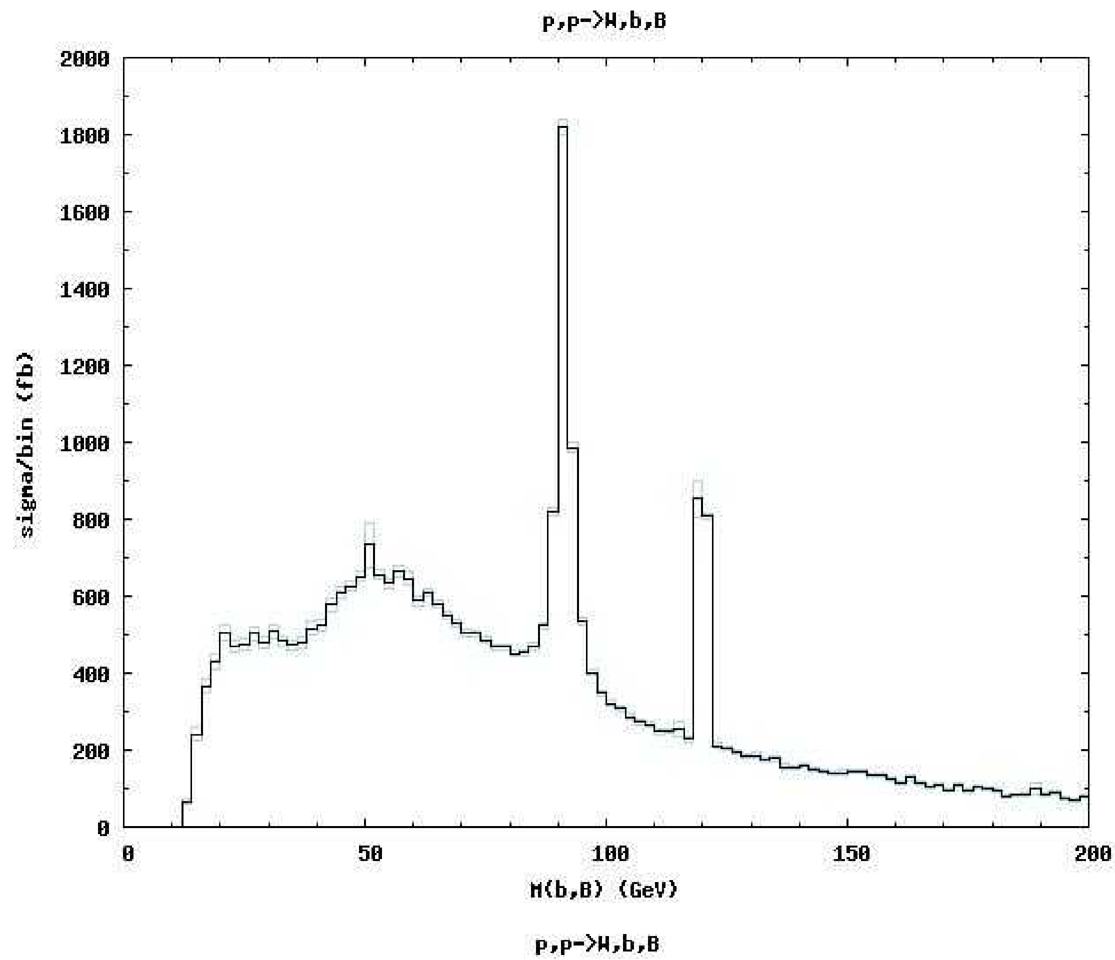
CalcHEP batch interface: results from CalcHEP in one shot

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

Distributions

Home
Symbolic Results
Numerical Results
Events Library
Process Library
Help

Thank you for using CalcHEP!
Please cite arXiv:0000.0000

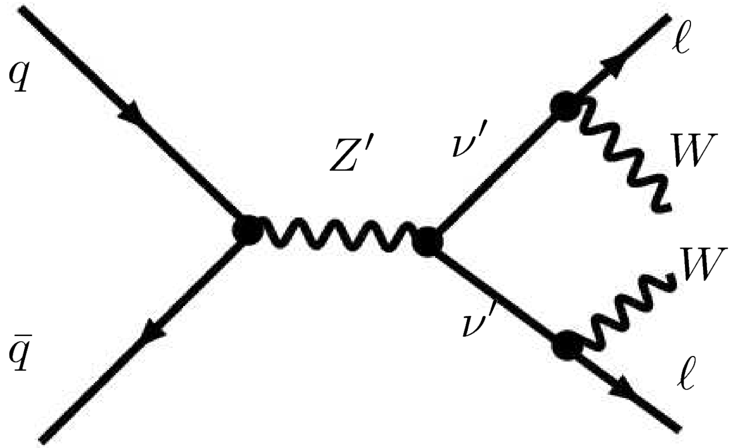


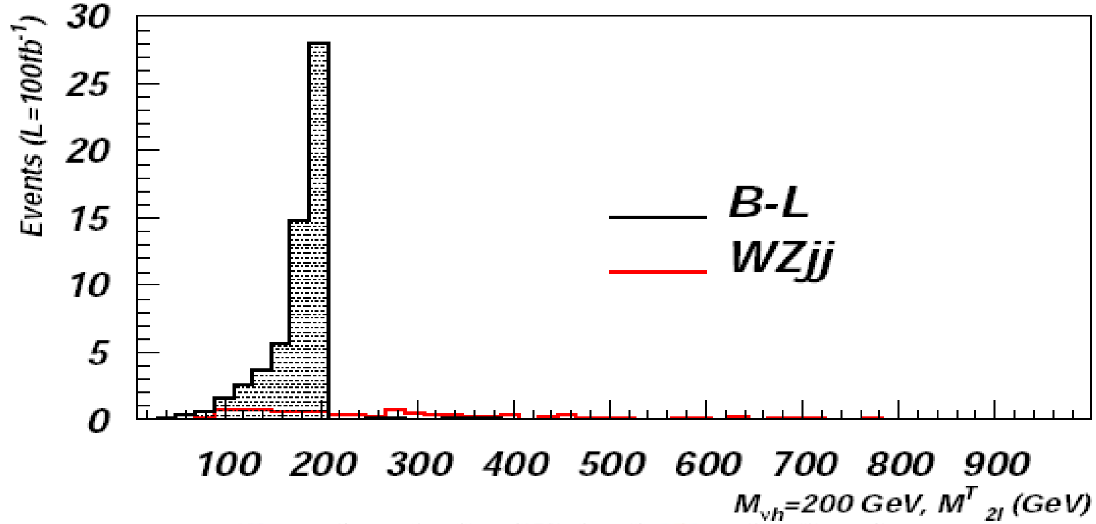
Recent applications: B-L extension of SM [see M. Pruna's talk]

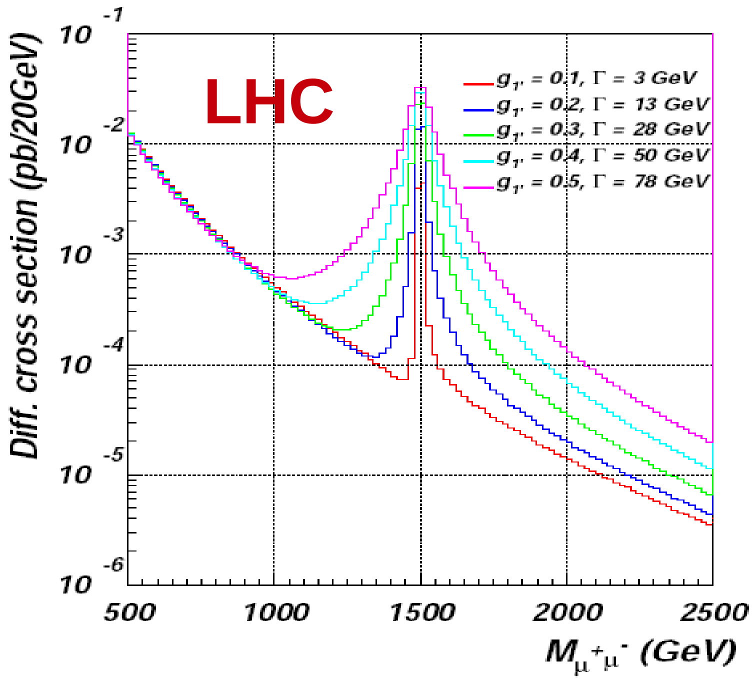
Extra U(1)' : Z', heavy long leaving neutrino

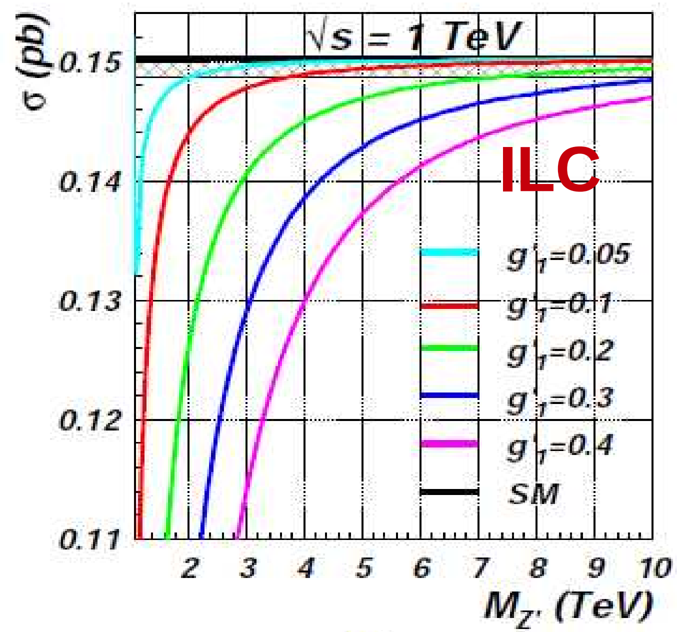
arXiv:0812.4313
arXiv:0903.4777

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









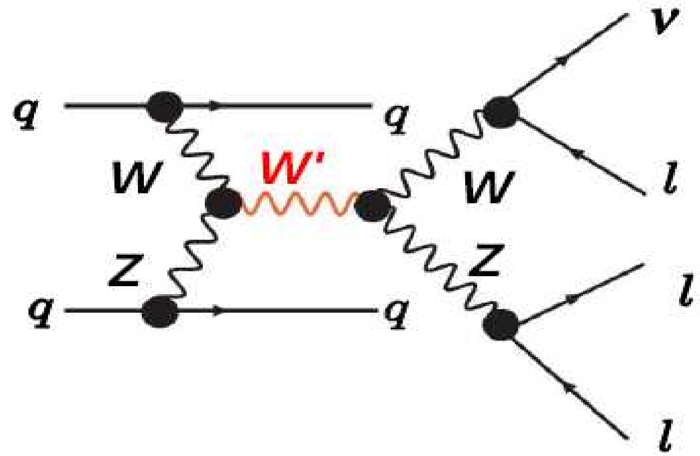
Recent applications:

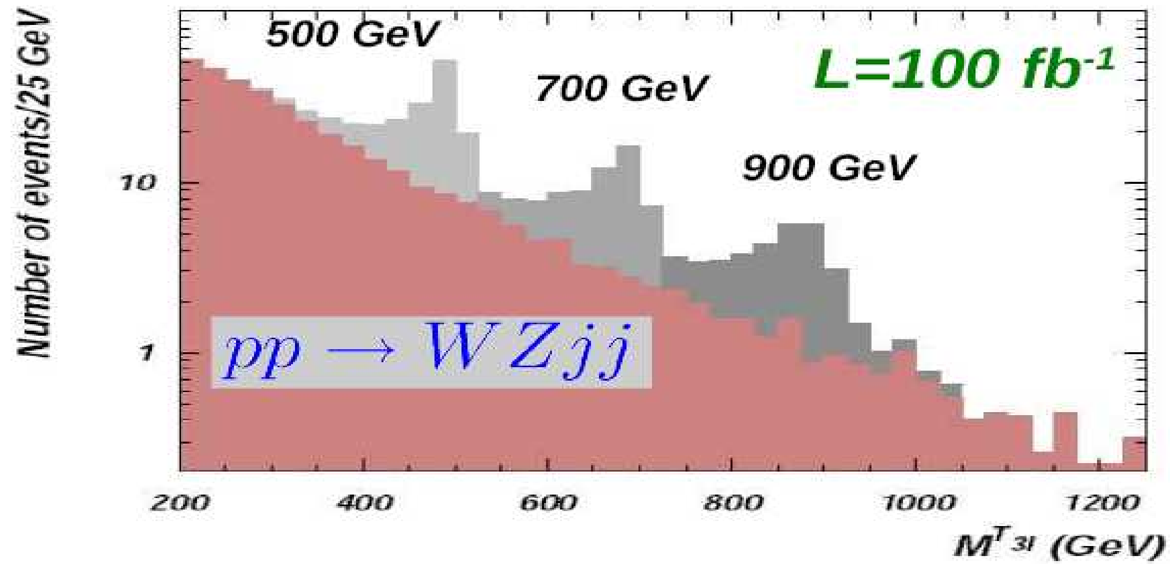
W' 3-lepton signatures from 3-site Higgsless model

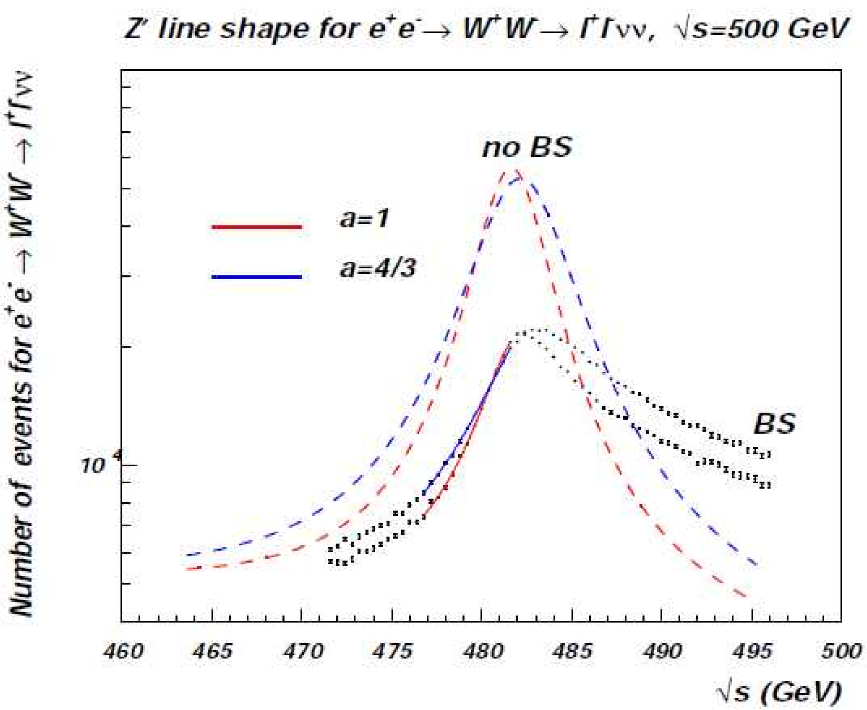
arXiv:0708.2588

LHC reach for WZ->W' process

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



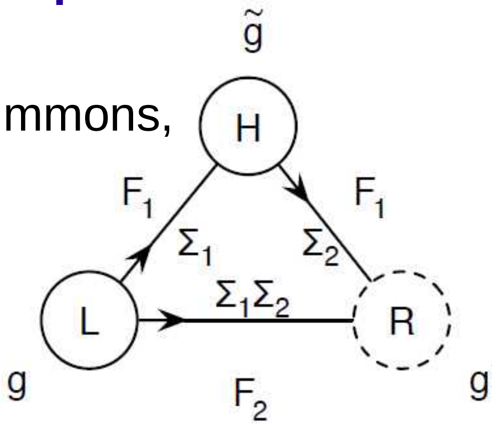




Z' line shape Z' study at ILC:
the Z' width can be measured precisely [2.5%],
So we will be able to understand
which higgsless model takes place!

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

[see F. Sannino's talk]

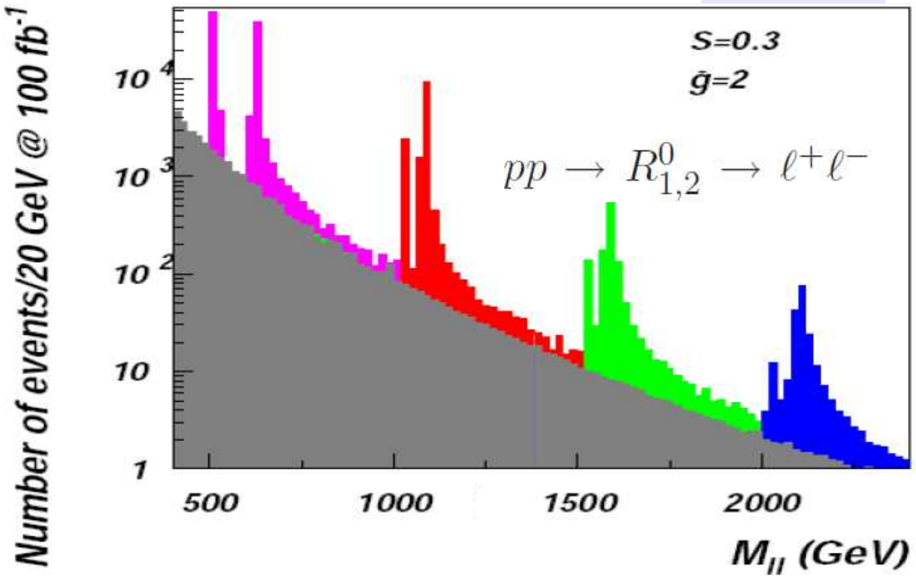
$N_c = 3$, $N_f = 2$
in the two-index symmetric
$SU(2)_L$ X $SU(2)_R$ –> $SU(2)_V$
two triplets of heavy mesons

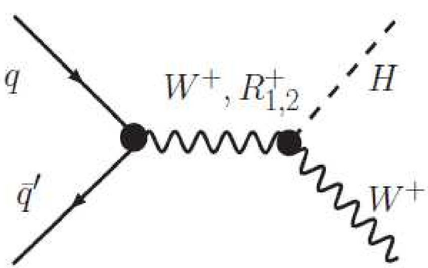
LHC

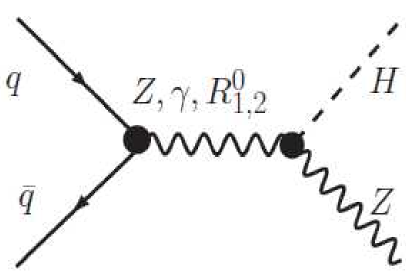
$R_1^{\pm}(R_2^{\pm})$

and

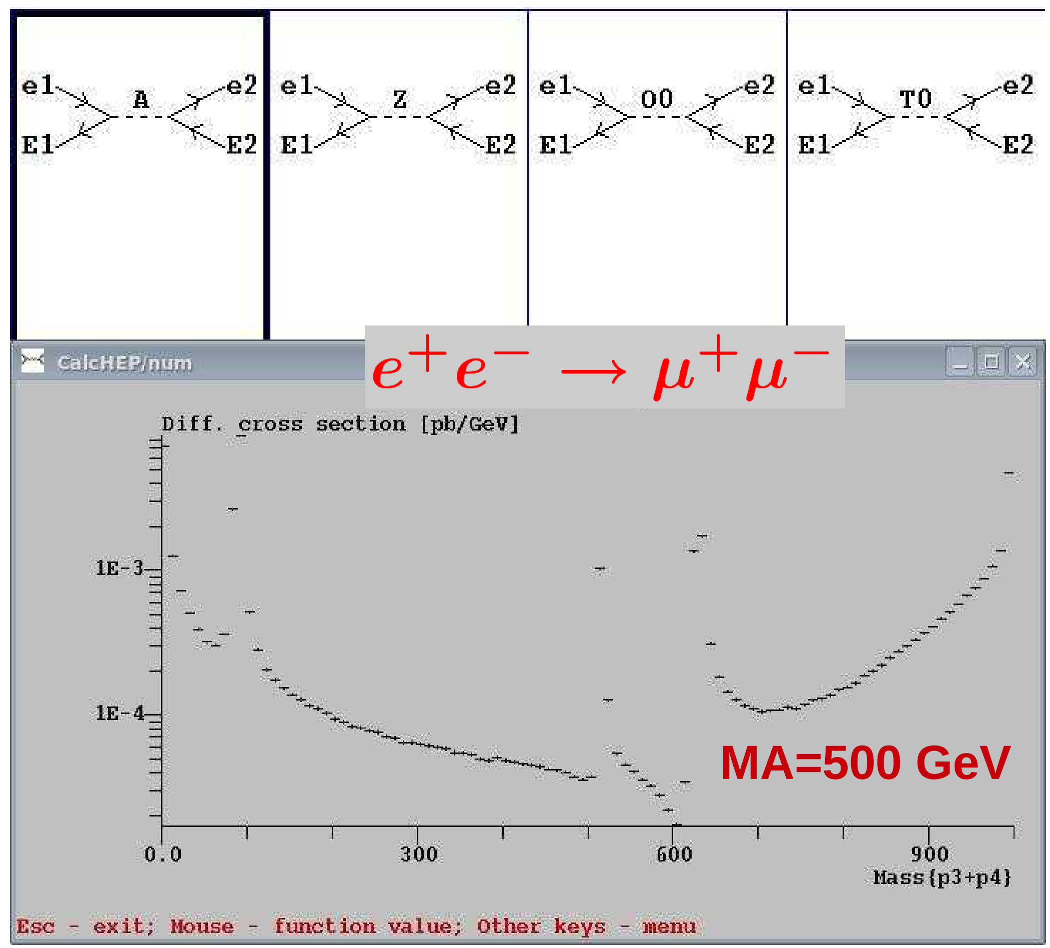
$R_1^0(R_2^0)$







ILC@1TeV
(work in progress)

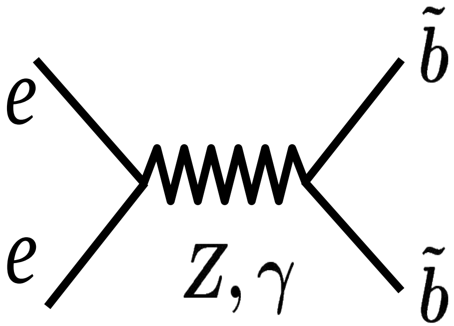


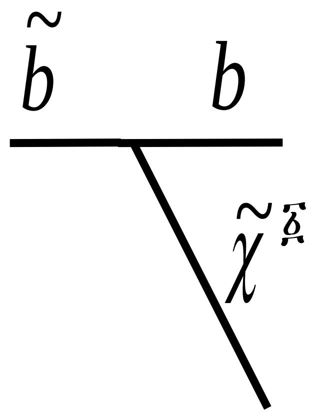
Recent applications:
sbottom coannihilation scenario at ILC

work in progress

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:

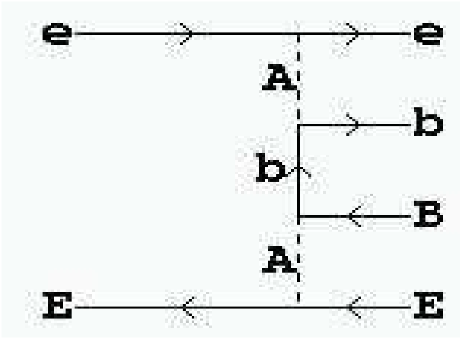




the small mass split leads to very soft b-jets and missing p_T.

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

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

$$-m_e^2\frac{(E_1-E_3)^2}{E_1E_3}$$

numerical cancellations are of the order of $m_e^4/E^4 \sim 10^{-30}$ and one should keep 30 digits this is possible only in quadruple precision

We have powerful tools connected in one chain!

Lagrangian → **LanHEP** / **FeynRules** → **CalcHEP** / **CompHEP** / **MadGraph** → **MC generators**

What is the most time consuming link?

We have powerful tools connected in one chain!

Lagrangian $\xrightarrow{?}$ **LanHEP / FeynRules** $\rightarrow$ **CalcHEP / CompHEP / MadGraph** $\rightarrow$ **MC generators**

What is the most time consuming link?

Future plans

- **Include finite width into production-decay connection (done!)**
- **Include polarization effects into production-decay chain**
- **kinematical cuts generalization (done!)**
- **QCD scale definition (leading diagram)**
- **polarization for massive particles**
- **database of the models**

Final remarks

- **Advantages of CalcHEP –**

  easy model implementation, convenient interface, batch mode.

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

  from model builders to experimentalists!

- **Read manuals/help – all details are there!**

- **Automation tools are powerful but**

  should not be blindly trusted or blamed !

Backup Slides

control of resonances

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

```
Breit-Wigner

BreitWigner range 2.7
T-channel widths   OFF
GI in t-channel    OFF
GI in s-channel    OFF
```

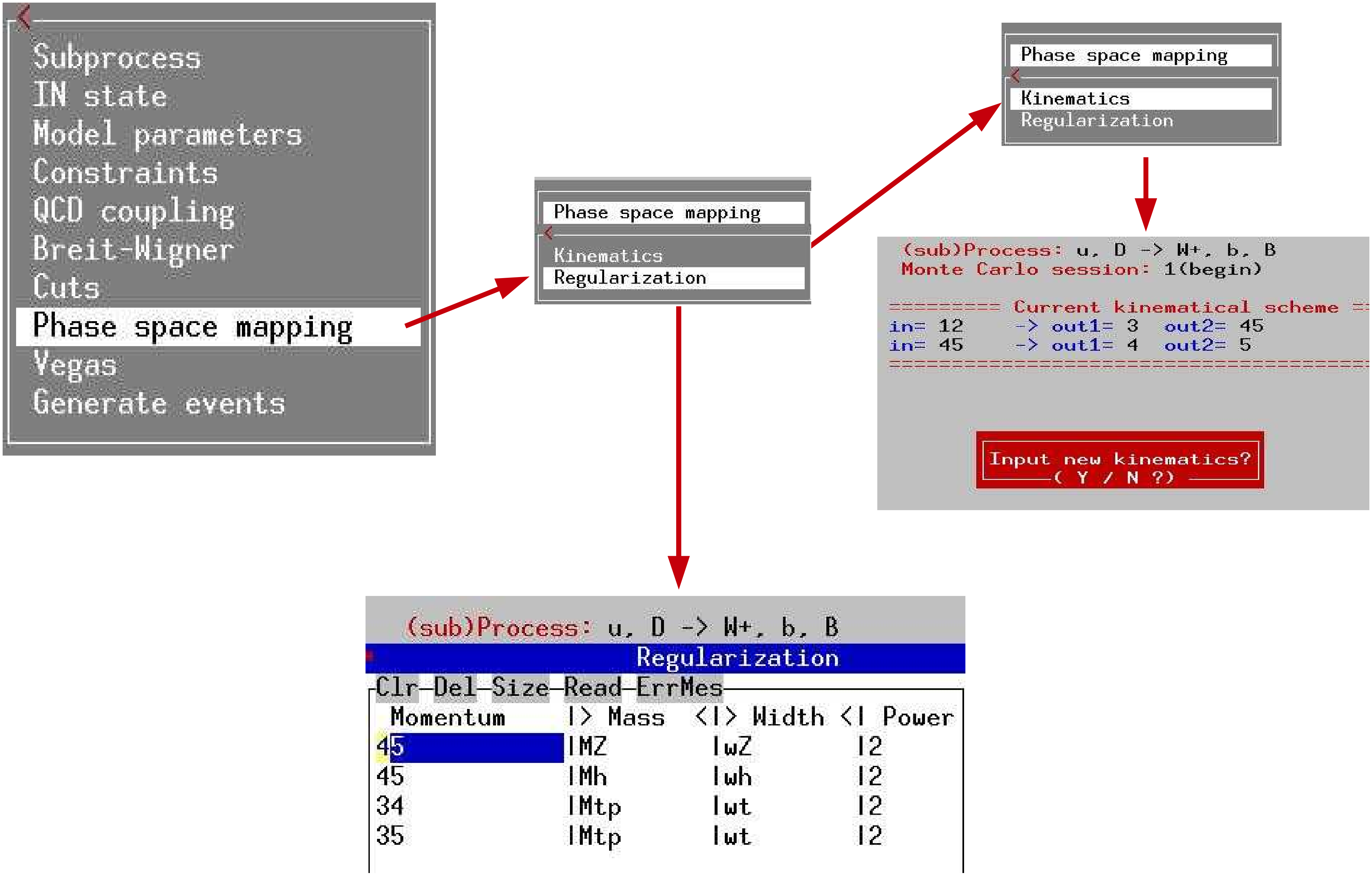
F1

```
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

pont cancellation between pole and non-pole diagra
ms
is not expected. We assume that close to pole the
problem also is not so serious. But far from the p
ole
we ignore width and restore gauge invariance.
```

phase-space mapping



running subproc_cycle for SM(CKM=1) model

```
../bin/subproc_cycle 0 0
#Subprocess 1 ( u, D -> W+, b, B ) Cross section = 9.8549E+00 , 0 events
#Subprocess 2 ( U, d -> W-, b, B ) Cross section = 5.6112E+00 , 0 events
#Subprocess 3 ( d, U -> W-, b, B ) Cross section = 5.6156E+00 , 0 events
#Subprocess 4 ( D, u -> W+, b, B ) Cross section = 9.9153E+00 , 0 events
#Subprocess 5 ( s, C -> W-, b, B ) Cross section = 1.5792E+00 , 0 events
#Subprocess 6 ( S, c -> W+, b, B ) Cross section = 1.3757E+00 , 0 events
#Subprocess 7 ( c, S -> W+, b, B ) Cross section = 1.3475E+00 , 0 events
#Subprocess 8 ( C, s -> W-, b, B ) Cross section = 1.6218E+00 , 0 events
Sum of distributions is stored in file distr_1_8
Total Cross Section 36.9212 [pb]
```

Note the d- and s- quarks IDs

```
d-quark   |d  |D  |81   |1  |0  |0  |3  |  |d
u-quark   |u  |U  |2    |1  |0  |0  |3  |  |u
s-quark   |s  |S  |83   |1  |0  |0  |3  |  |s
```

For SM(CKM=1) model PDF of d- and s- quarks is redefined

Syntax of LanHEP

- *The LanHEP input file is the sequence of statements, each starts with a special identifier (such as parameter, lterm, etc) and ends with the full-stop '.' symbol. Statement can occupy several lines*
- *Identifiers: Indentfiers are the names of particles, parameters etc.*
- *Constants: integers, floating point numbers, strings*
- *Comments:* '%' ,'/*' ... '*/'
- *Order of the indices of the objects (default):*
  [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*).

Syntax of LanHEP

- ***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

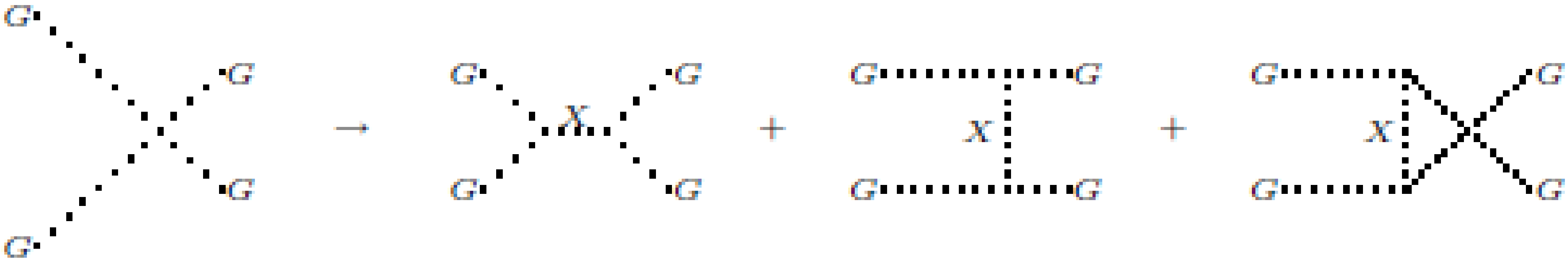
  `-texLineLength` *num* Controls width of the Lagrangian

Vertices with color particles in CalcHEP

- The CalcHEP Lagrangian tables do not describe explicitly the color structure of a vertex.
- If color particles are present in the vertex, the following implicit contractions are assumed (p, q, r are color indices):
  - δ_{pq} for two color particles $A^{\text{“}\varepsilon\text{”}}_{\mathsf{p}}$ and $A^{\text{“}r\text{”}}_{\mathsf{q}}$
  - $\lambda^{\mathsf{r}}_{\mathsf{pq}}$ for three particles, which are color triplet, antitriplet and octet
  - f^{pqr} for three color octets $\boldsymbol{f^{pqr} G^{p}_{\mu} G^{q}_{\nu} G^{r}_{\lambda}}$
  - ***There are no other color structures in CalcHEP***

Vertices with color particles in CalcHEP

- 4-gluon vertex can be split it into 3-legs vertices $f^{pqr} G^q_\mu G^r_\nu X^p_{\mu\nu}$



- Here the field $X^p_{\mu\nu}$ is a Lorenz tensor and color 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_' ('_' is the number of the particle in table item).

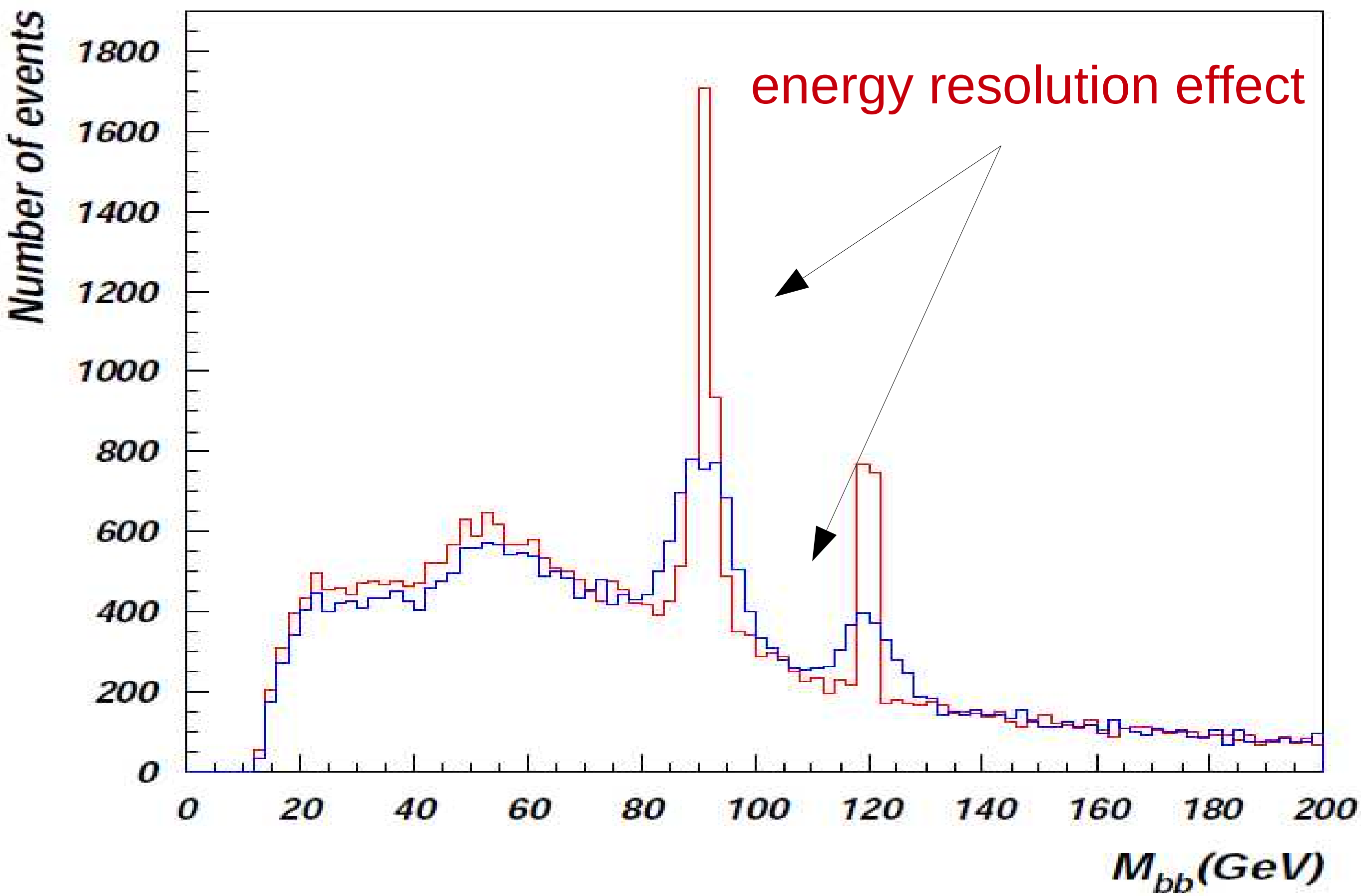
```
                                        Vertices
Clr-Del-Size-Read-ErrMes
A1     |A2     |A3     |A4     |>            Factor             <|>  Lorentz part
G      |G      |G      |       |GG                                |m1.m2*(p1-p2).m3+m2.m3*(p2-p3).m1+m3.m1*(p3-p1).m2
G      |G      |G.t    |       |GG/Sqrt2                          |m1.M3*m2.m3-m1.m3*m2.M3
```

Vertices with color particles in LanHEP

- The splitting of vertex with 4 colored particle into 3-particles vertices is done by LanHEP automatically: each vertex containing 4 color 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*
- 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).*
- the default value is 2 for SplitCol1 and 1 for SplitCol2

What do we do with LHE file?

- *one of the options is to convert LHE file into ntuple and use* **PAW/Root** *packages to perform event analysis at the parton level*
- bin/nt_maker event_mixer.lhe → produces event_mixer_1.nt
- cd paw ; pawX11 ; exe dubna.kumac




```
      SUBROUTINE SMEAR(P,I, DELTA)
      REAL P(4,*)  , mass
      PI=ACOS(-1.)

      EI=P(4,I)

      RGEN1=SQRT(-2.*ALOG(RNDM()))
      RGEN2=2.*PI*RNDM()
      R1=RGEN1*COS(RGEN2)

c DELTA=0.15 for EM
c DELTA=0.5  for HAD

     & EIP=(1.+ DELTA/sqrt(EI)*R1)
      DO J=1,4
         P(J,I)=P(J,I)*EIP
      ENDDO

      RETURN
      END
```