BSM phenomenology at the LHC using Monte Carlo tools

Alexander Belyaev

Southampton University & Rutherford Appleton LAB

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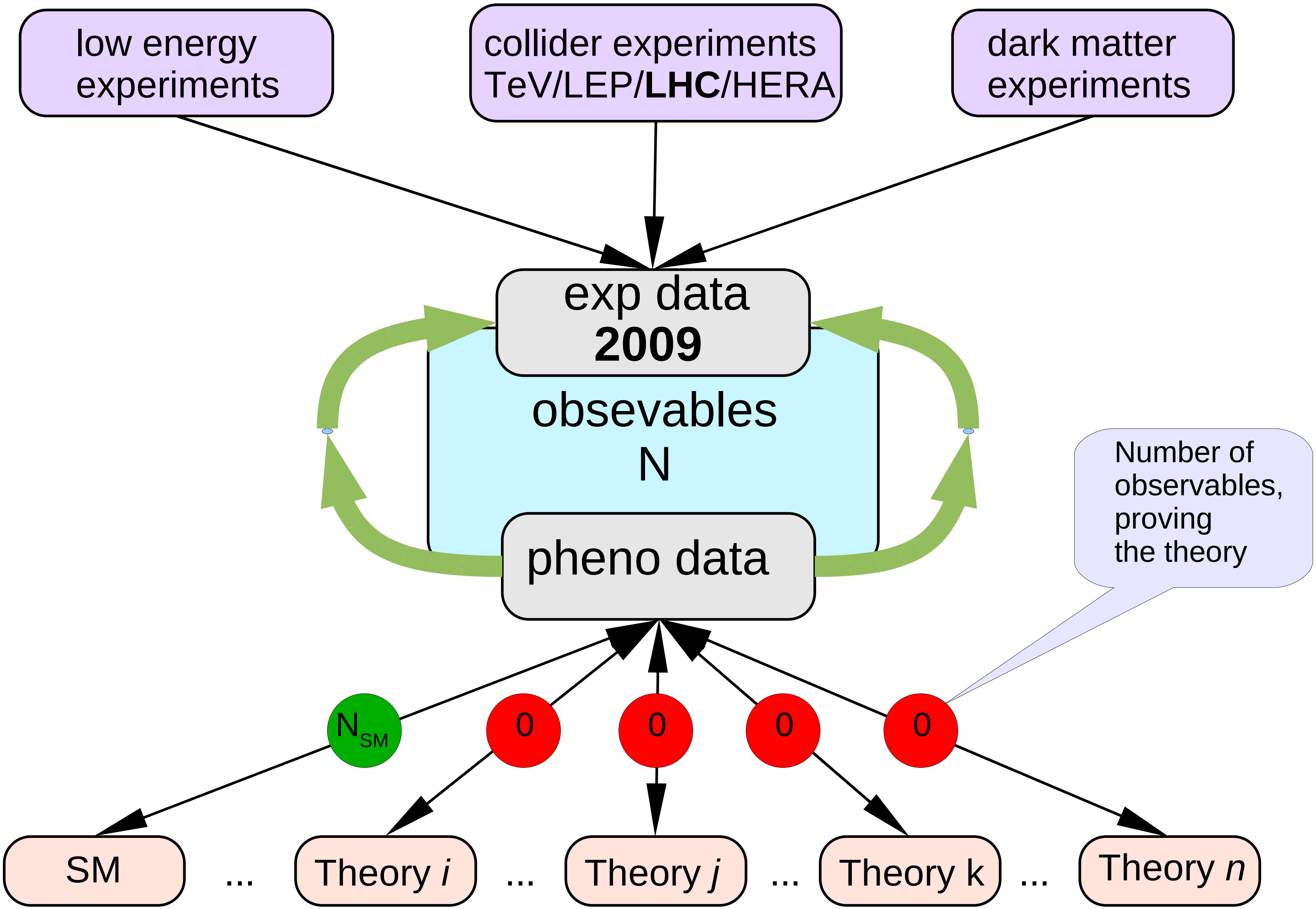
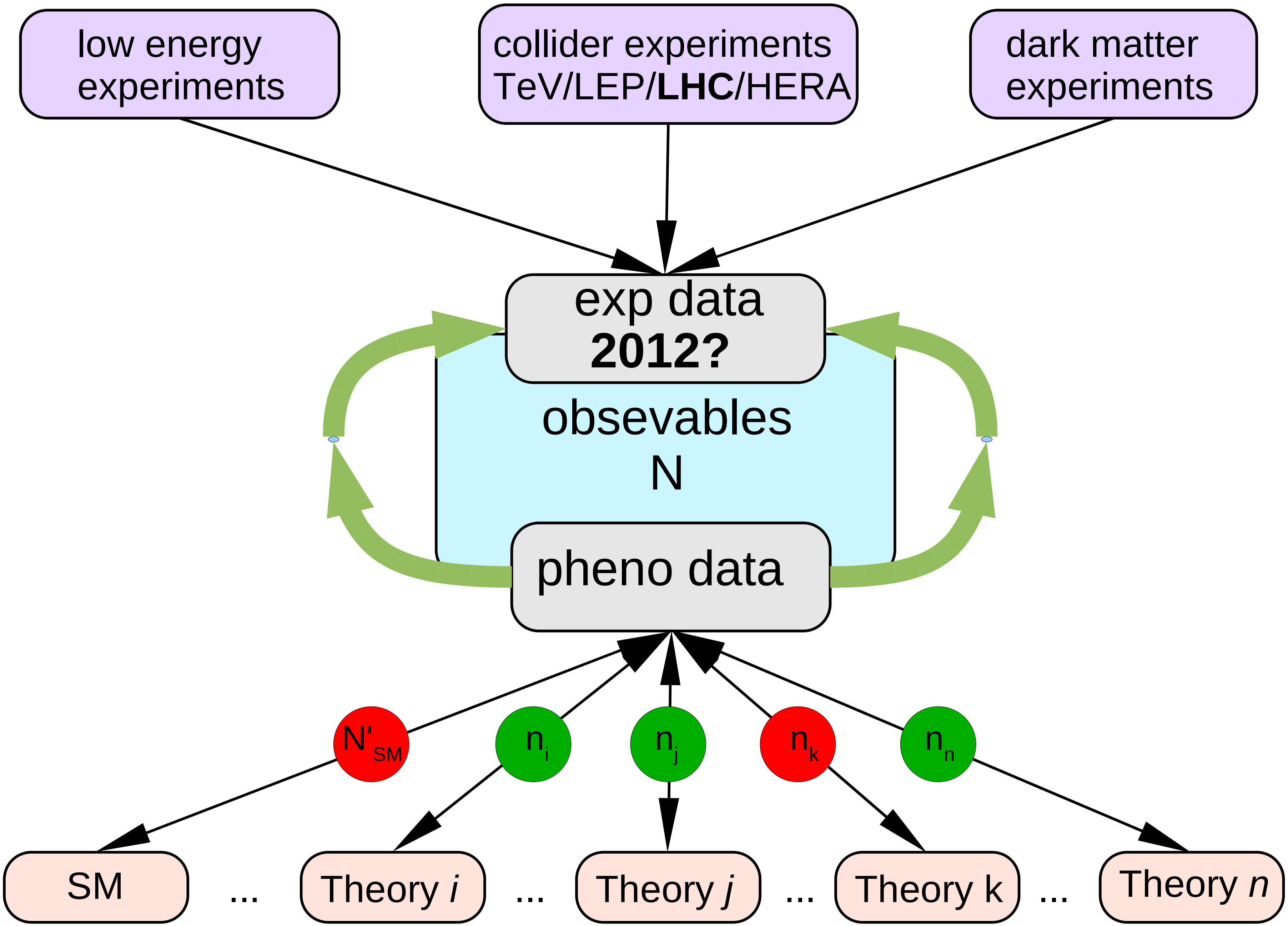
FeynRules 2010 Workshop on automatization for BSM physics

Possible scenario in the near future



Possible scenario in the near future



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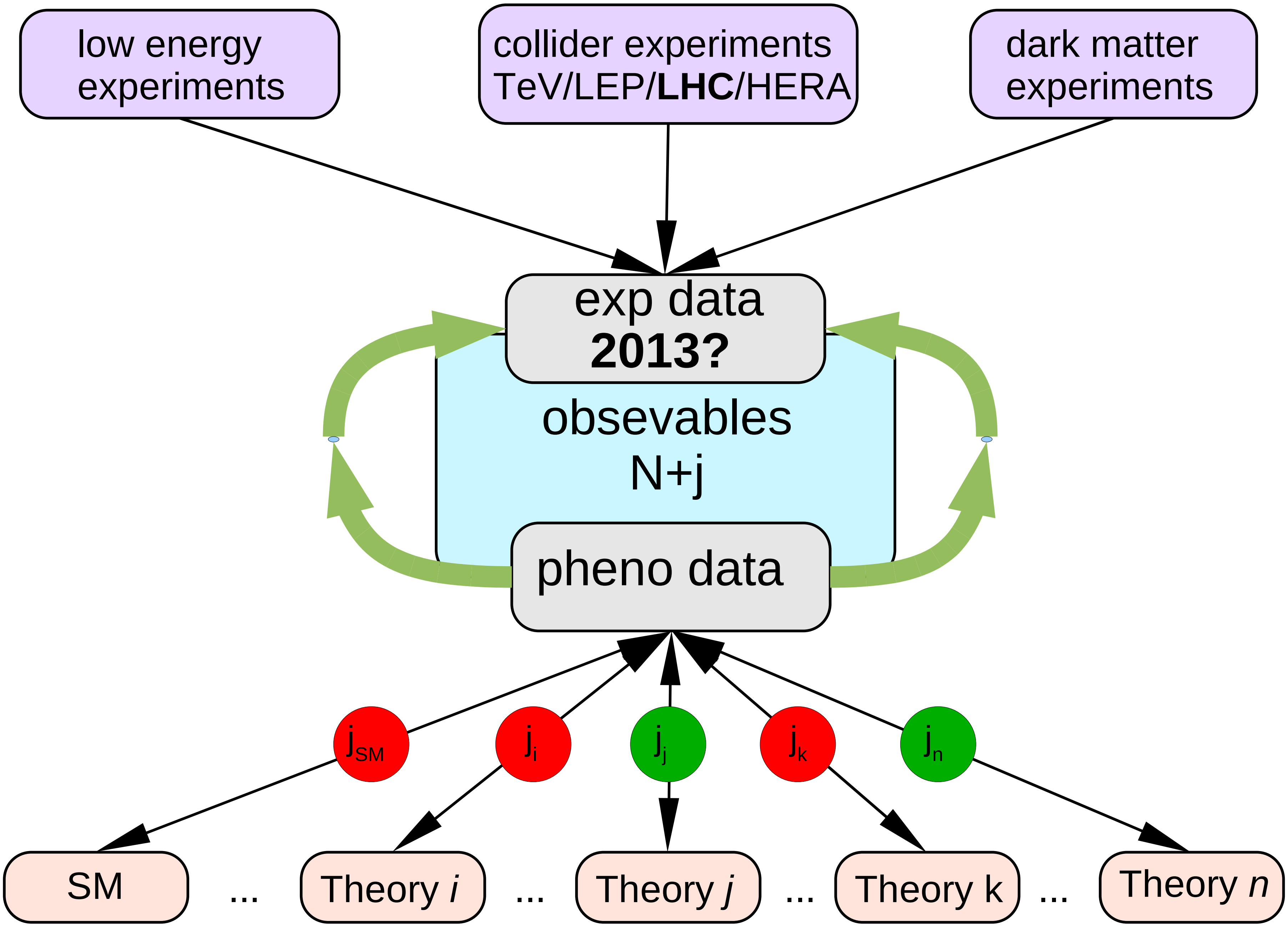
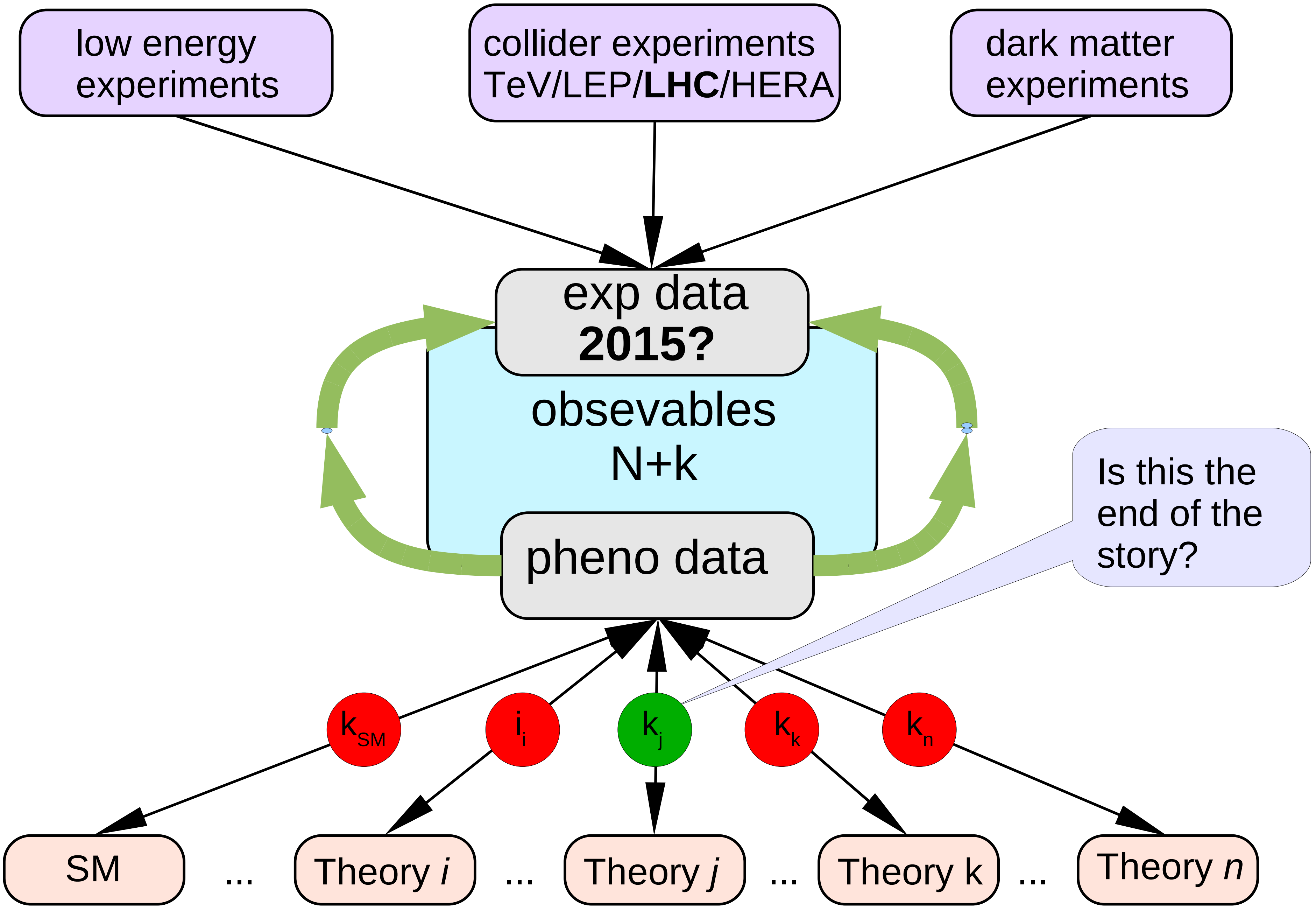
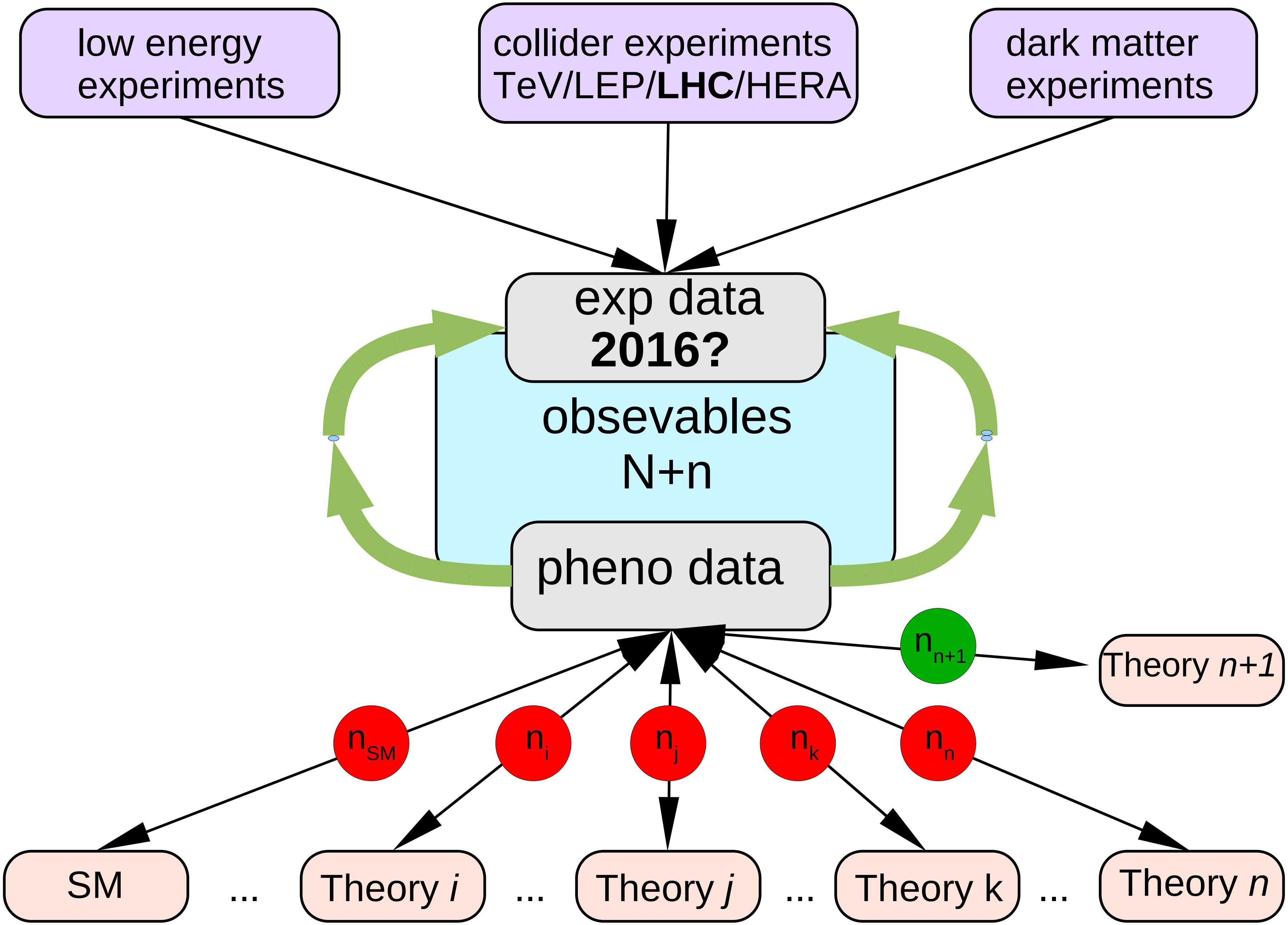


Possible scenario in the near future



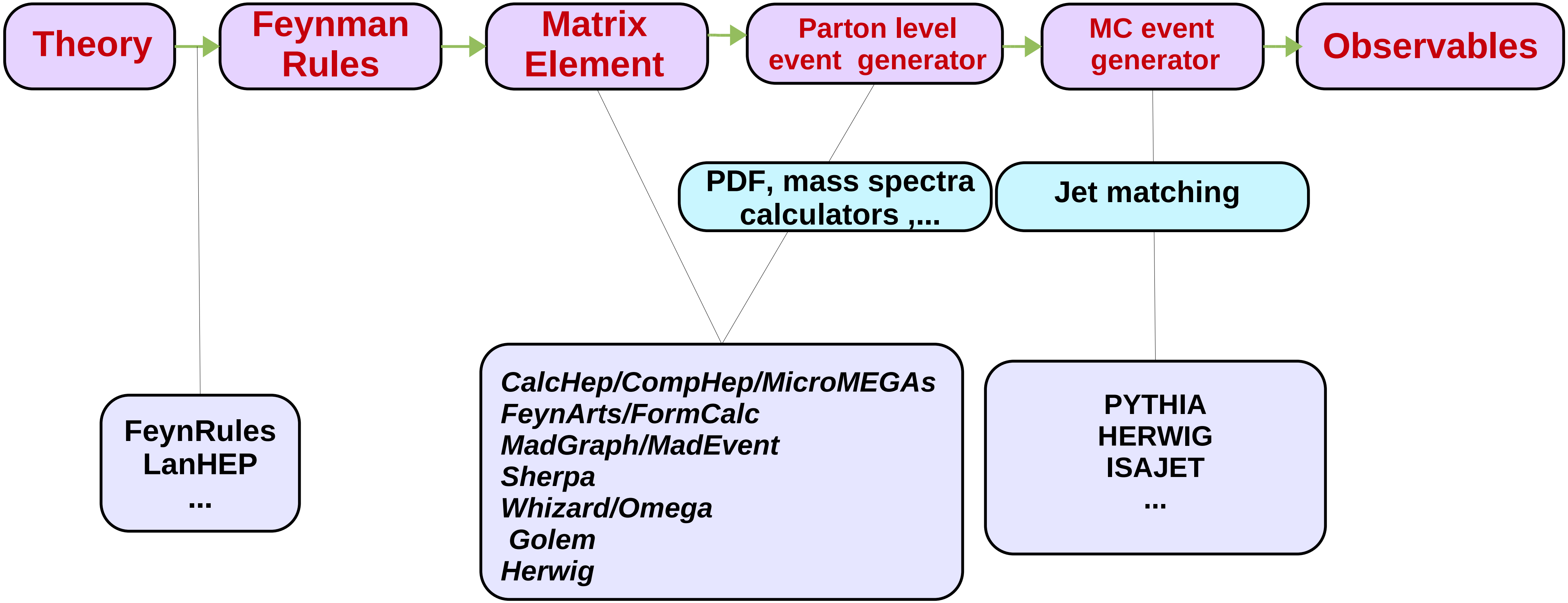
Possible scenario in the near future



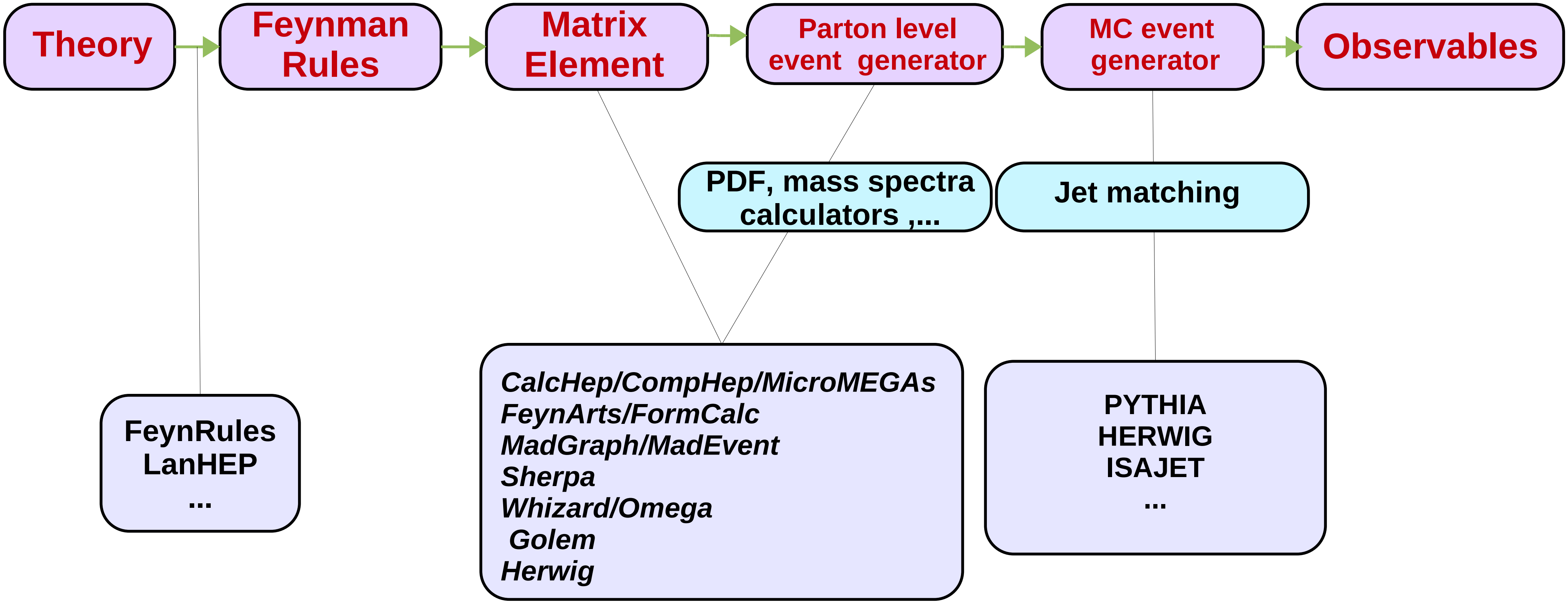
Theory ⟷ **Observables**

is the crucial link

What does this link actually mean?

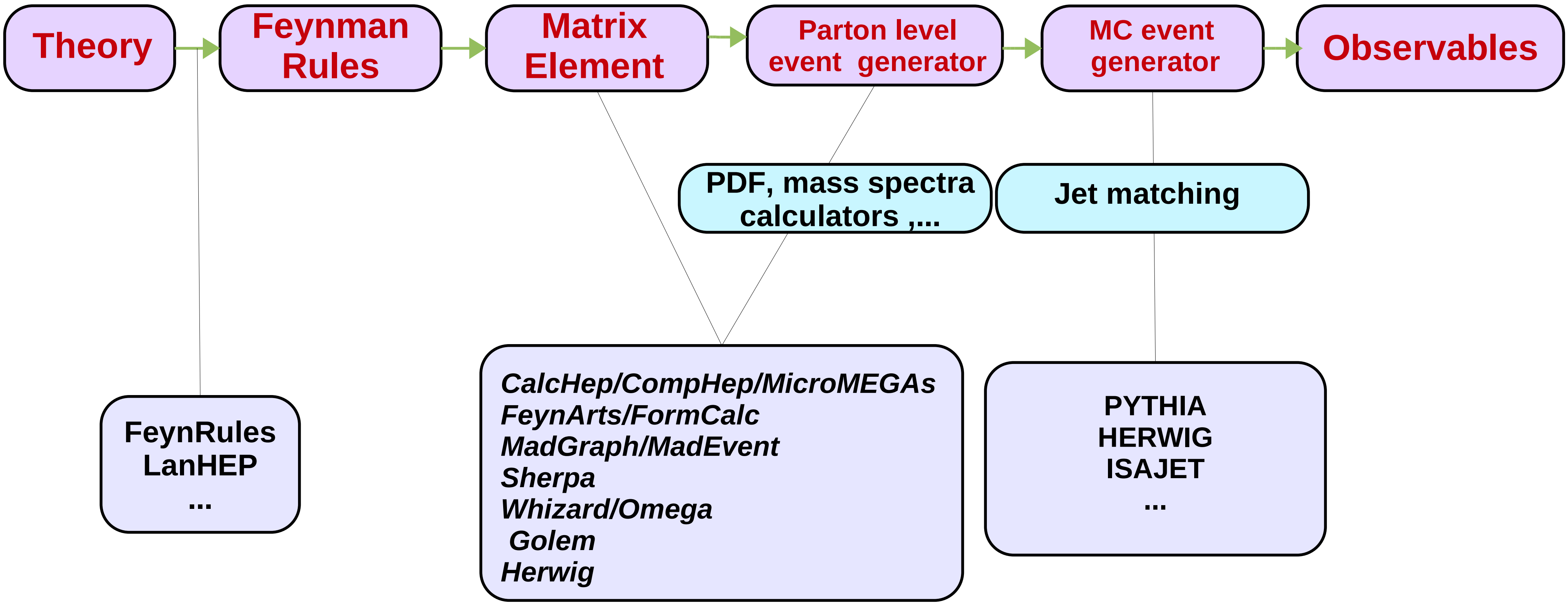


http://www.ippp.dur.ac.uk/montecarlo/BSM/



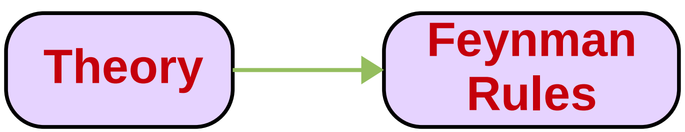
http://www.ippp.dur.ac.uk/montecarlo/BSM/

What is the most time-consuming link?



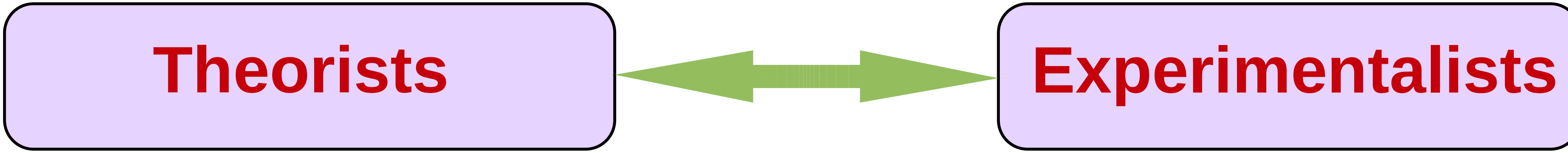
http://www.ippp.dur.ac.uk/montecarlo/BSM/

What is the most time-consuming link?



Even with the help of FeynRules and LanHEP this link requires serious theoretical work to introduce new model!

Another crucial link



- Theorist is dreaming about confirming his beautiful theory at the LHC
  Experimentalist is dreaming about exciting signals at the LHC

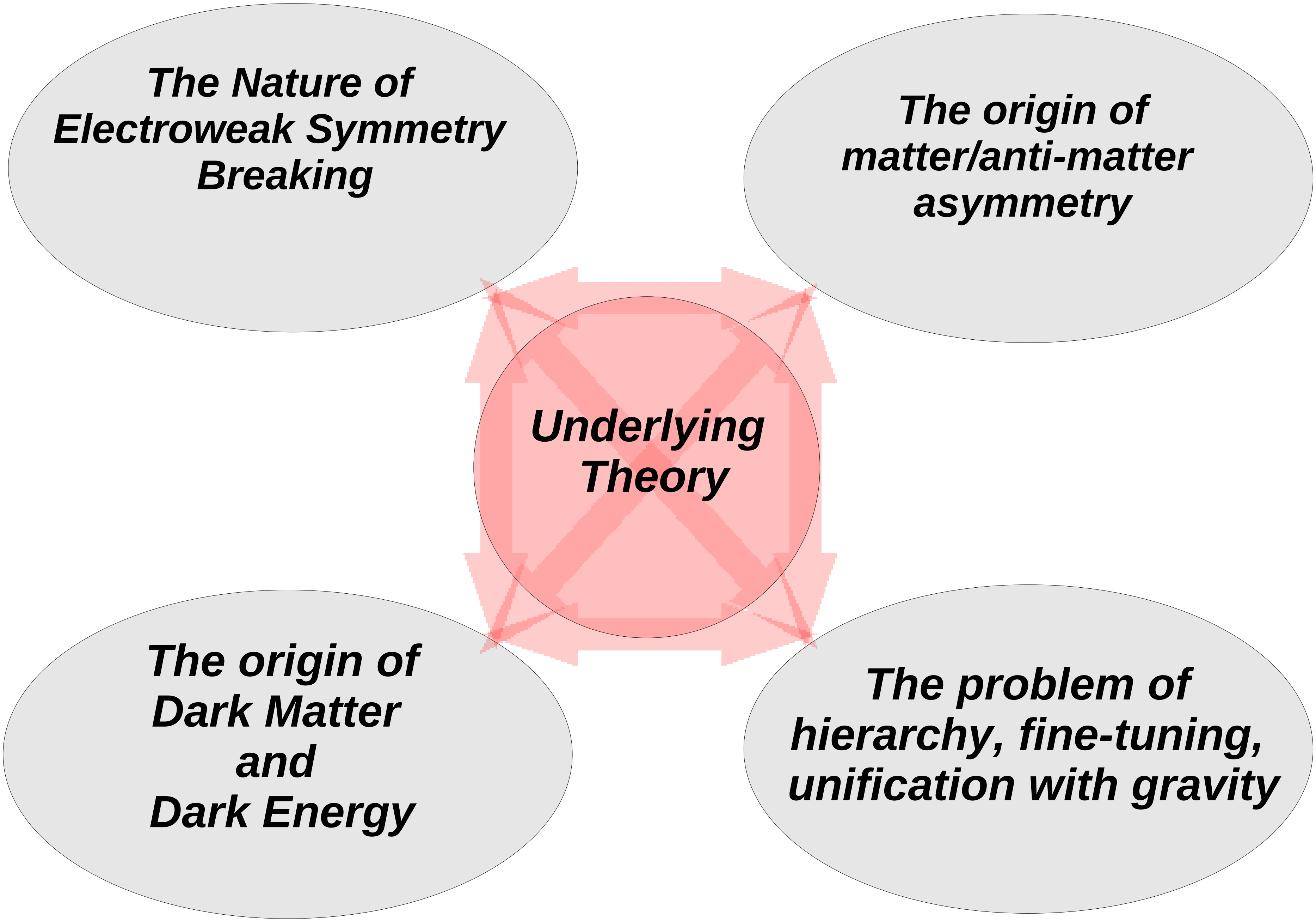
- But there are many different theories and many respective signatures preferred by different people ...
  and just one underlying theory preferred by Nature!

- Can we delineate THIS theory from LHC signatures?

To answer this question theorists and experimentalists should work very tightly together

- *to have quick and multiple mutual feedback loops*
- *to mentor each other, learn theoretical and experimental details*
- *To predict new signatures and converge finally on the theory which can be delineated from others*

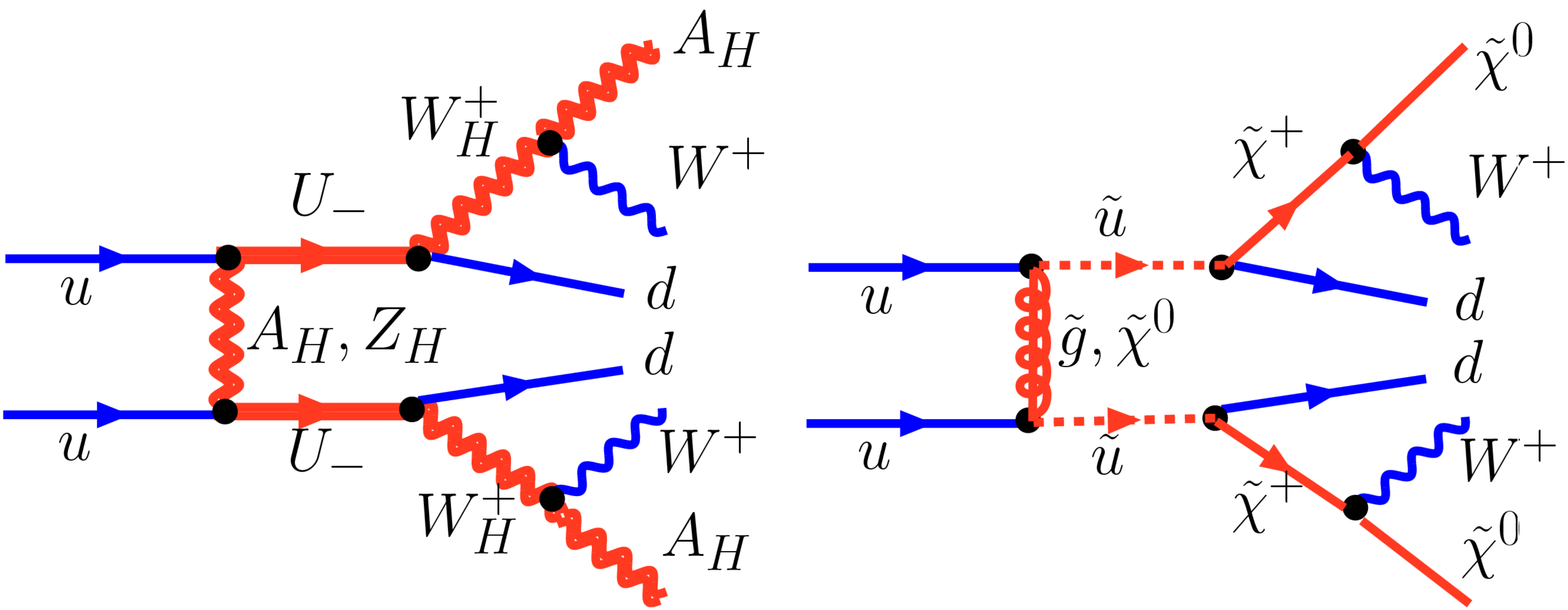
What underlying theory should explain?



Promising candidates for underlying theory ...

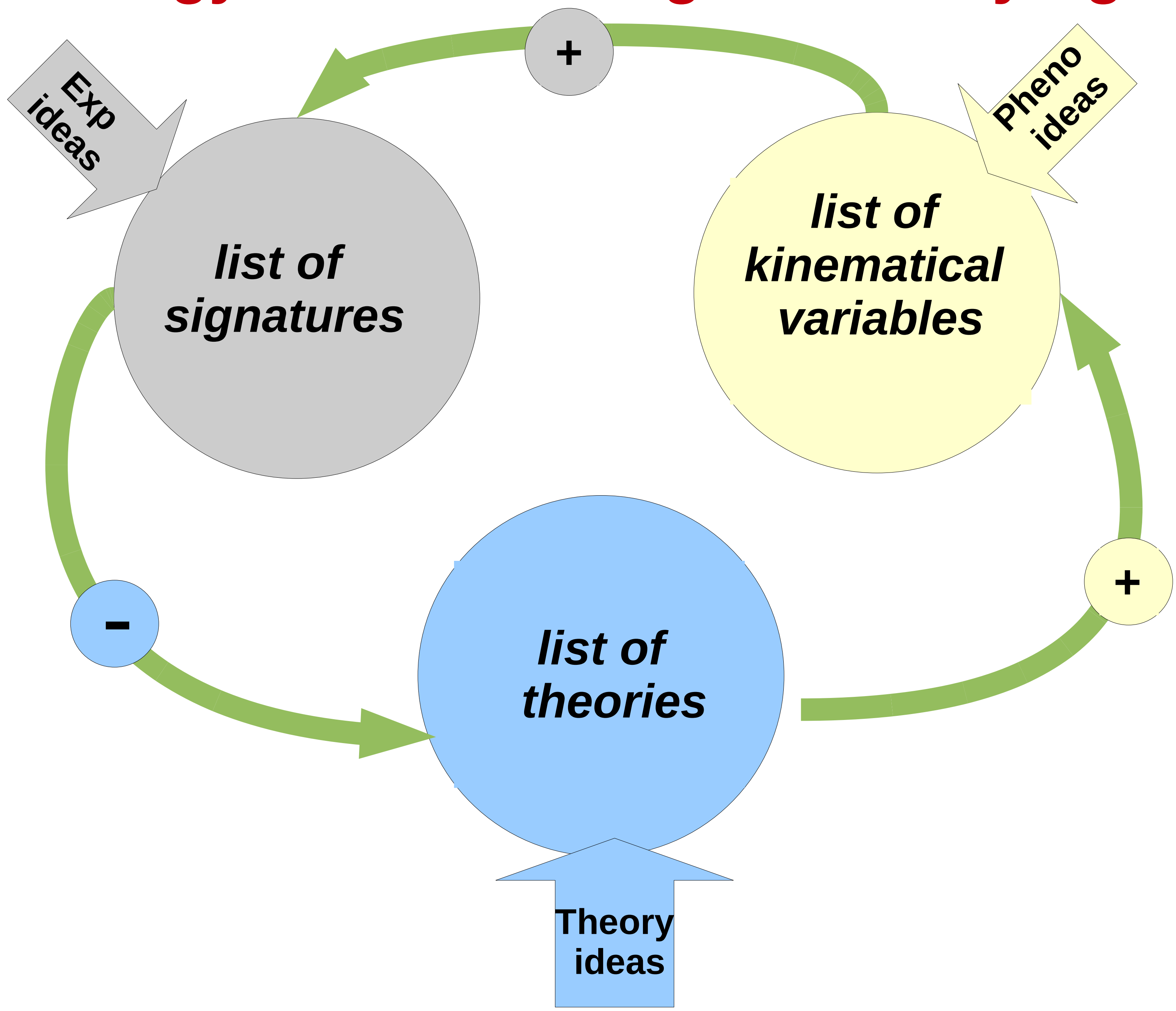
- **Supersymmetry:**
  - *cMSSM, MSSM, NMSSM, E_6SSM, ...*
- **Walking Technicolor**
- **Little Higgs models with T-parity**
- **Extradimensional Models:**
  - *Universal and Warp extra dimensions*

Signatures could look alike

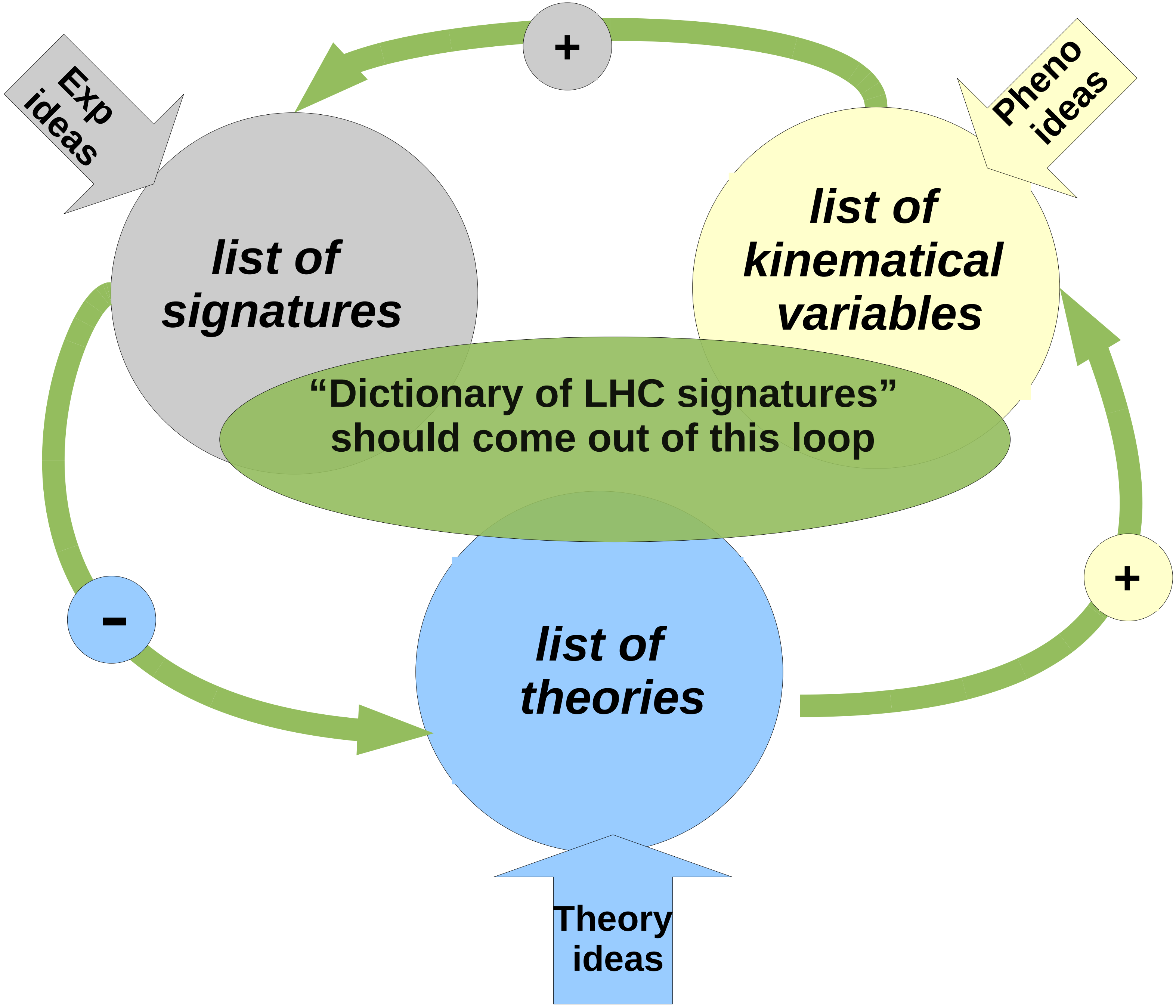


LHT **SUSY**

The strategy for delineating of underlying theory



The strategy for delineating of underlying theory



First Steps towards "Dictionary"

A.B., Asesh Datta, Rohini Godbole, Bruce Mellado, Andreas Nyffeler, Chara Petridou, D.P. Roy, Pramana 72:229-238,2009. e-Print: arXiv:0806.2838 [hep-ph]

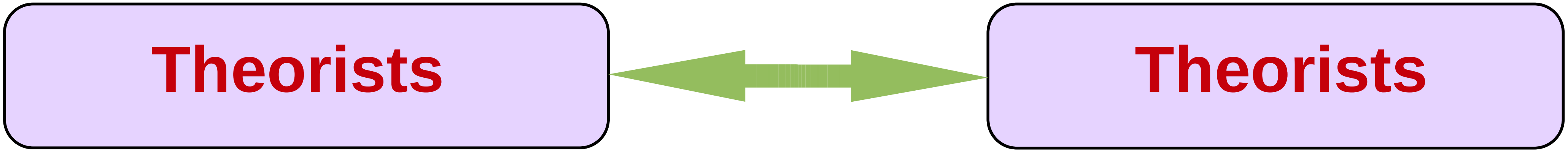
Variables		SUSY (MSSM)	LHT	UED
Spin		heavy partners differ in spin by 1/2	heavy partners have the same spin, no heavy gluon	heavy partners have the same spin
Higher level modes		NO heavy partners	NO heavy partners	YES heavy partners
$N_{l^+l^+}/N_{l^-l^-}$		$R_{SUSY} < R_{LHT}$	R_{LHT}	$R_{UED} \simeq R_{LHT}$
SS leptons rates		from several channels: SS heavy fermions, Majorana fermions	only from SS heavy fermions	only from SS heavy fermions
$R = \frac{N(\not{E}_T + jets)}{N(l's + \not{E}_T + \text{jets})}$		R_{SUSY}	$R_{\text{LHT}} < R_{\text{SUSY}}$	R_{UED} to be studied
b-jet multiplicity		enhanced (FP)	not enhanced	not enhanced
Single heavy top		NO	YES	YES via KK2 decay
polarization effects	$tt + \not{E}_T$ $\tau\tau + \not{E}_T$	to be studied to be studied	to be studied to be studied	to be studied to be studied
Direct DM detection rate		high (FP) low (coann)	low (Bino-like LTP)	typically low for γ_1(5D) DM [22] typically high for γ_H(6D) DM [22]

Theorists ⟷ **Experimentalists**

What we can do at this workshop?

- Define the strategy on joint effort on creating and validation of FR for the most requested models
- Discuss related physics/publications
- Define the way of unambiguous reproduction of parton-level events
  - *need a database of the models (under construction in Southampton) with unique model identifier*
  - *database will be the collection of models from FeynRules, Lanhep as well as manually created ones*
  - *we should make LHE events traceable – generate tag for tools chain*
  - *organize meeting with CERN representatives*
  - *convince experimentalists to accept this accord, which would be extremely powerful tool/way for an effective exploration of new physics*

Another crucial link



We should talk to each other! This is what this workshop for!

- Let understand complementary of our tools and join efforts
  - *validate models*
  - *work on common papers*
- Talk openly about current problems and think about the way of their effective solution
- One model is validated we could share our efforts on working challenging physics problem using different packages

Few words about 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, ...

- **Features/Limitations of the 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 → 6 (1→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**

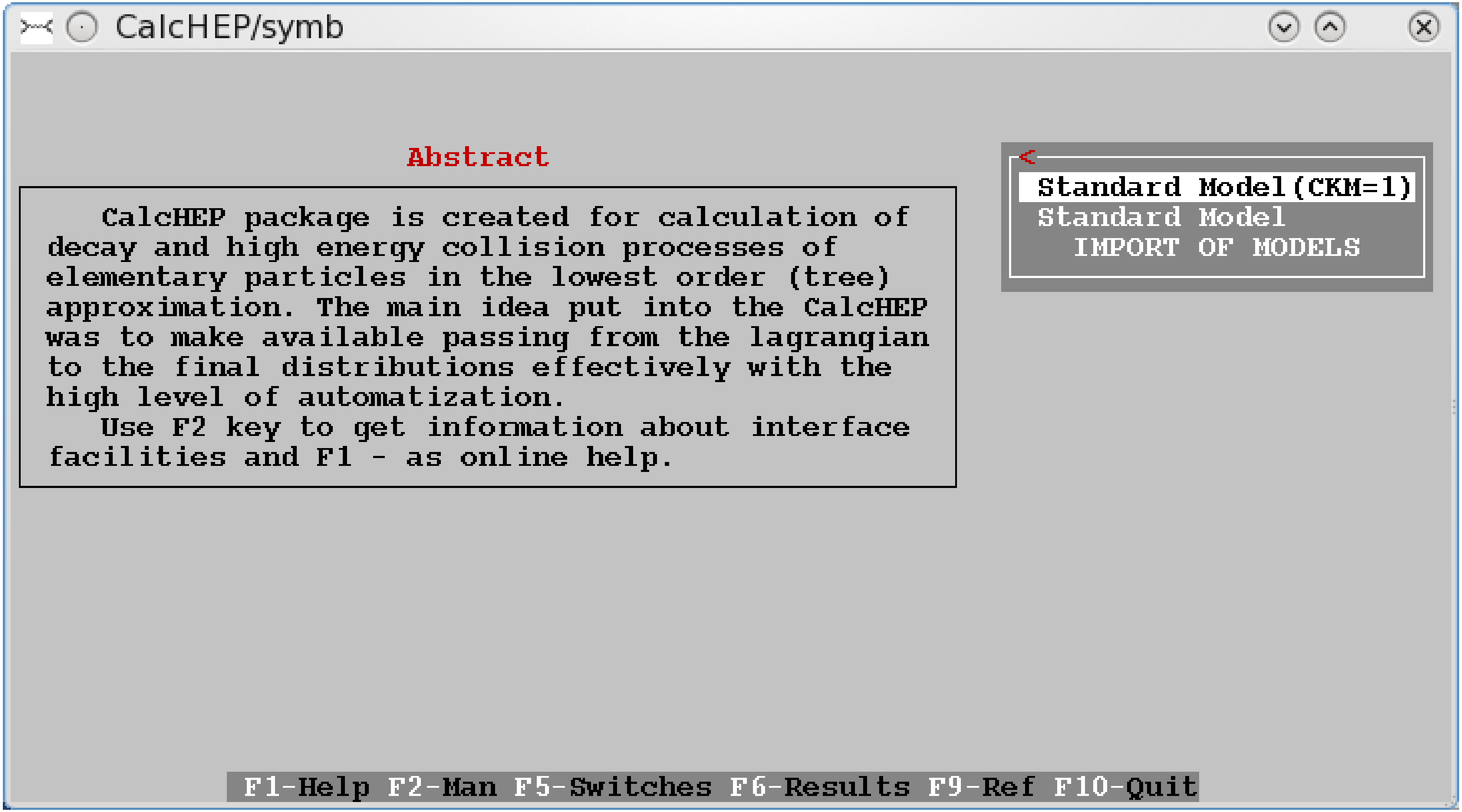
- **Files:**

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

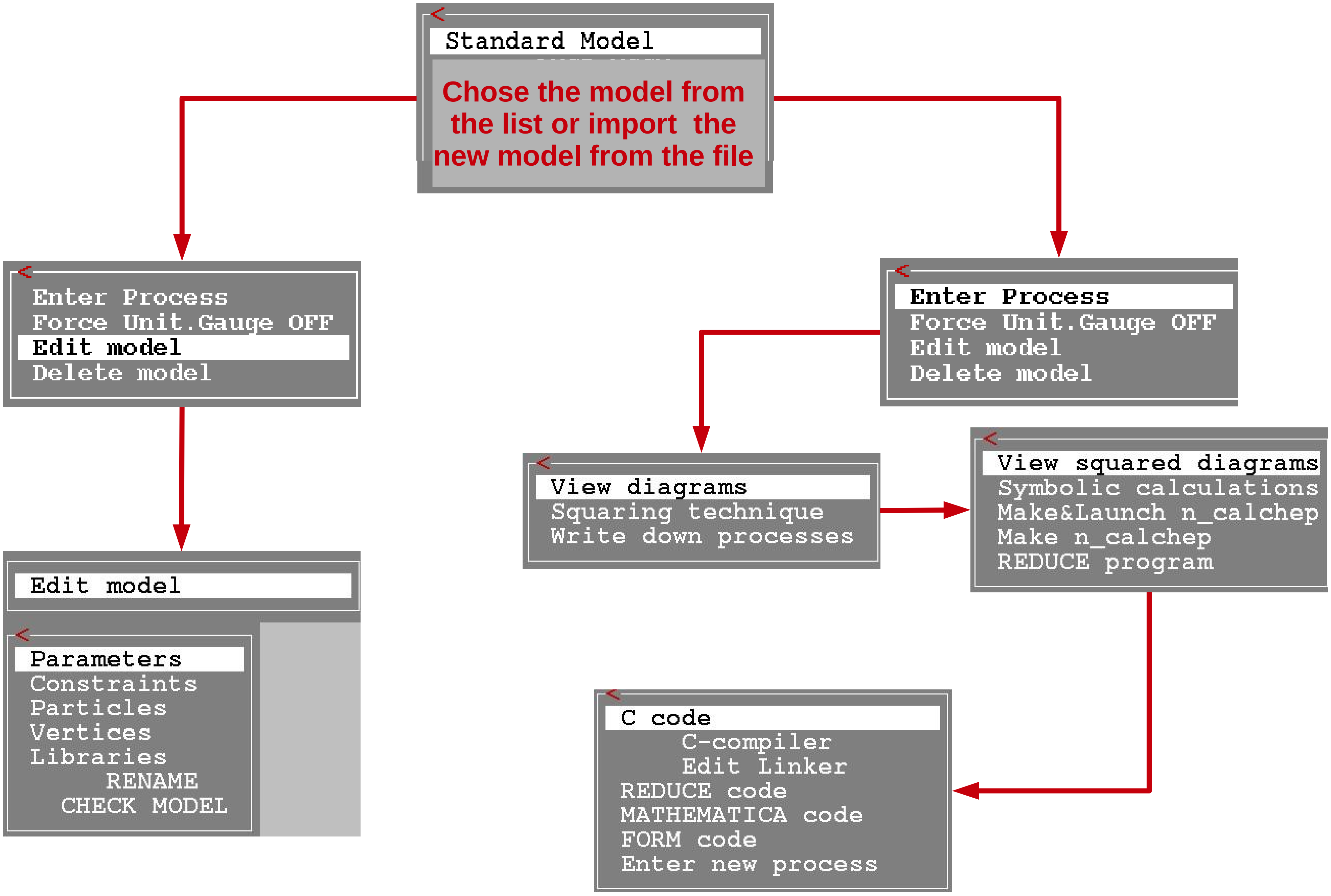
- **Start:**

  ./calchep

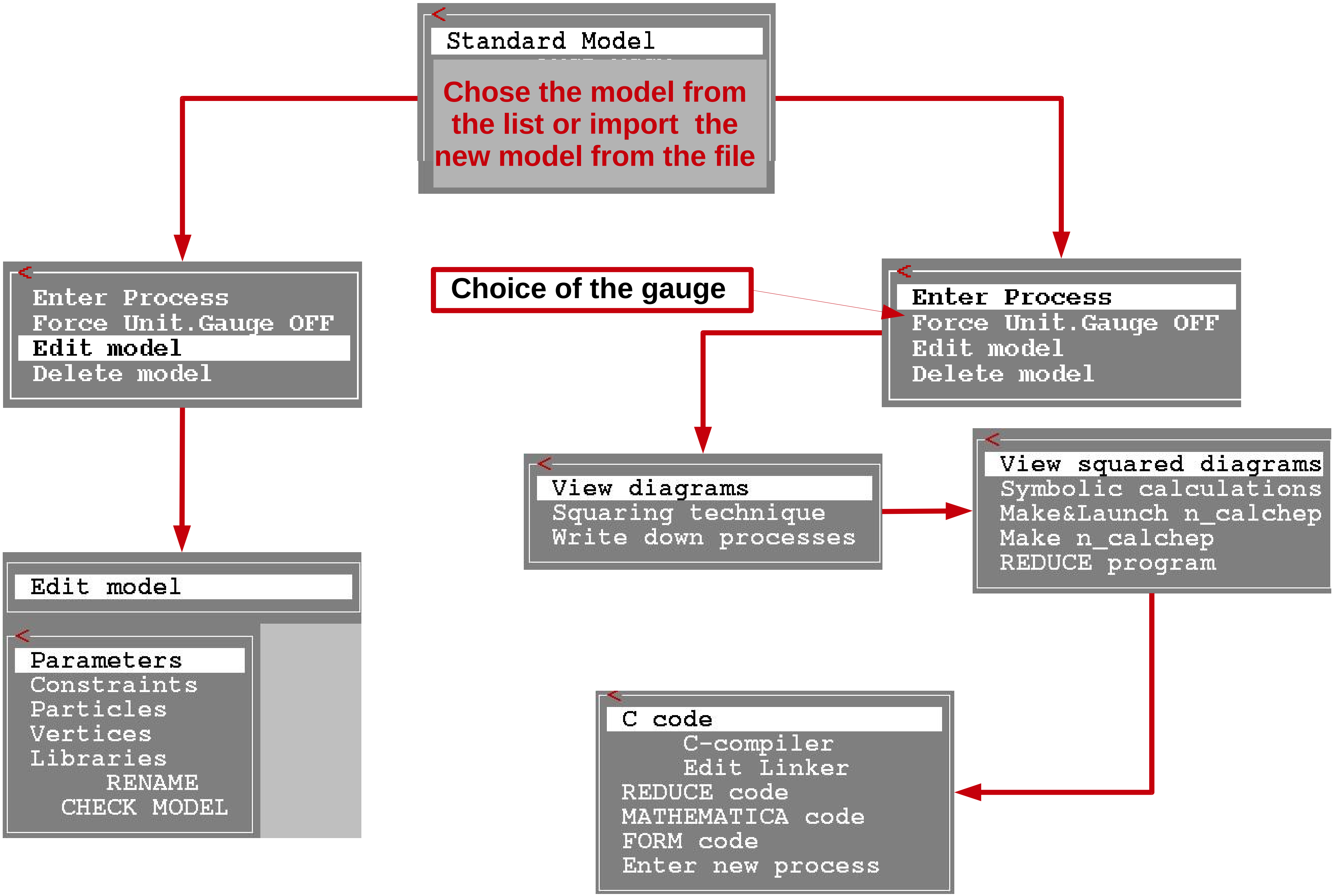
Starting CalcHEP



CalcHEP menu structure: symbolic part

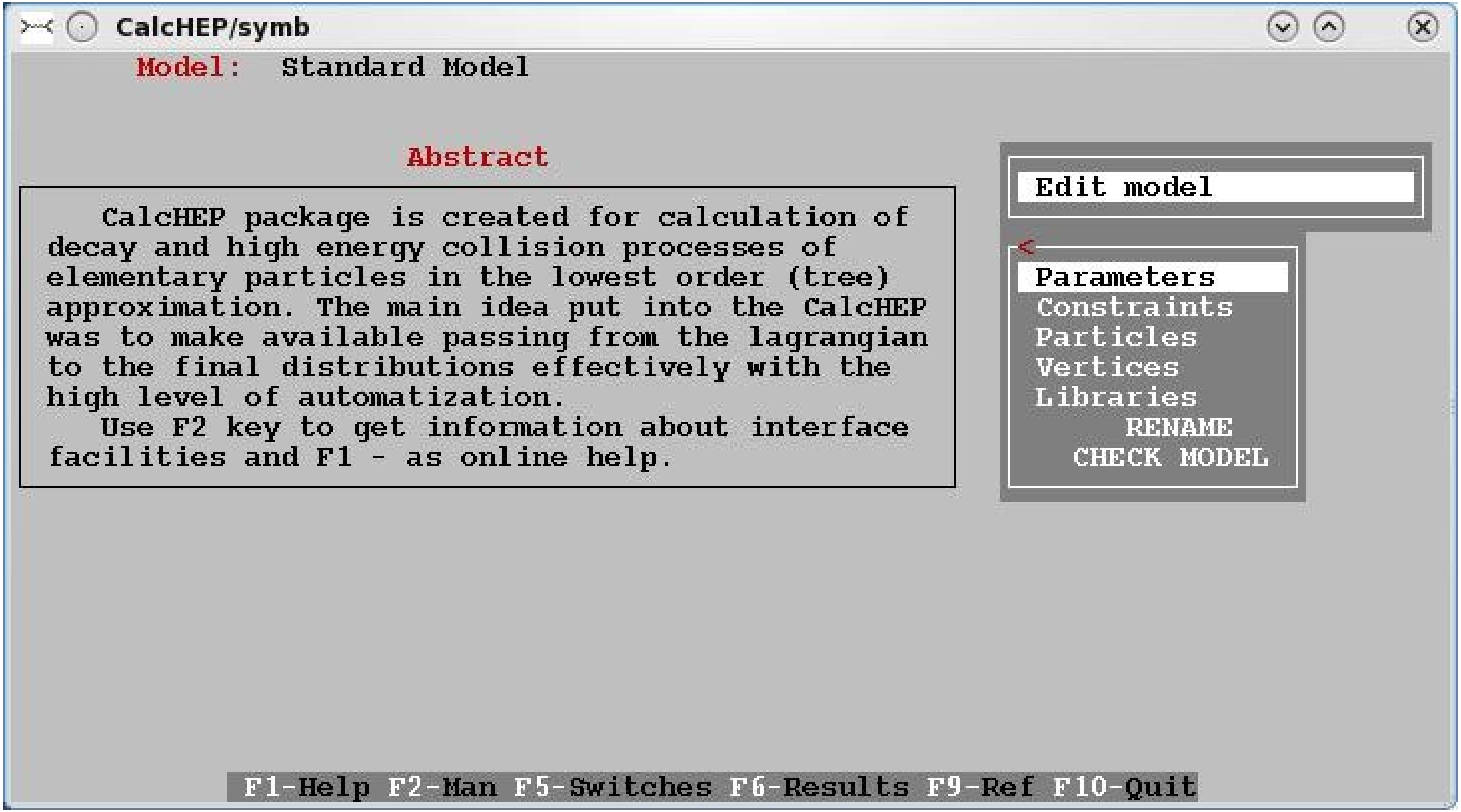


CalcHEP menu structure: symbolic part



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

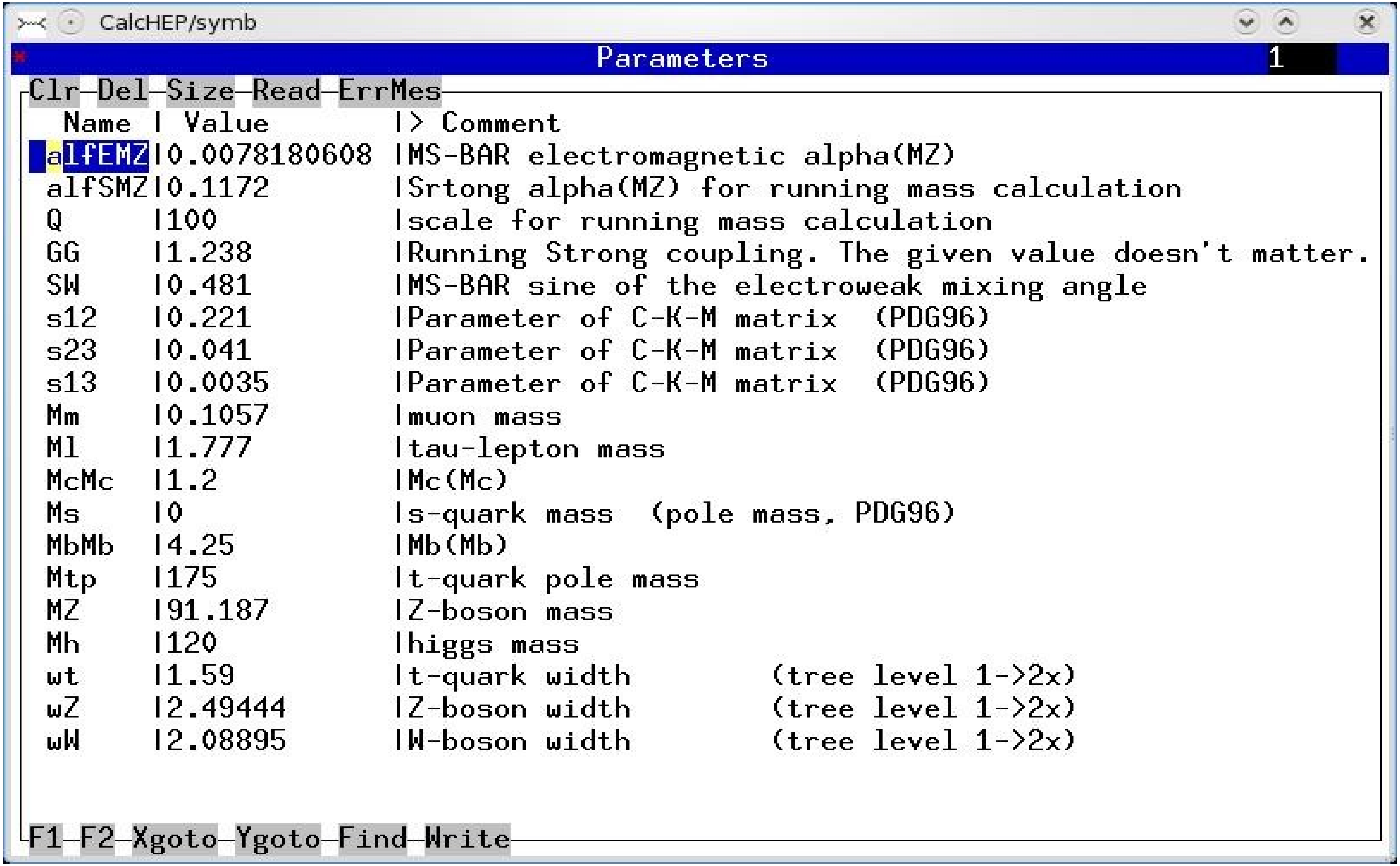
Clr-Del-Size-Read-ErrMes

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): funcxx.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)

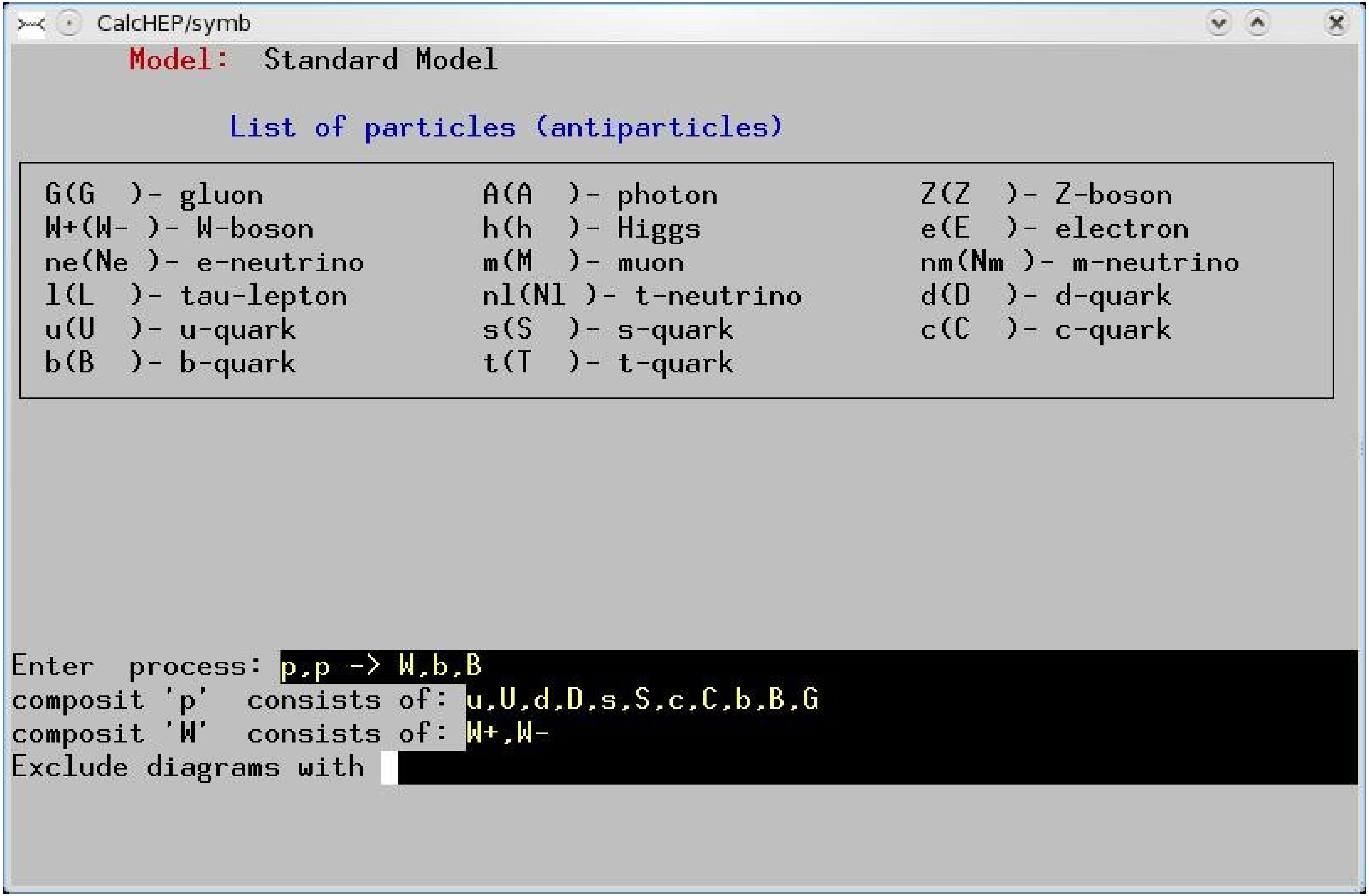
F1 F2 Xgoto Ygoto Find Write

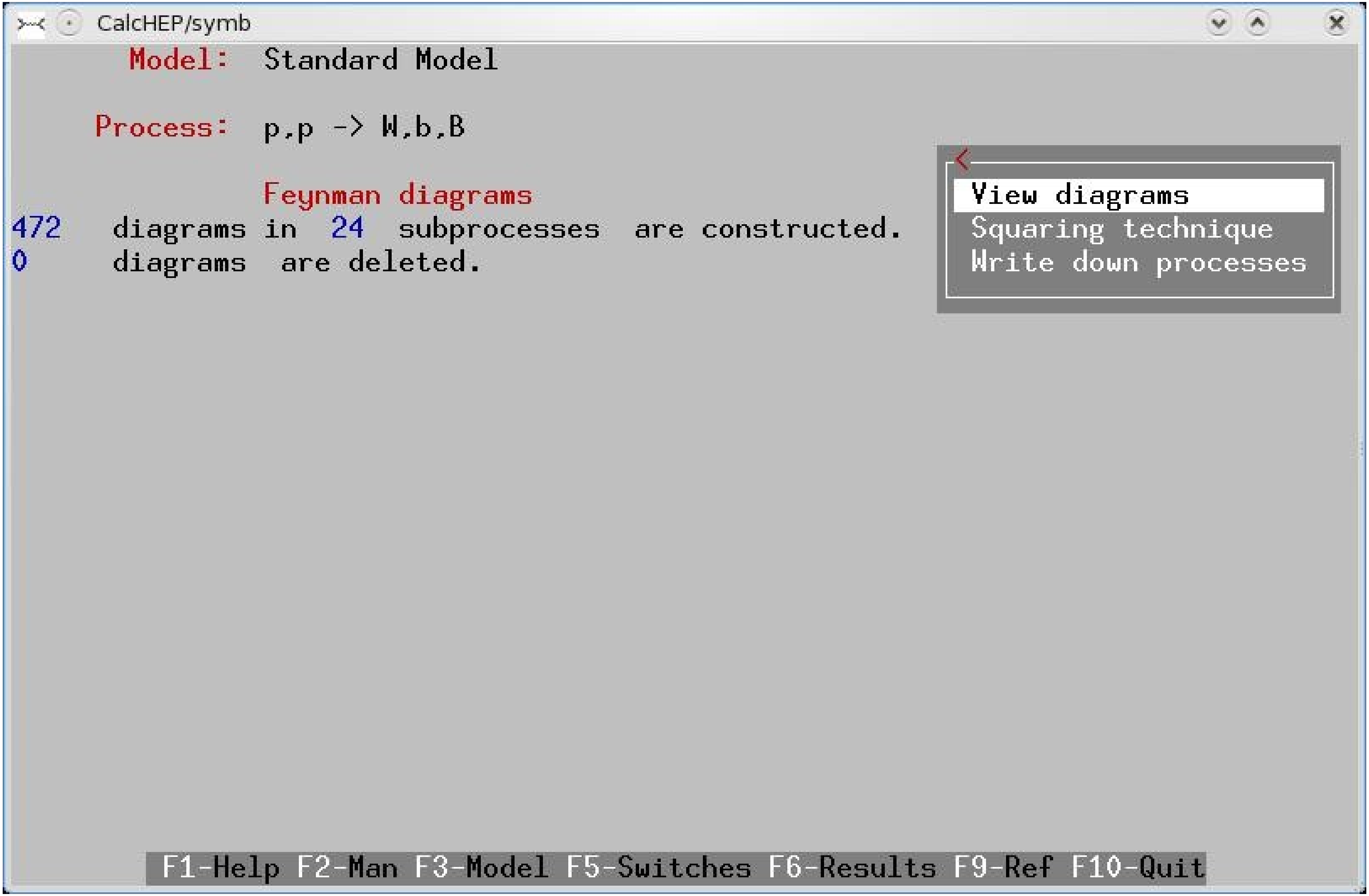
Principle KEYS for CalcHEP's GUI

Enter menu selection (forward)

Exit menu selection (back)

Help! (details on the menu choice)


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


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
Squaring technique
Write down processes
F1-Help F2-Man F3-Model F5-Switches F6-Results F9-Ref F10-Quit

CalcHEP/symb

Model: Standard Model

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

Feynman diagrams

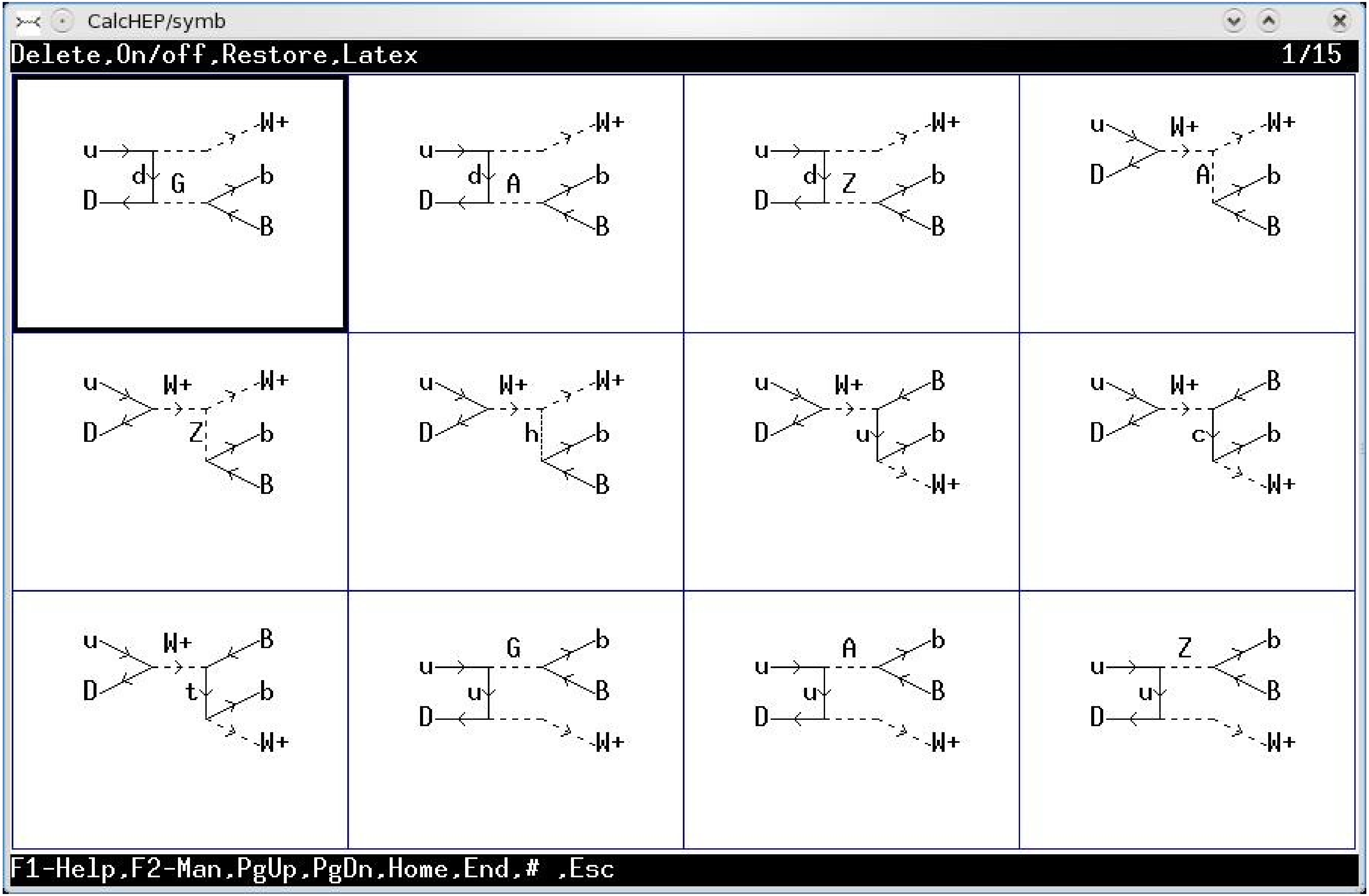
472 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.

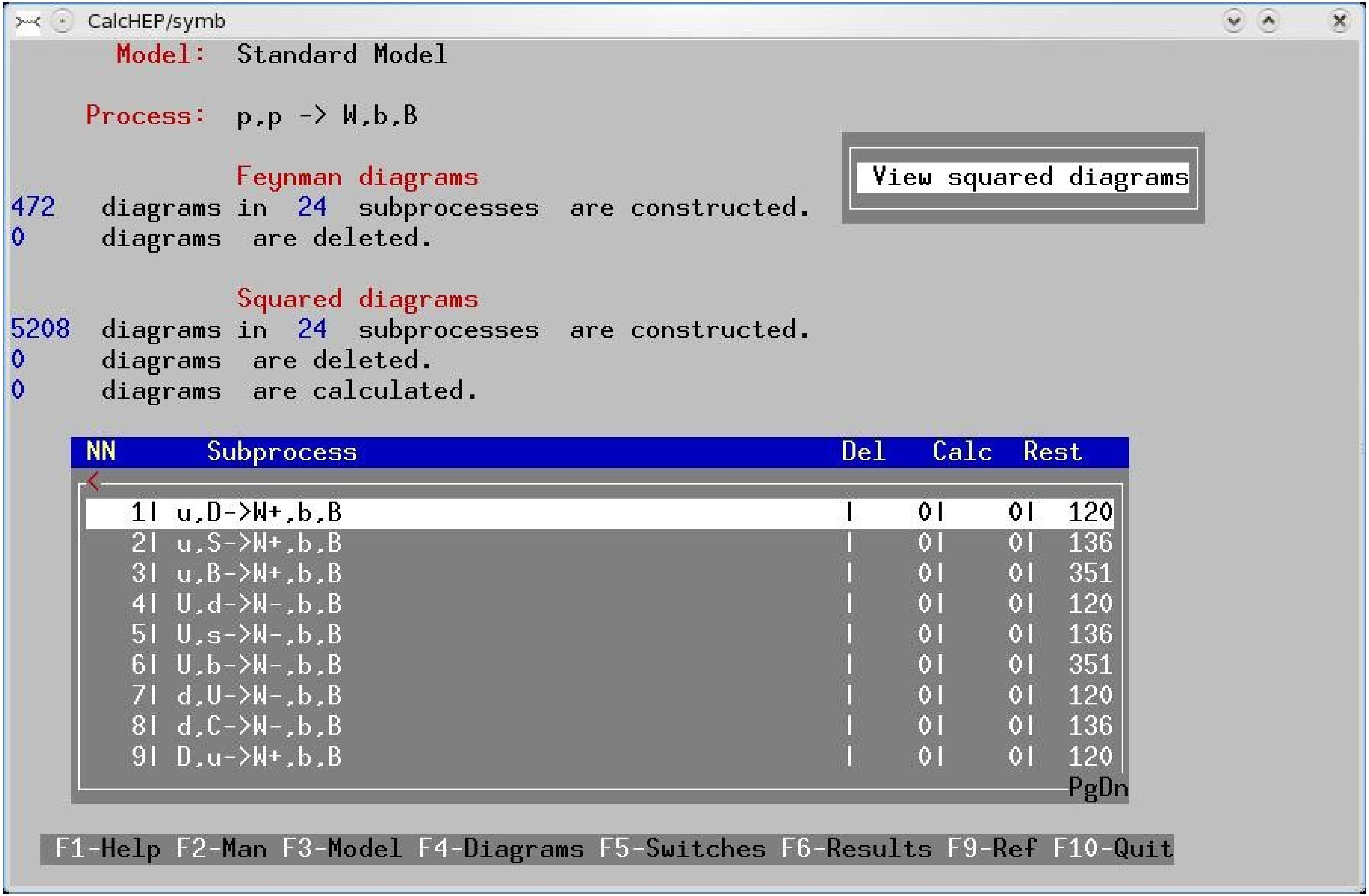
View diagrams

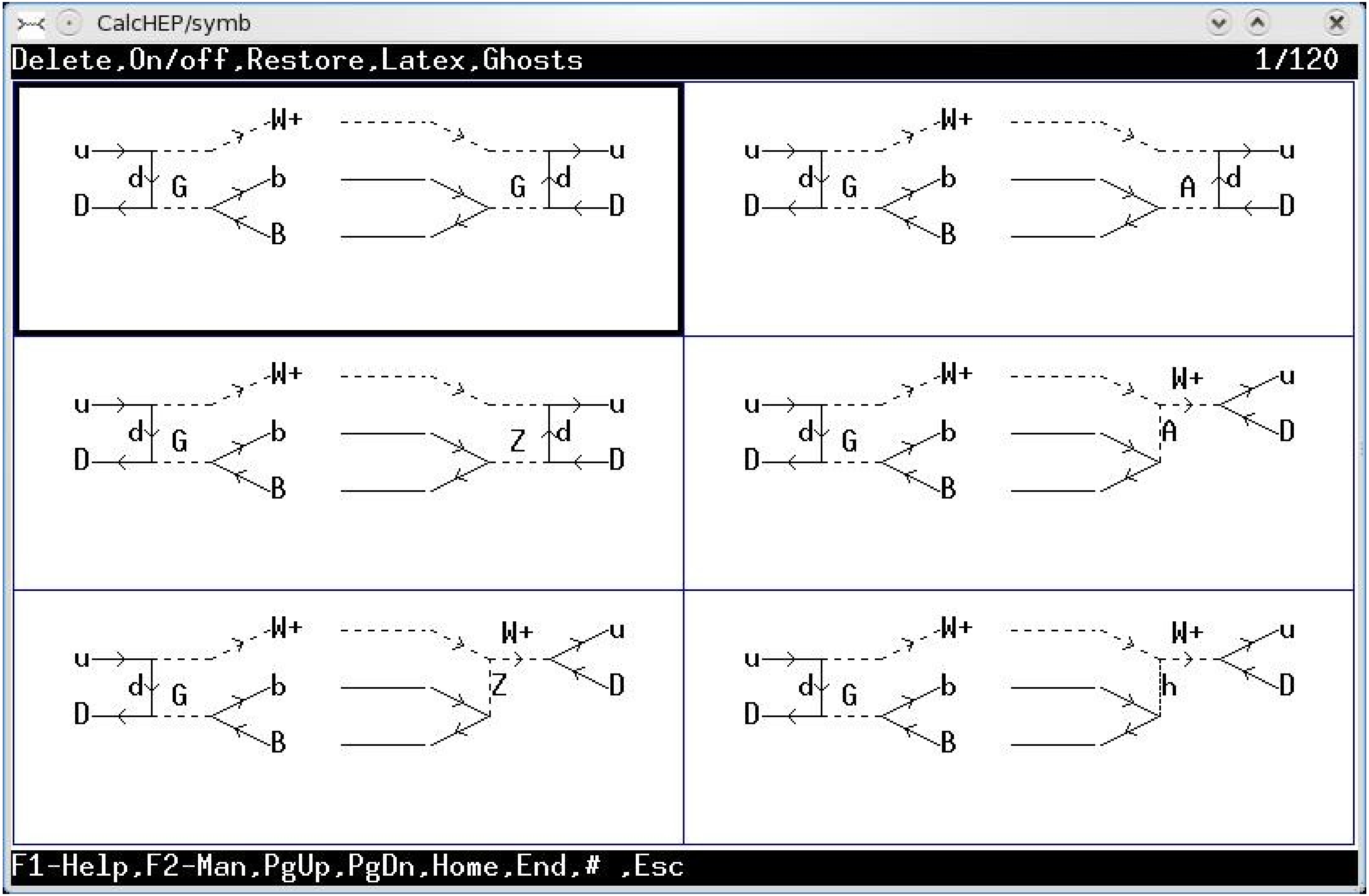
NN	Subprocess	Del	Rest
1	u,D -> W+,b,B	0	15
2	u,S -> W+,b,B	0	16
3	u,B -> W+,b,B	0	26
4	U,d -> W-,b,B	0	15
5	U,s -> W-,b,B	0	16
6	U,b -> W-,b,B	0	26
7	d,U -> W-,b,B	0	15
8	d,C -> W-,b,B	0	16
9	D,u -> W+,b,B	0	15
10	D,c -> W+,b,B	0	16
11	s,U -> W-,b,B	0	16

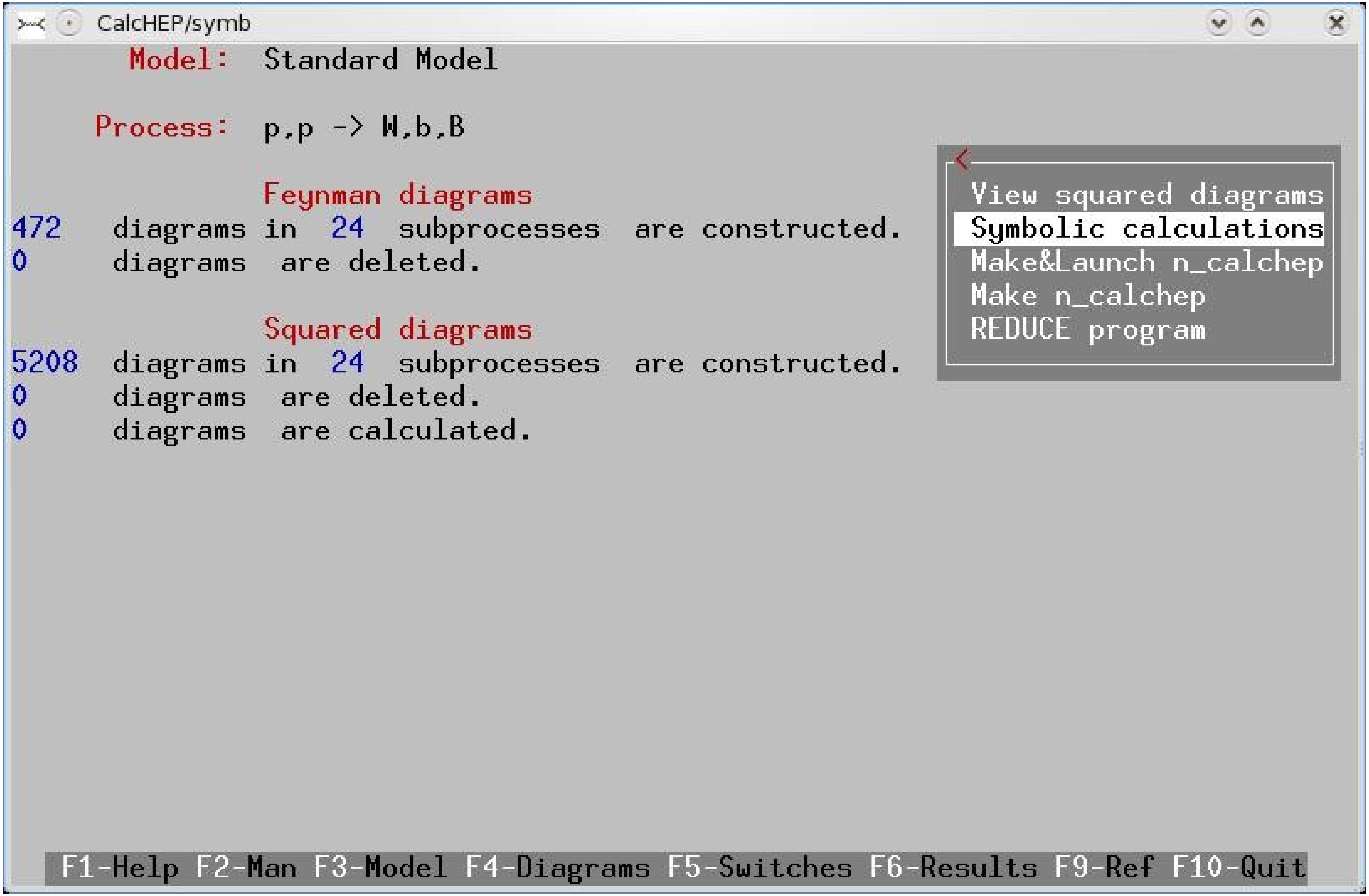
PgDn

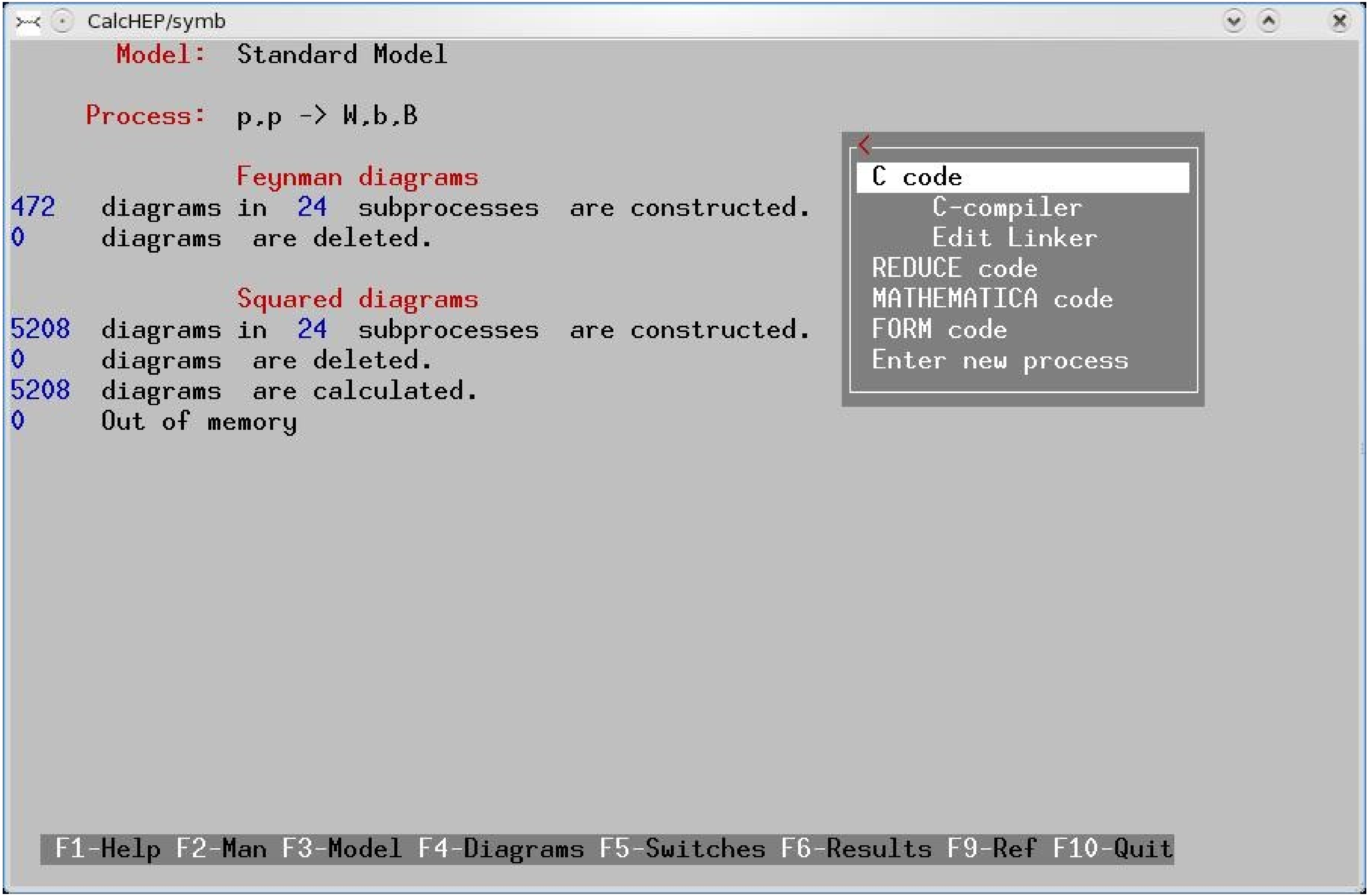
F1-Help F2-Man F3-Model F5-Switches F6-Results F7-Del F8-UnDel F9-Ref F10-Quit


CalcHEP/symb
Delete,On/off,Restore,Latex
1/15
F1-Help,F2-Man,PgUp,PgDn,Home,End,# ,Esc

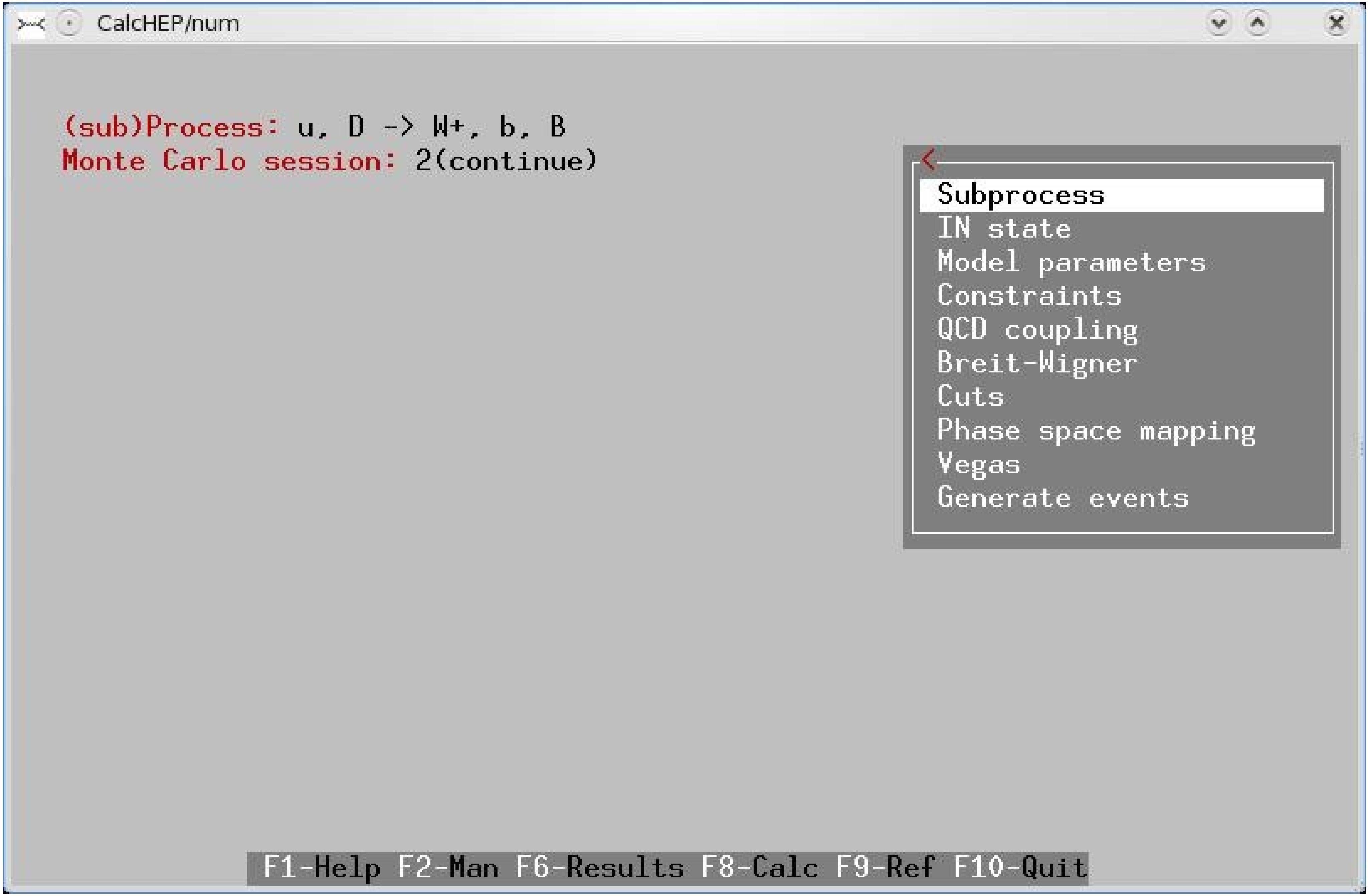

CalcHEP/symb
Model: Standard Model
Process: p,p -> W,b,B
Feynman diagrams
472 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.
Squared diagrams
5208 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.
0 diagrams are calculated.
View squared diagrams
NN Subprocess 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


CalcHEP/symb
Delete,On/off,Restore,Latex,Ghosts
1/120
F1-Help,F2-Man,PgUp,PgDn,Home,End,# ,Esc

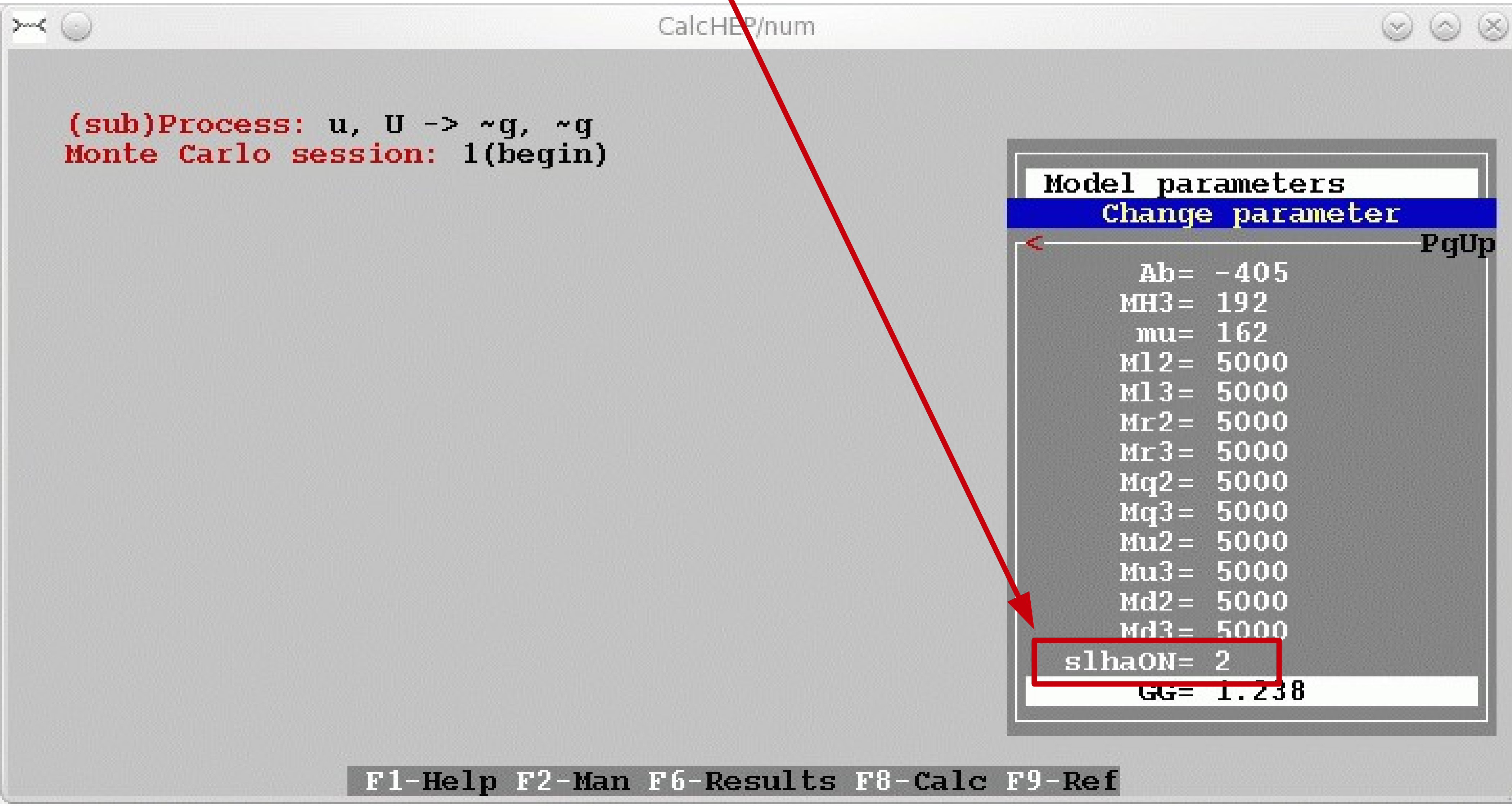

CalcHEP/symb
Model: Standard Model
Process: p,p -> W,b,B
Feynman diagrams
472 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.
Squared diagrams
5208 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.
0 diagrams are calculated.
View squared diagrams
Symbolic calculations
Make&Launch n_calchep
Make n_calchep
REDUCE program
F1-Help F2-Man F3-Model F4-Diagrams F5-Switches F6-Results F9-Ref F10-Quit


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
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

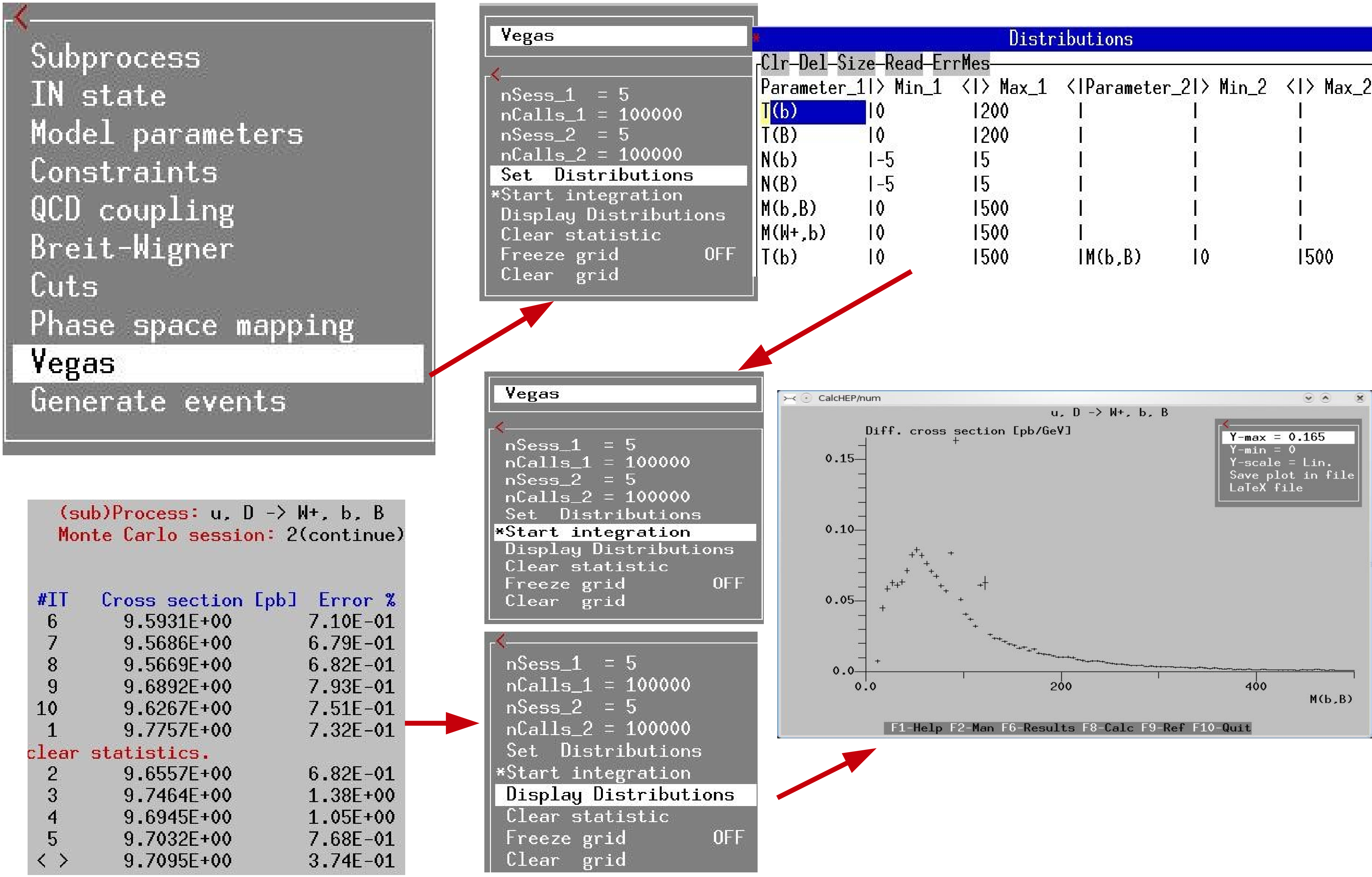
```
CalcHEP/symb

    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

 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
```


CalcHEP/num
(sub)Process: u, D -> W+, b, B
Monte Carlo session: 2(continue)
Subprocess
IN state
Model parameters
Constraints
QCD coupling
Breit-Wigner
Cuts
Phase space mapping
Vegas
Generate events
F1-Help F2-Man F6-Results F8-Calc F9-Ref F10-Quit

Option to read-write LHA file (MSSM case)



Total cross section and distributions



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 = 7.8180609999999999E-03
    alfSMZ = 1.1720000000000000E-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
............................................
............................................
```

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.
```

Few words about 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 $\mathcal{L}_{GF} = -\frac{1}{2}(\partial_\mu G^{\mu}_{a})^2 + i g_s f^{abc} \bar{c}^a G^{b}_{\mu} \partial^\mu c^c,$

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 e-mail from Andrei!

```
model uedqwd/3.

parameter ee = 0.3133: 'Electric charge', R=1e-4.

vector A/A:photon, A1/A1:(photon1, mass Ma1=1000), ....
                       ^
scalar s1/s1:(phot51, 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

Home
Symbolic Results
Numerical Results
Events Library
Process Library
Help

Thank you for using CalcHEP!
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
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	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!

- 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			

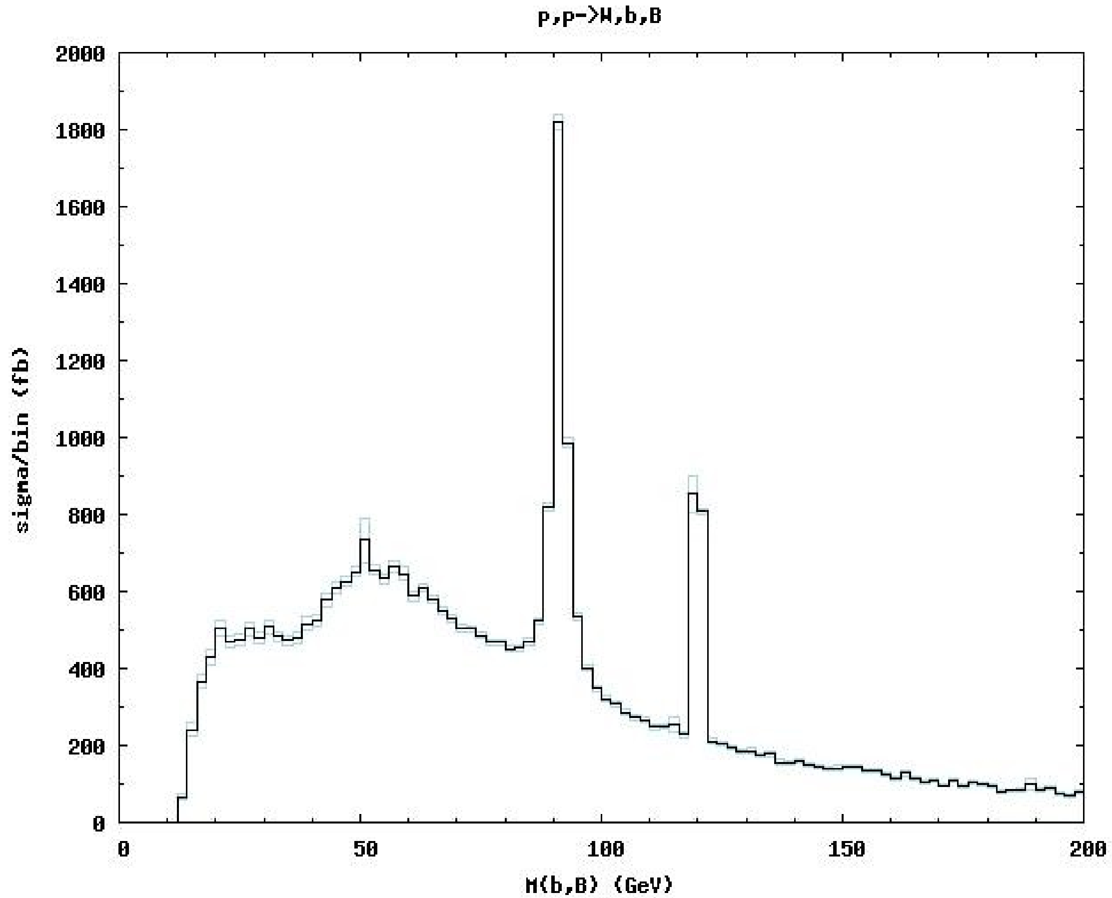
CalcHEP batch interface: results from CalcHEP in one shot

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

Home
Symbolic Results
Numerical Results
Events Library
Process Library
Help

Thank you for using CalcHEP!
Please cite arXiv:0000.0000

Distributions



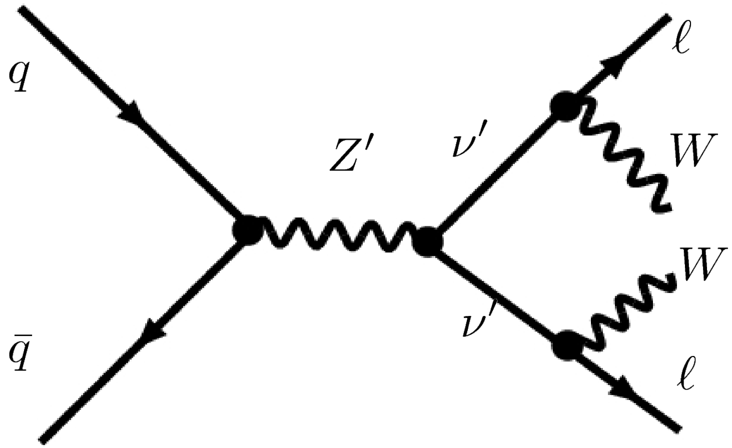
p,p->H,b,B

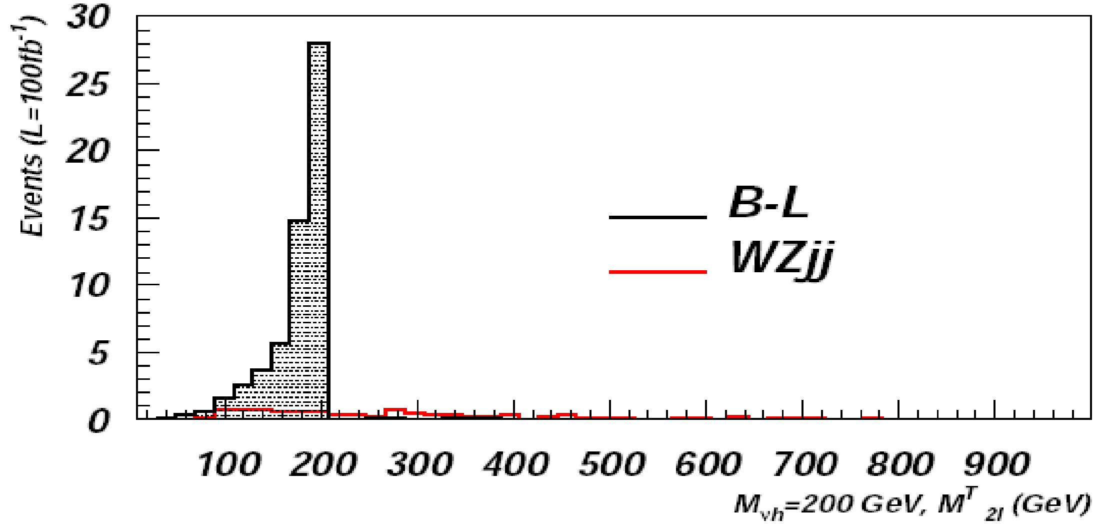
Recent applications: B-L extension of SM

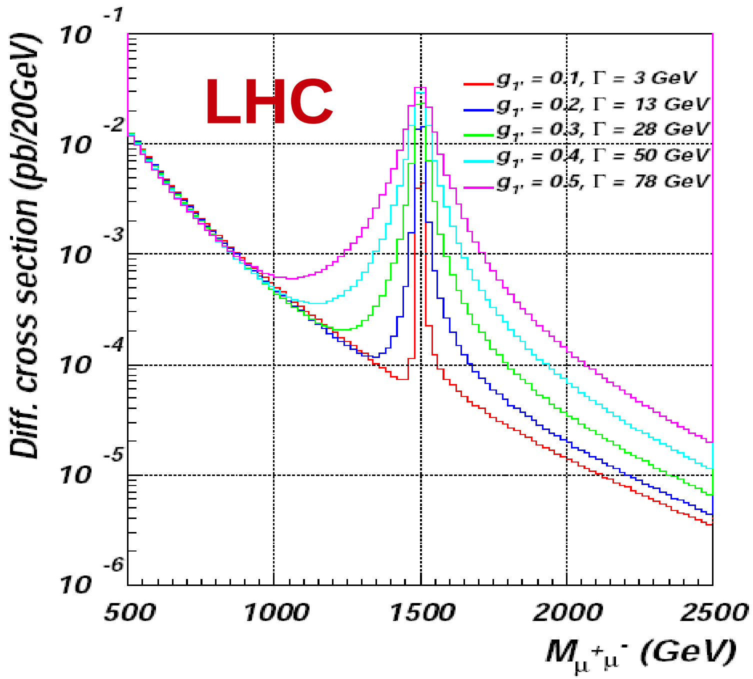
Extra U(1)' : Z', heavy long leaving neutrino

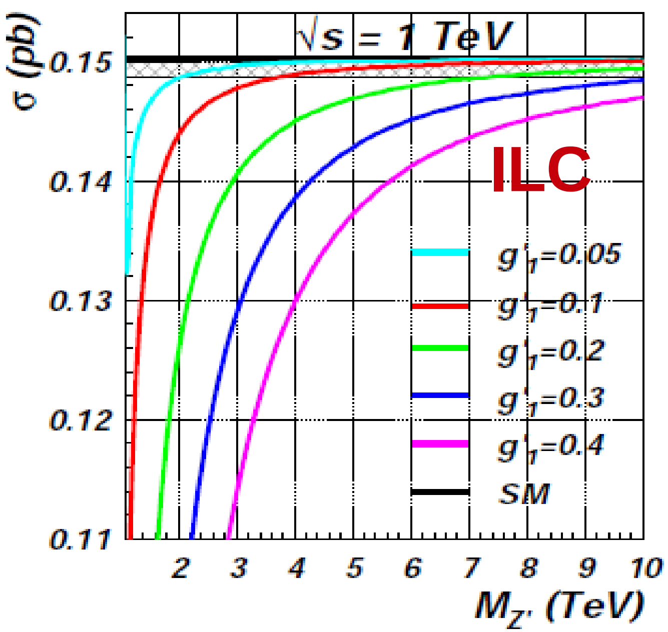
(in collaboration with S. Moretti, L. Basso, M.Pruna, C. Shepherd)

arXiv:0812.4313
arXiv:0903.4777









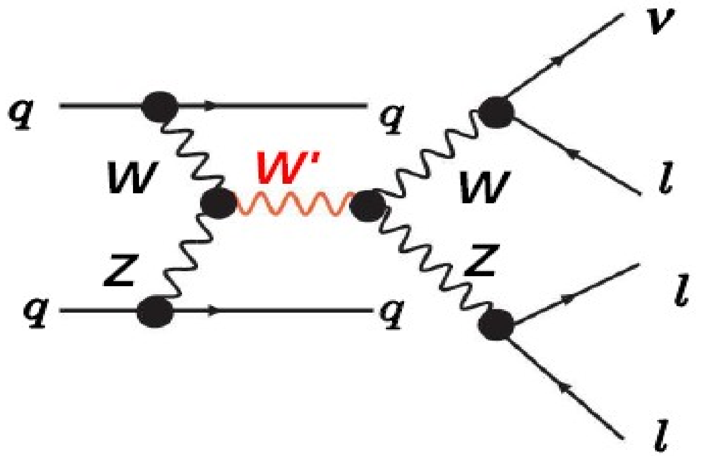
Recent applications:

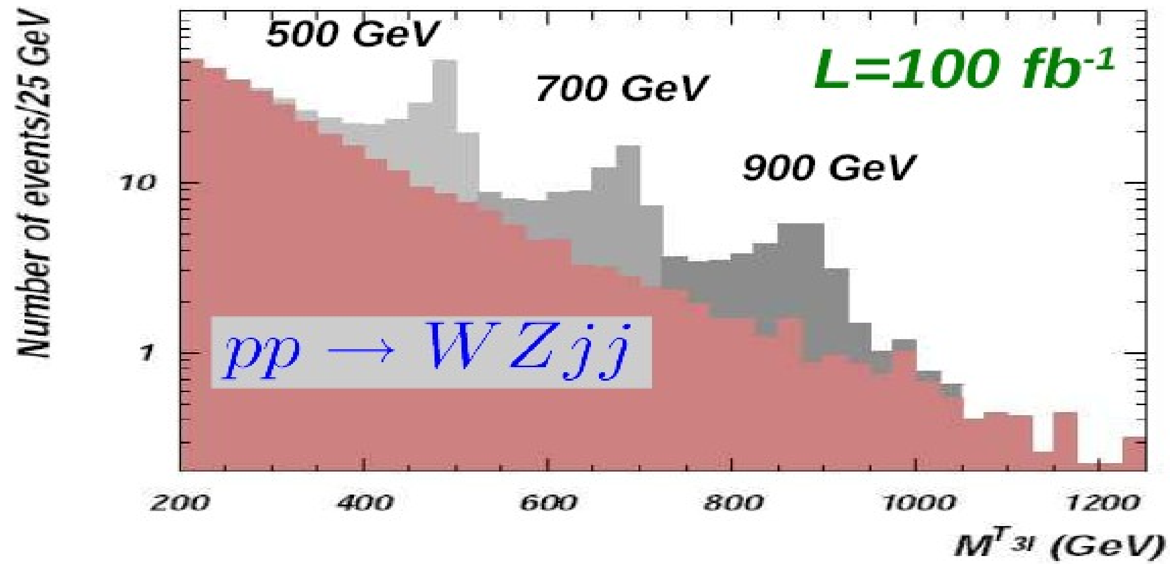
W' 3-lepton signatures from 3-site Higgsless model

arXiv:0708.2588

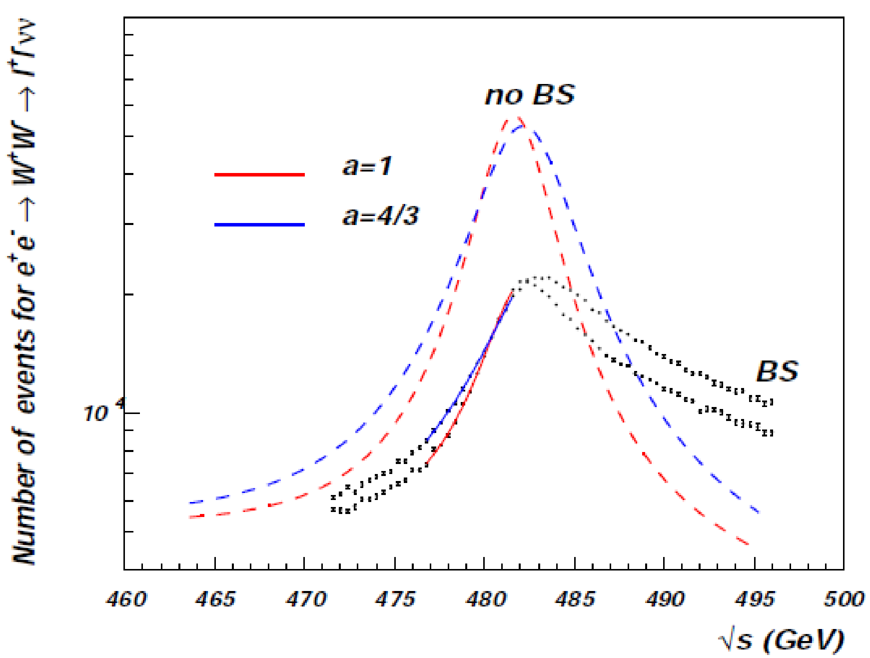
LHC reach for WZ->W' process

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





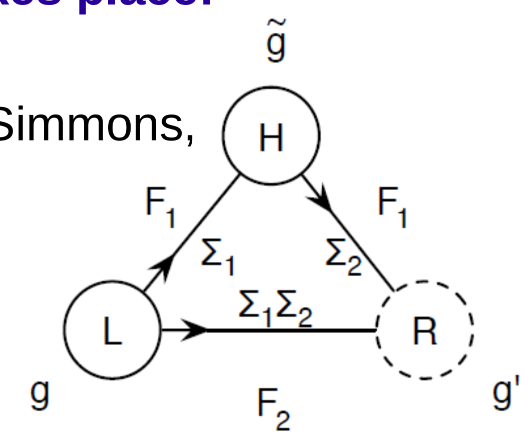
Z' line shape for $e^+e^- \to W^+W^- \to l^+l^-\nu\nu$, $\sqrt{s}$=500 GeV



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

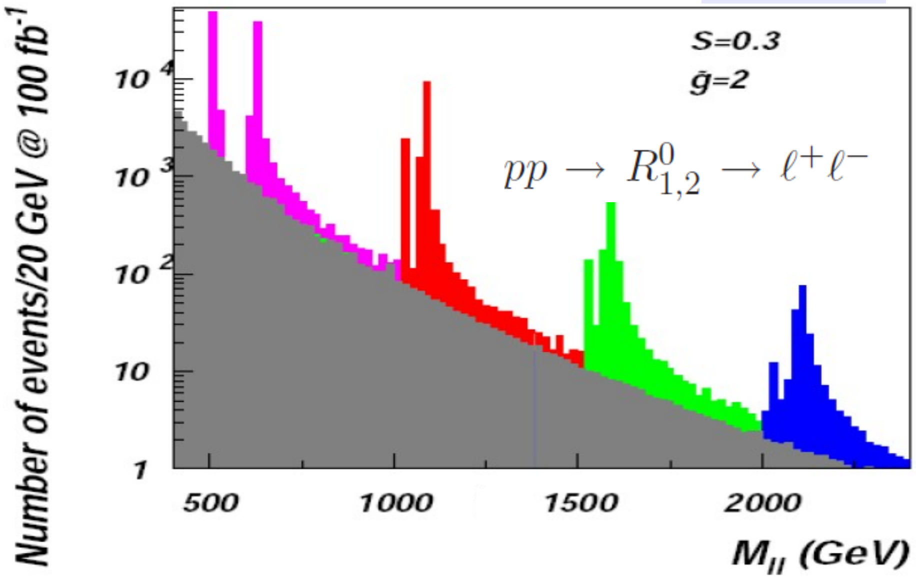
$N_c = 3$, $N_f = 2$
in the two-index symmetric
$SU(2)_L \times SU(2)_R \to SU(2)_V$
two triplets of heavy mesons

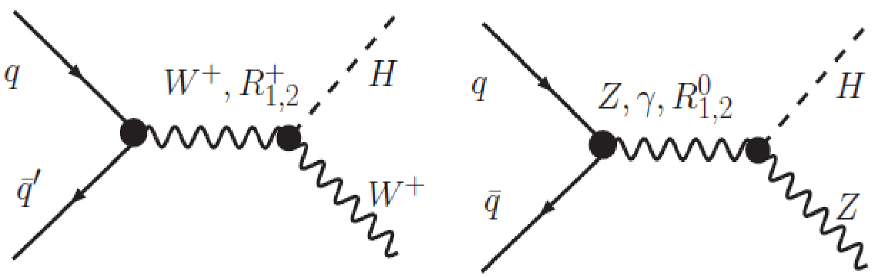
LHC

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

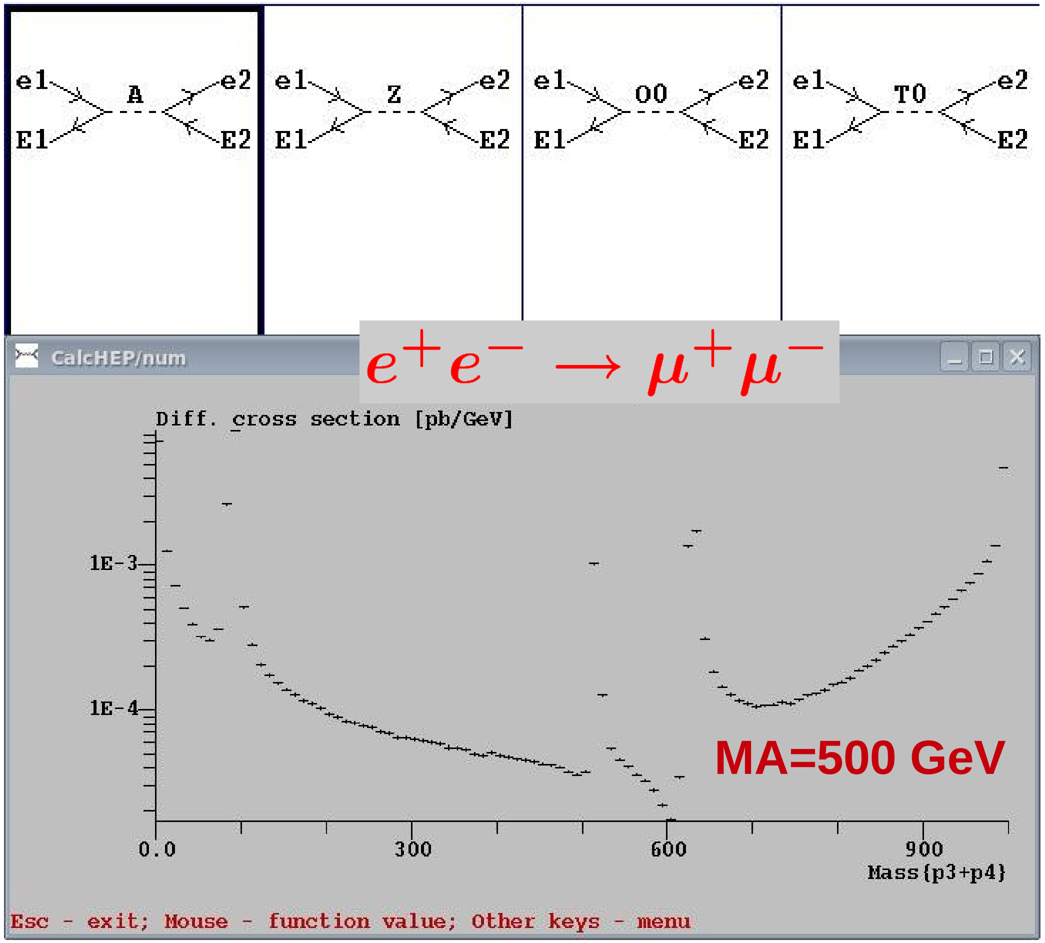
and

$R_1^0(R_2^0)$





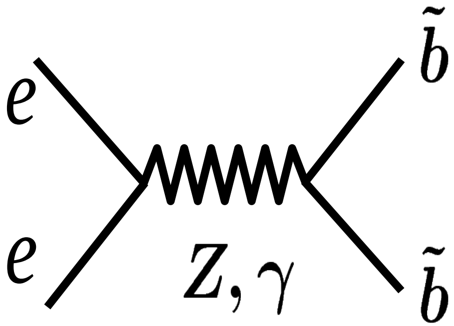
ILC@1TeV
(work in progress)

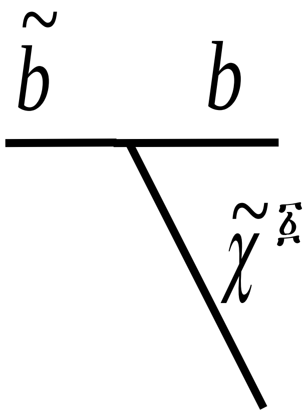


Recent applications:
sbottom coannihilation scenario at ILC

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:

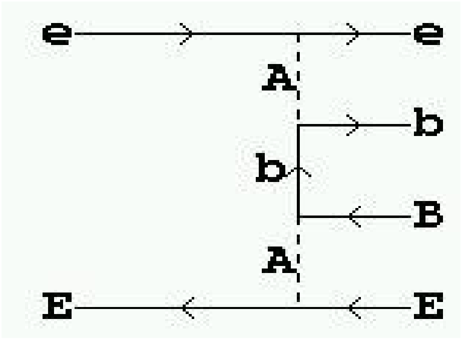




the small mass split leads to very soft b-jets and missing p_T.

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

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

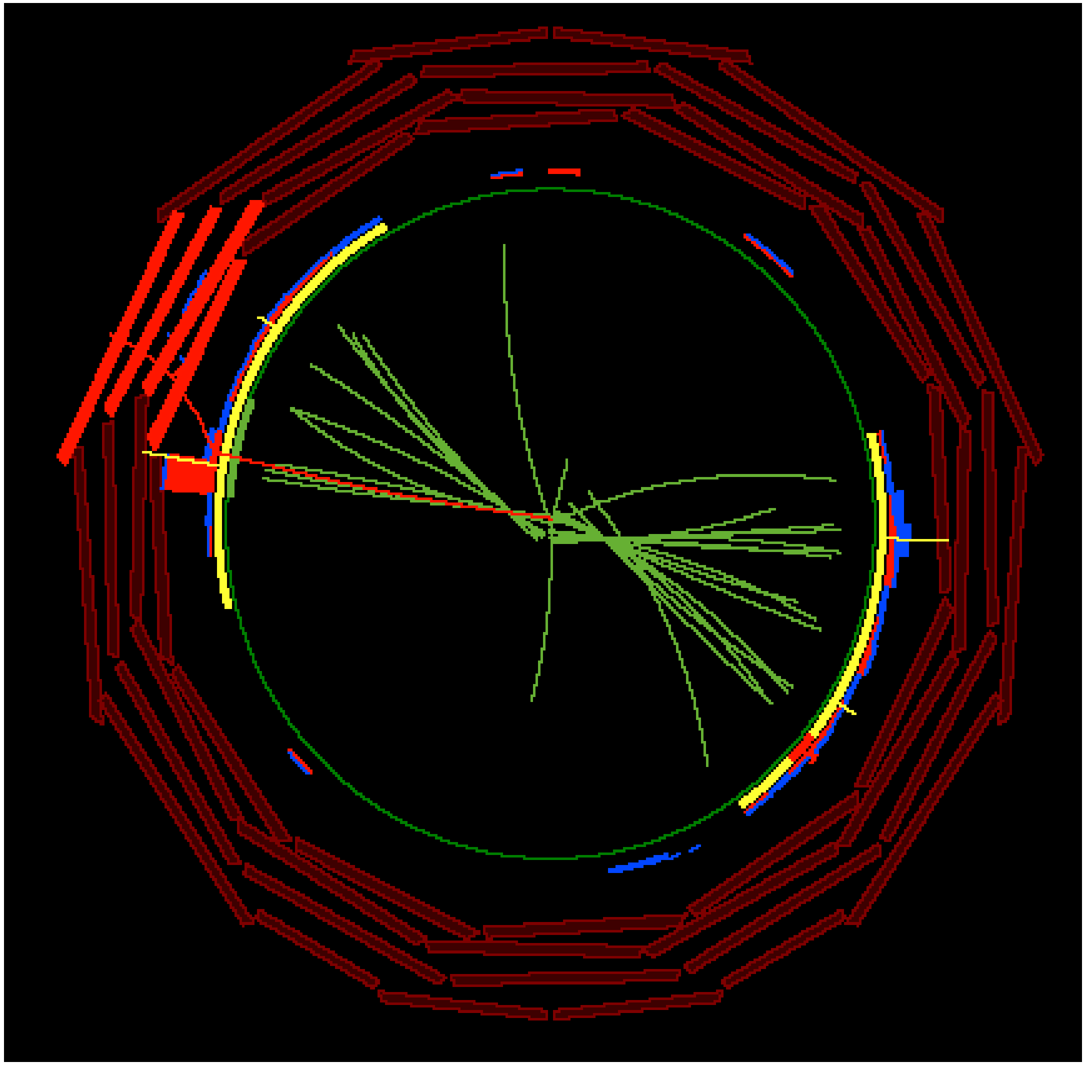
$$-m_e^2 \frac{(E_1 - E_3)^2}{E_1 E_3}$$

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

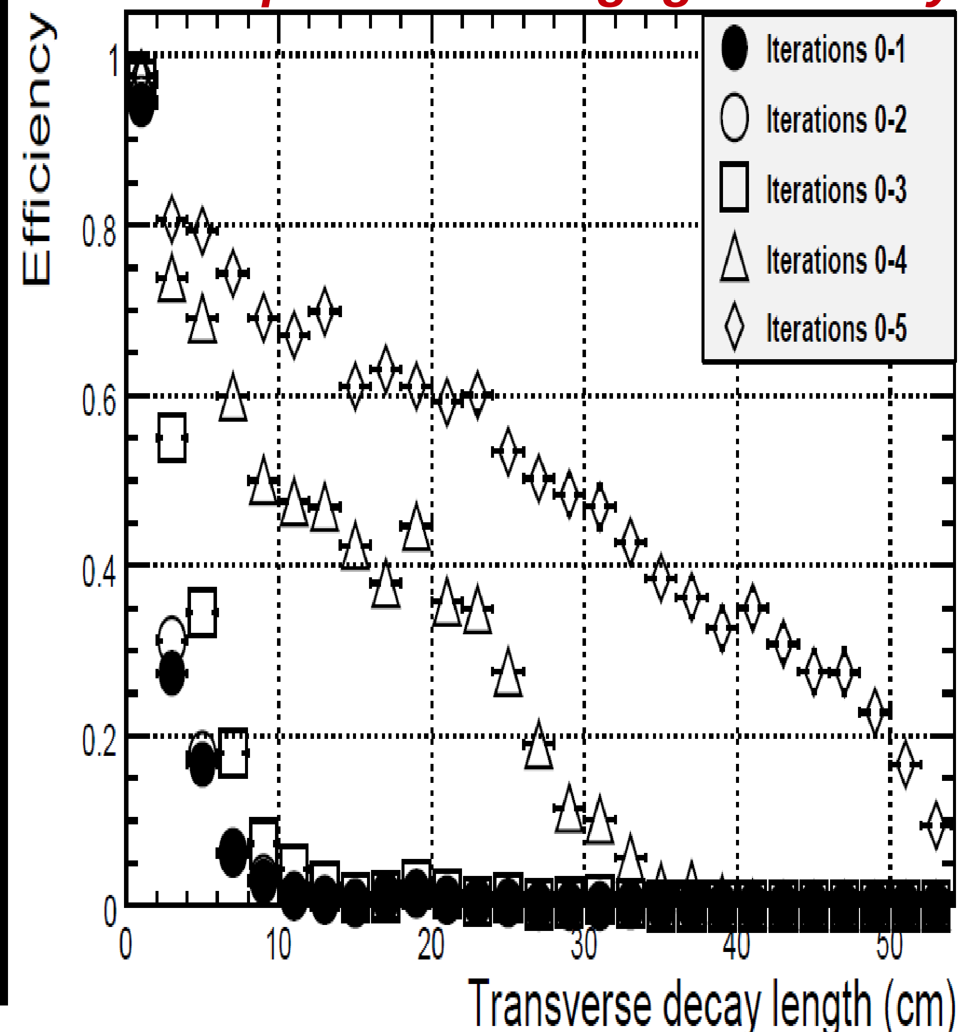
Ongoing project:

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

In collaboration with Ian Tomalin and Arnaud Gay



Improved trackigng efficiency

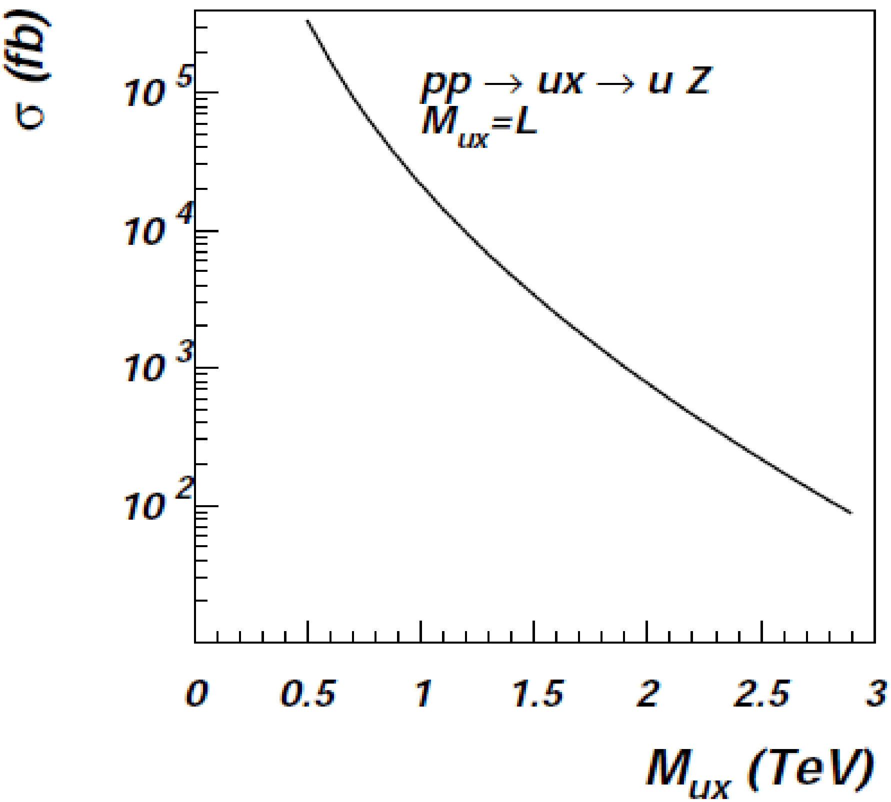


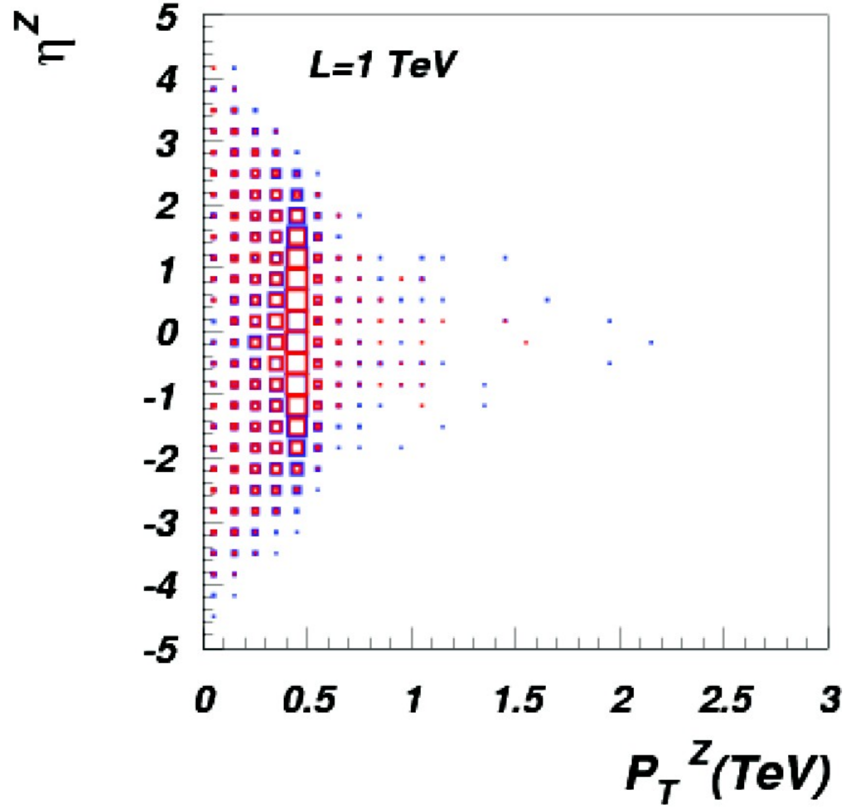
2 displaced vertices from 2 heavy photons decay

Ongoing project:
Boosted Z-bosons

In collaboration with James Jackson and Claire Shepherd-Themistocleous

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

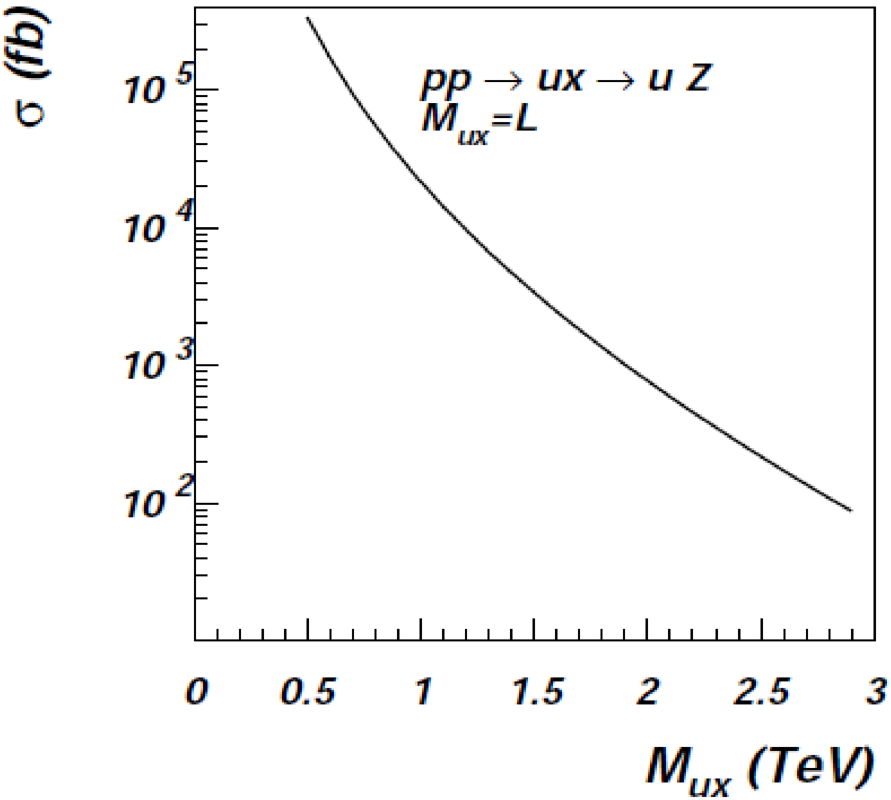


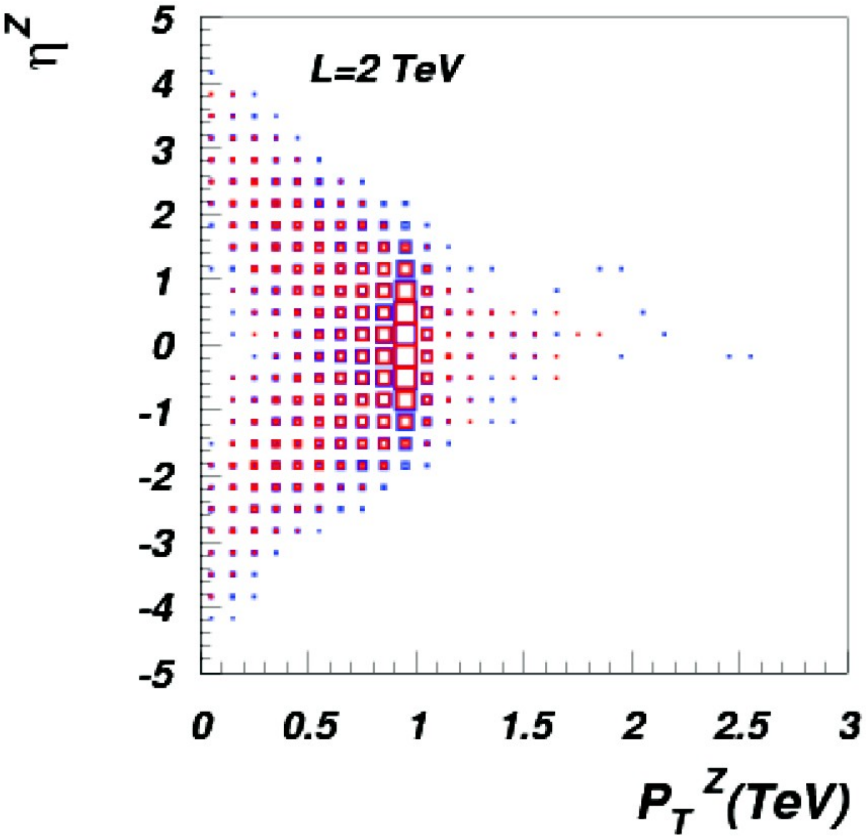


Ongoing project:
Boosted Z-bosons

In collaboration with James Jackson and Claire Shepherd-Themistocleous

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





Ongoing project:
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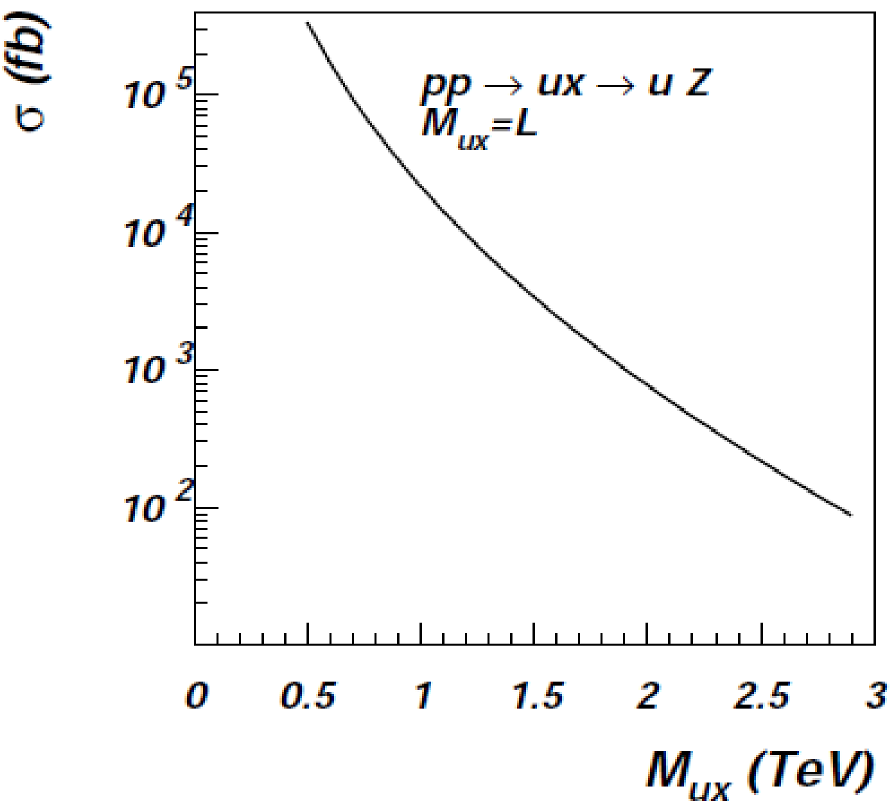
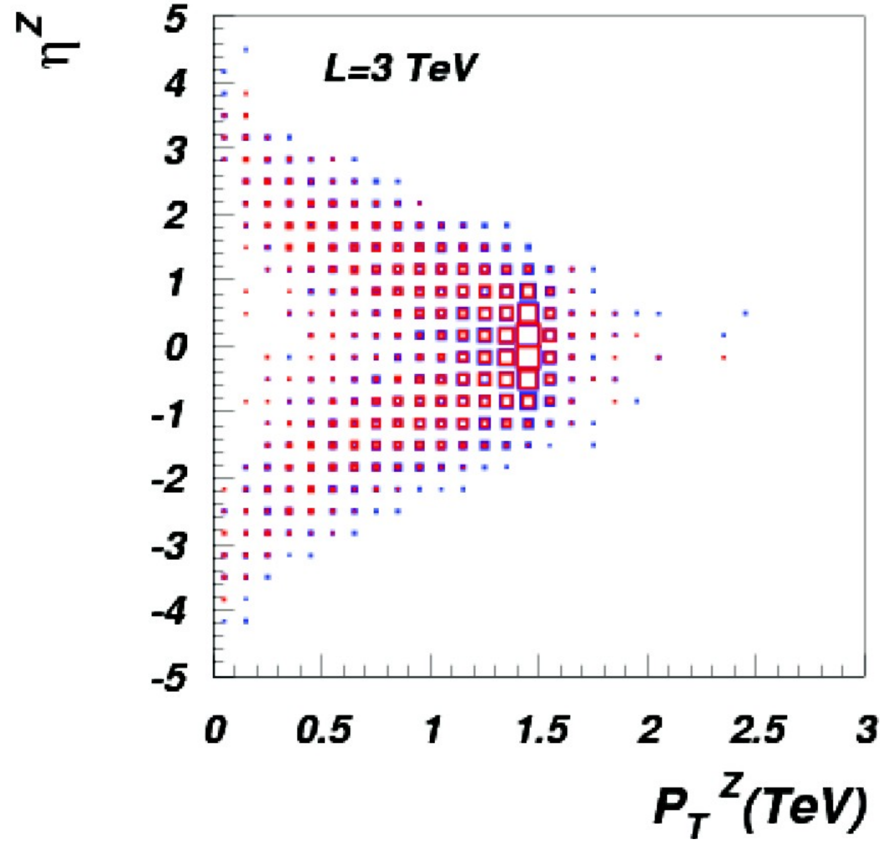




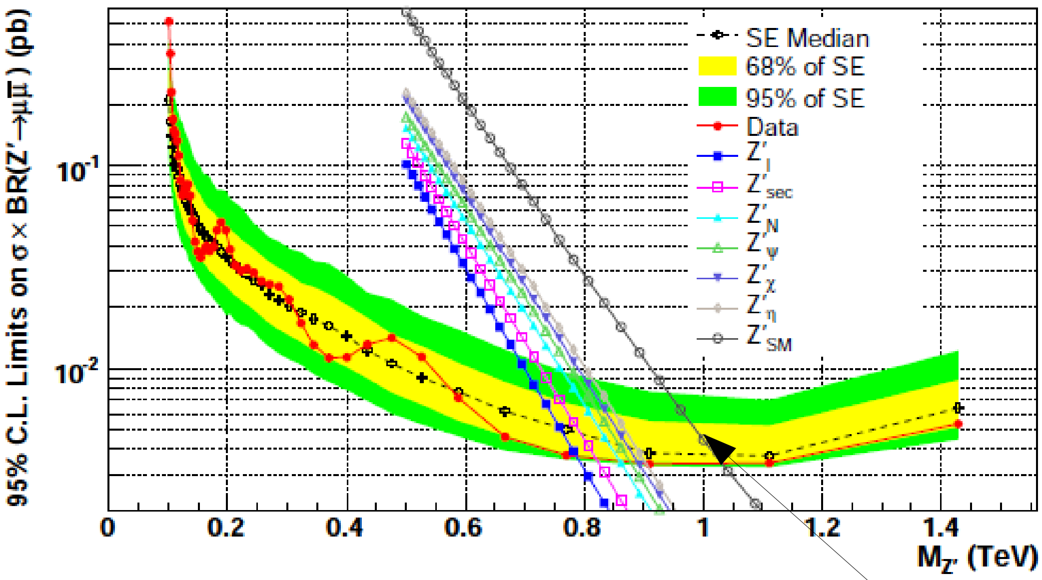
- ***Motivated by several promising candidates for New Physics such as***
  - *SUSY (cascase squark and gluinos decays)*
  - *Technicolor (W' -> WZ decays)*
- ***Study of multiparticle final states should be performed for efficiency estimation***

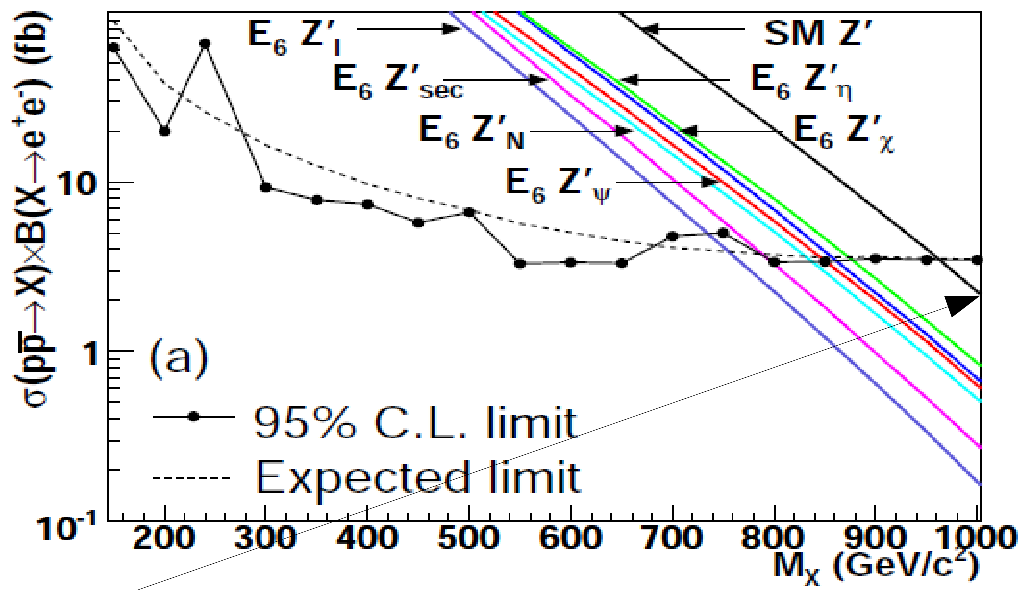
One more remark on why experimentalists should talk more to theorists

arXiv:0811.0053 di-electrons

CDF

arXiv:0810.2059 di-muons





Z' model	Z' mass limit
Z'_I	789
Z'_{sec}	821
Z'_N	861
Z'_ψ	878
Z'_χ	892
Z'_η	904
Z'_{SM}	1030

same point with cs different by factor 2!

signal definition does not include interference:
s=σ[pp->Z'->e+e-(m+m-)]
rather than
s=σ[pp->γ/Z/Z'->e+e-(m+m-)]-σ[pp->Z'->e+e-(m+m-)]

Future plans

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

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!

- **Powerful tool which**

  should not be blindly trusted or blamed !

Summary

- **It is very productive workshop, we should keep this tradition**
- **Important common projects, interesting new results**
- **we have powerful tools**
  - CalcHEP/LanHEP are among them – for new physics studies, implementation of new models is easy: MSSM, NMSSM, LHT, UET, Walking Technicolor models have been already implemented (as well as many more!)
- **Connection to experiment is crucial**
  - Creating of model database
  - Model validation
  - Traceable tag for LHE events
- **Let do our best to constructively combine our expertise!**