Practical introduction into selected TOOLS for High Energy Physics

Alexander Belyaev

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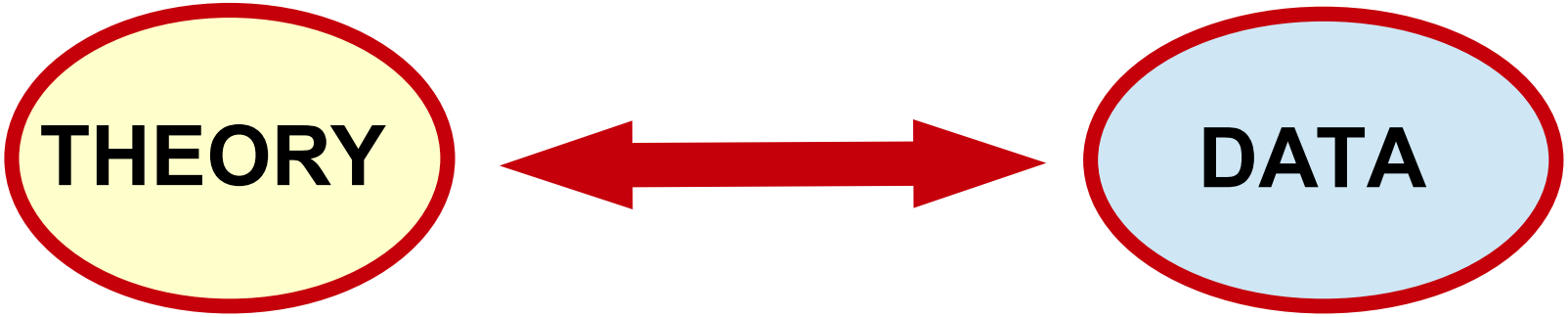
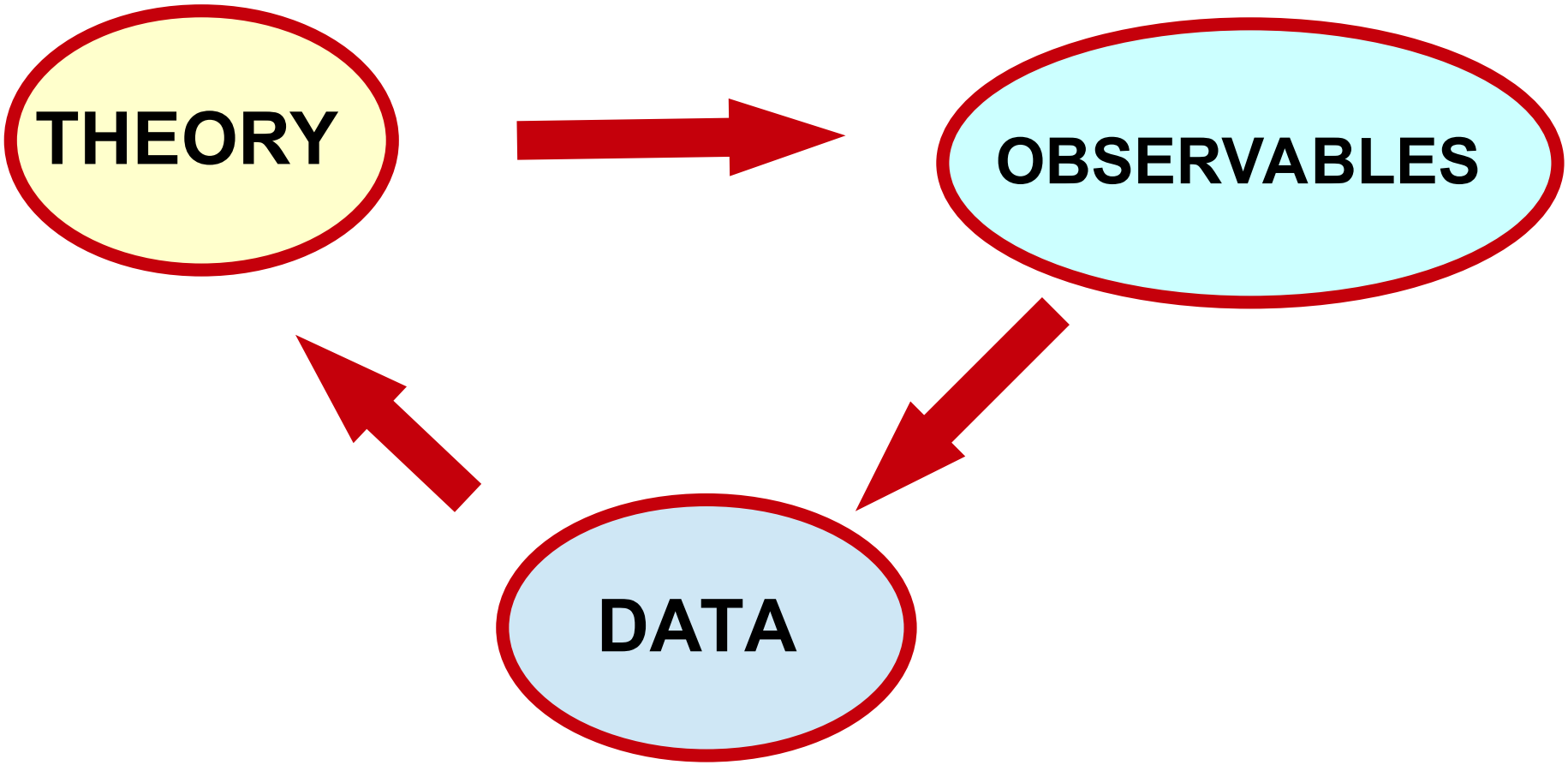
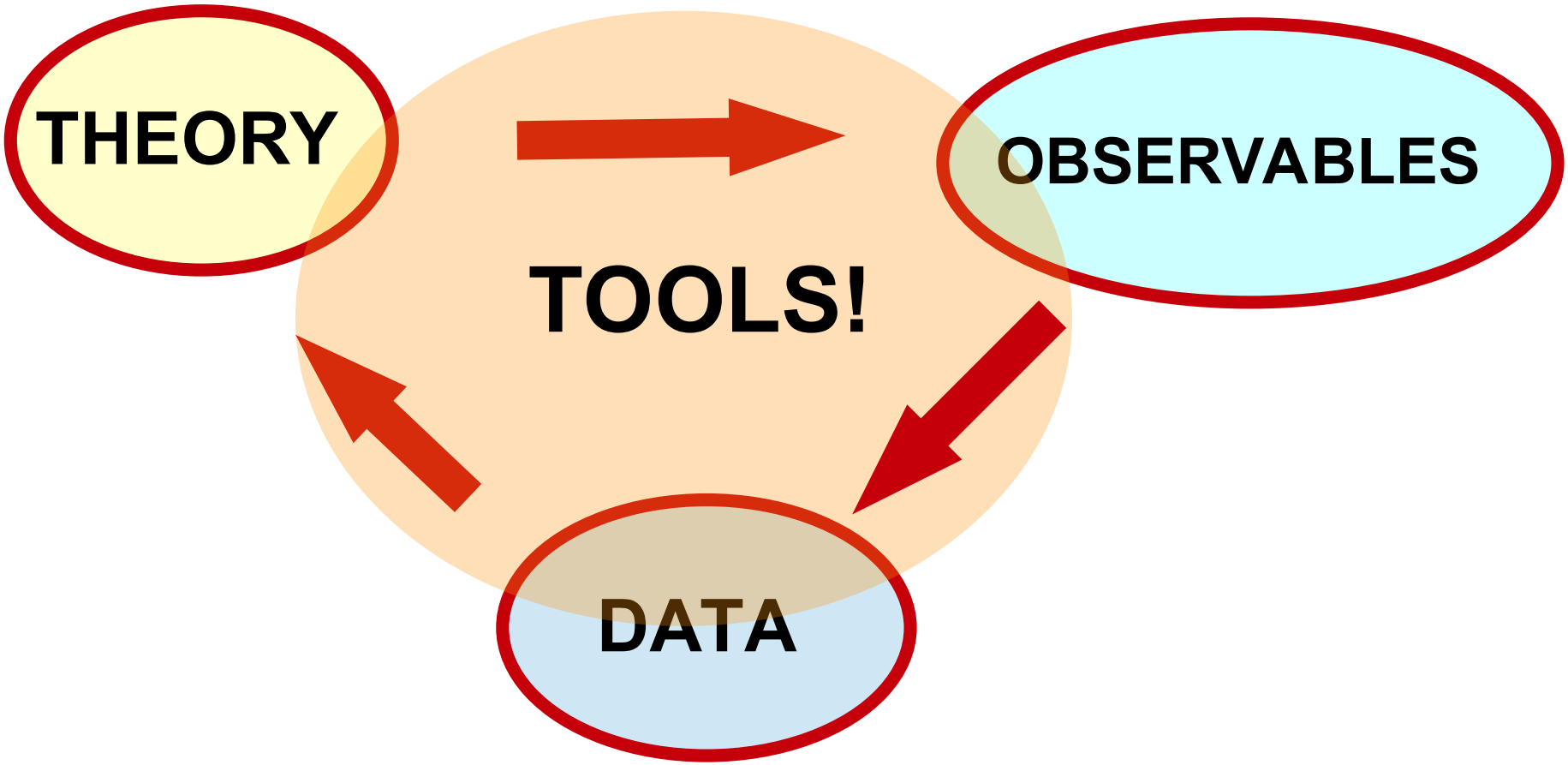
To test theory we need
theory ↔ data link
which is actually a non-trivial story



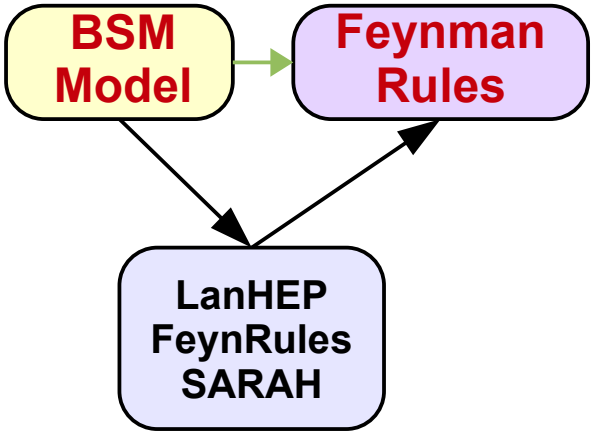
theory ↔ data requires observables to be compared with data



theory ↔ data requires observables to be compared with data and we need TOOLS to do this!



Tools for theory → observables link



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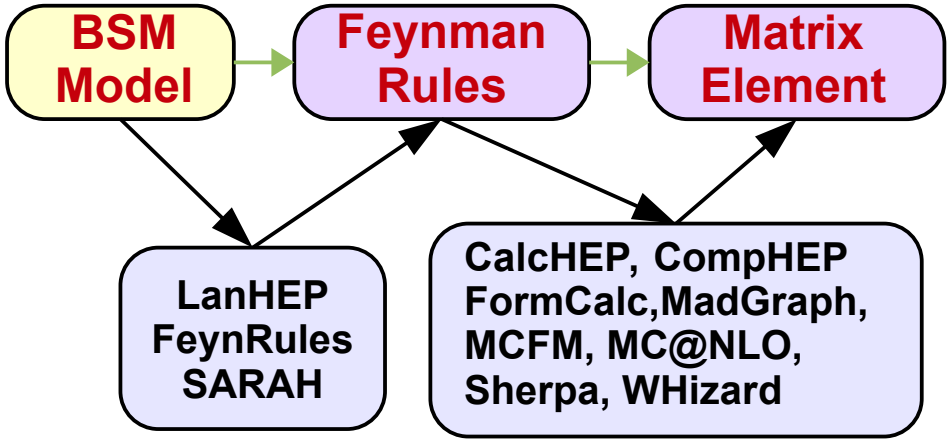

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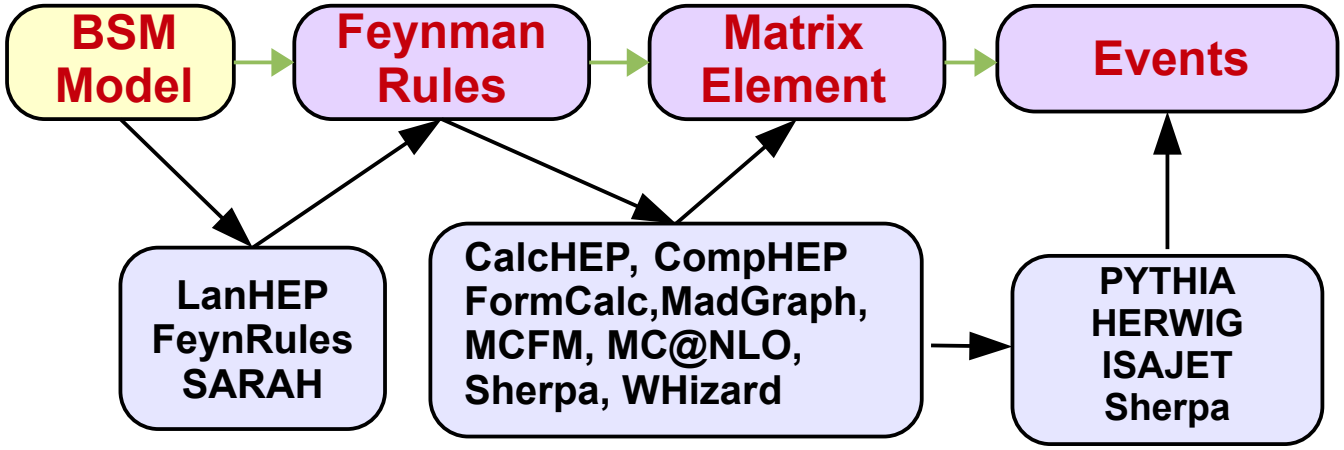

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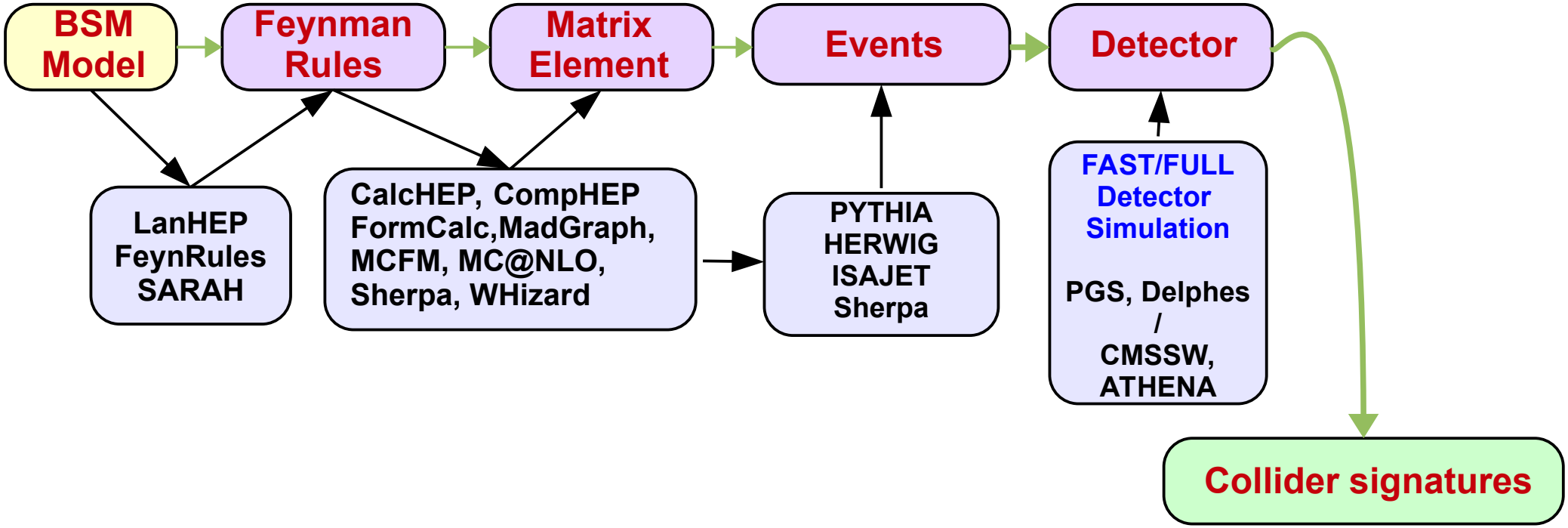
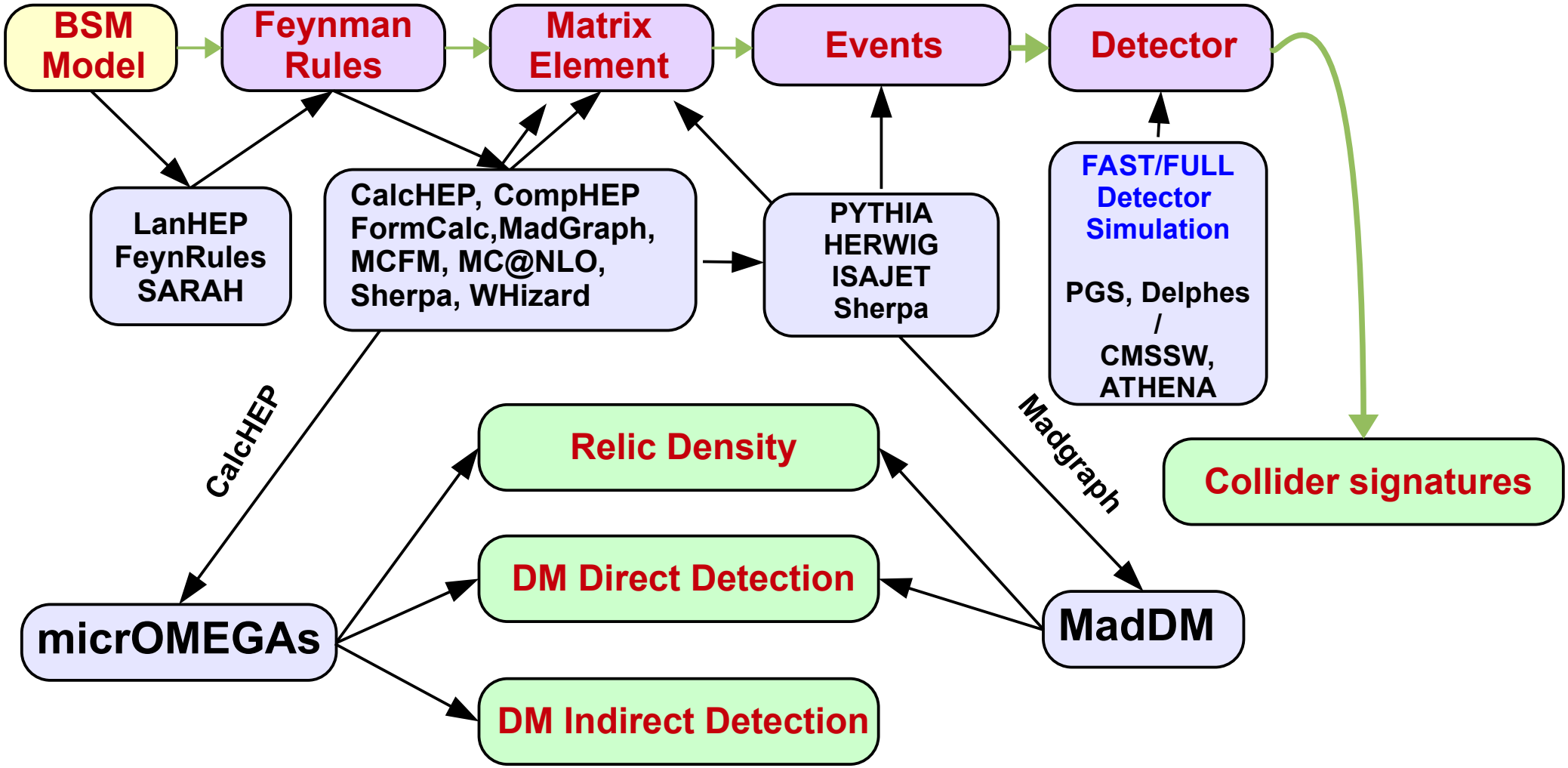


Tools for theory → observables link



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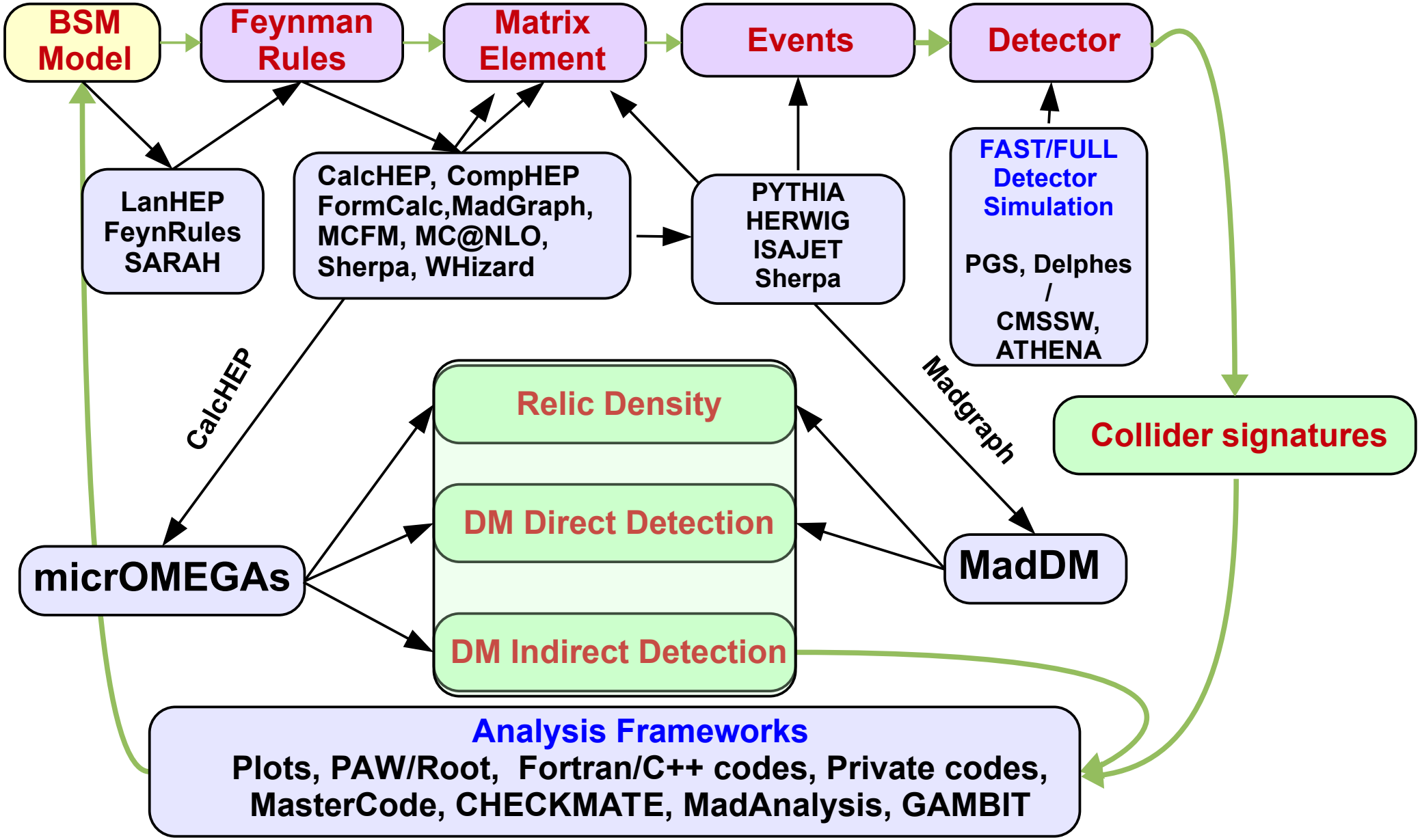

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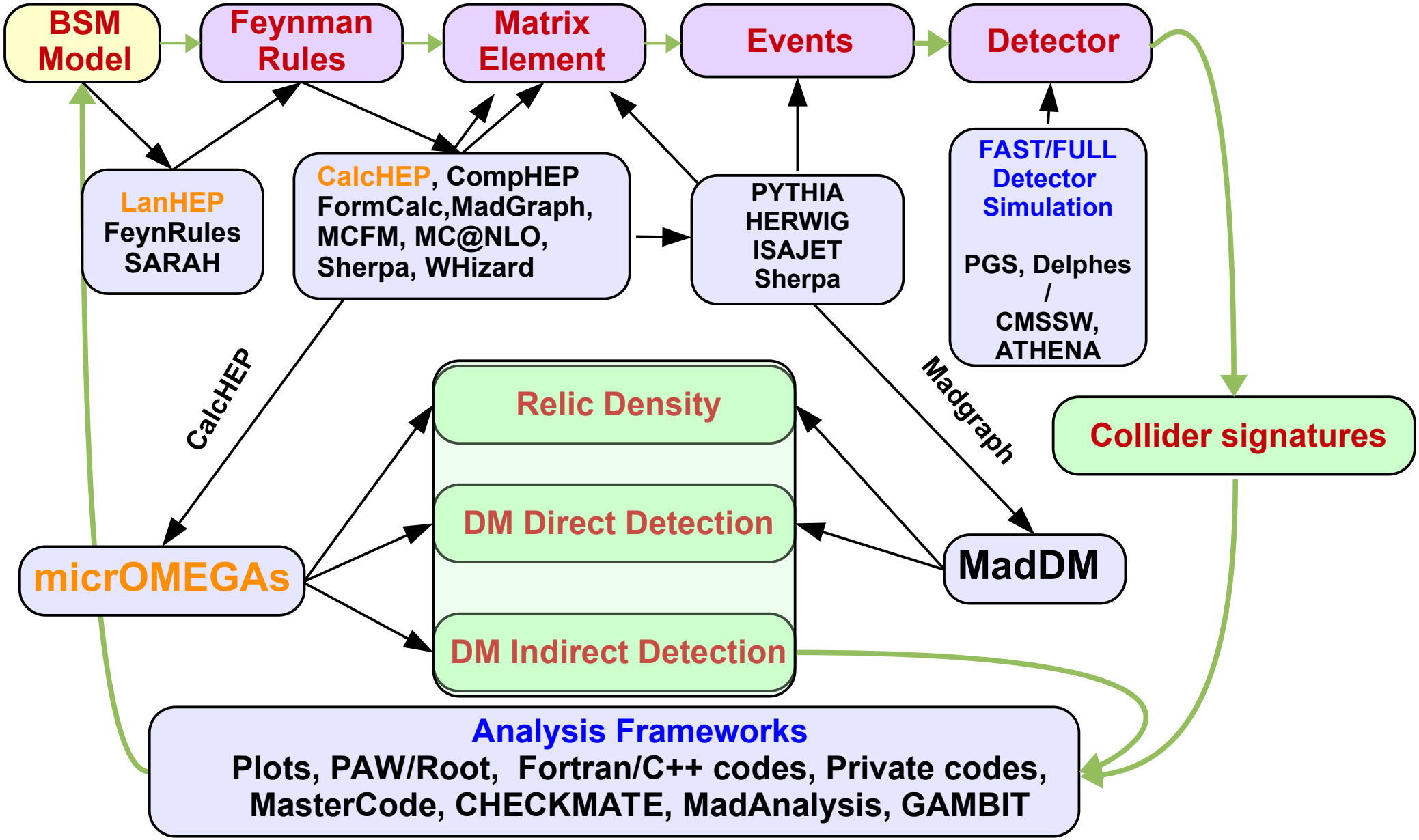

Outline

- **Lecture I:**
  - ***Matrix Element Calculations: CalcHEP***
- **Lecture II:**
  - ***Model Implementation : LanHEP***
  - ***Dark Matter: micrOMEGAS***

- *Do not hesitate to ask questions **during** the lecture*

- *There are **exercises (ex#)** to do*

Lecture I:

Introduction into CalcHEP

- *system requirements & linux primer*
- *installation*
- *models and symbolic session*
- *numerical session and kinematical distributions*
- *event generation*
- *CalcHEP Batch Interface*

Web page & contacts

- *The WEB page of CalcHEP*
  http://theory.npi.msu.su/~pukhov/calchep.html
  arXiv:1207.6082

- *e-mails*
  calchep@googlegroups.com
  a.belyaev@soton.ac.uk

CalcHEP

Calculator for High Energy Physics

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

- **Authors**

  Alexander Pukhov, AB, Neil Christensen

  (AB and Neil Christensen have joined the project in 2009)
  http://theory.npi.msu.su/~pukhov/calchep.html

- **Idea**

  The effective study of HEP phenomenology passing at high level of automation from your favorite model to physical observables such as decay width, branching ratios, cross sections kinematic distributions, parton-level events, ...

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

  - **CompHEP (Boos et al)**
  - **MadGraph/MadEvent (Maltoni, Stelzer et al)**
  - **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
- 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

The Highlights of CalcHEP

- **Convenient graphical interface – to understand process in details**
  (e.g. one can select diagrams at squared level to study interference, plot dependent parameters, etc)

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- **Has different modules for user modifications:**
  user-defined cuts, user form factor etc.

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

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

Authors - Alexander Pukhov, Alexander Belyaev, Neil Christensen

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

General information

Main features , Acknowledgments Publications&Lectures Contributions

---

Manual

calchep_man_3.3.6.pdf (manual for version 3.3.6, July 19, 2012)

HEP computer tools (Lecture by Alexander Belyaev)

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

Code download.

License GPL-3

Installation Current version 3.8.10(updated 07.06.2021) New Options and Bugs Fixed All versions

---

Models:

MSSM_10.14(15.10.2014) NMSSM_8.15(25.08.2015) CPVMSSM_10.14(16.10.2014) SUSY models By A.Semenov LeptoQuarks 5DSM 6DSM

Model database HEPMDB

Related packages on Web:

Packages for model generation: LanHEP FeynRules SARAH

RGE and spectrum calculation: SuSpect Isajet SoftSUSY SPheno CPsuperH NMSSMTools

Particle widths in MSSM: SUSY-HIT HDECAY

Parton showers: PYTHIA

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CalcHEP

Overview Code Bugs Blueprints Translations **Answers**

Questions for CalcHEP

by relevancy Search

Status

☑ Open ☑ Needs information ☑ Answered ☑ Solved ☐ Expired ☐ Invalid

Summary	Created	Submitter	Assignee	Status
701811 Way to Import Model	2022-05-16	Yechan Kim	—	Solved
701409 Implementing massless graviton in Calchep	2022-04-19	Basabendu	—	Answered
701019 line 24: 50140 Segmentation fault: 11 $CALCHEP/bin/s_calchep $*	2022-03-21	Suneth Kassapa	—	Answered
700986 font size	2022-03-19	Thejus Mary S.	—	Solved
699930 Problem showing in loading SM.fr file from feynrules	2021-12-	Elsa	—	Answered

Quick start with CalcHEP: practical notes on the installation

- Download code, read manual and compile
  http://theory.npi.msu.su/~pukhov/calchep.html

  wget https://theory.sinp.msu.ru/~pukhov/CALCHEP/calchep_3.8.10.tgz

  tar -zxvf calchep_3.8.10.tgz

  cd calchep_3.8.10

  make

  cd work

  (*or your own work directory* ./mkWORKdir ../calc_work)
- You need to have only c compiler and X11 sources
- Supported operating system

  Linux, IRIX, IRIX64, HP-UX, OSF1, SunOS, Darwin,

  Windows Subsystem for Linux (WSL)

  (see *getFlags* file)

ex#1: Install CalcHEP

Compilation, potential problem and its solution

- To compile the CalcHEP source code you need:
  C compiler, the X11 graphics library and the X11 include files
  "CalcHEP is compiled successfully and can be started "
  is a good sign

- Compilation for High Precision Calculations
  - Intel C compiler has a _Quad type, -D QUAD has to be added to FlagsForSh as
    CFLAGS="-D_QUAD_ -fPIC -fsigned-char -Qoption,cpp,--extended_float_type"

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    CFLAGS="-D_QUAD_ -fPIC -fsigned-char -Qoption,cpp,--extended_float_type"
- **Potential problem in compilation**
  - **The most frequent compilation problem is due to the absence of the X11 include files; CalcHEP still compiles, however, it only runs in non-interactive mode ./calchep will give**

    Error: You have launched the interactive session for a version of CalcHEP that has been compiled without the X11 library. Presumably, the X11 development package is not installed on your computer.
  - **the following additional package should be install to run CalcHEP in GUI mode**
    - **libX11-devel for Fedora/Scientific, Darwin(MAC)**
    - **libX11-dev for Ubuntu/Debian ; xorg-x11-devel for SUSE**
    - **MAC users: install Xquartz https://www.xquartz.org AND REBOOT your MAC**

Starting CalcHEP

- ***Files in the work folder:***

bin -> ..... /calchep_3.**x.y.z**/bin
calchep
calchep_batch
calchep.ini
models/
results/
tmp/

- ***Start:***

./calchep

Starting CalcHEP

```
   CalcHEP - a package for Calculation in High Energy Physics
           Version 3.8.9: Last correction  March 25, 2021


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

 For contacts:    email       : <calchep@googlegroups.com>
                  Questions   : https://answers.launchpad.net/calchep
                  Bugs        : https://bugs.launchpad.net/calchep
                  Code&Models: http://theory.sinp.msu.ru/~pukhov/calchep.html
 The BSMs for CalcHEP were developed in collaboration with:
       G.Belanger,F.Boudjema,A.Semenov

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

                  Press F9 or click the box below to get

                 References, Contributions, Acknowledgments

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

Principle KEYS for CalcHEPs GUI

Enter menu selection (forward)

Exit menu selection (back)

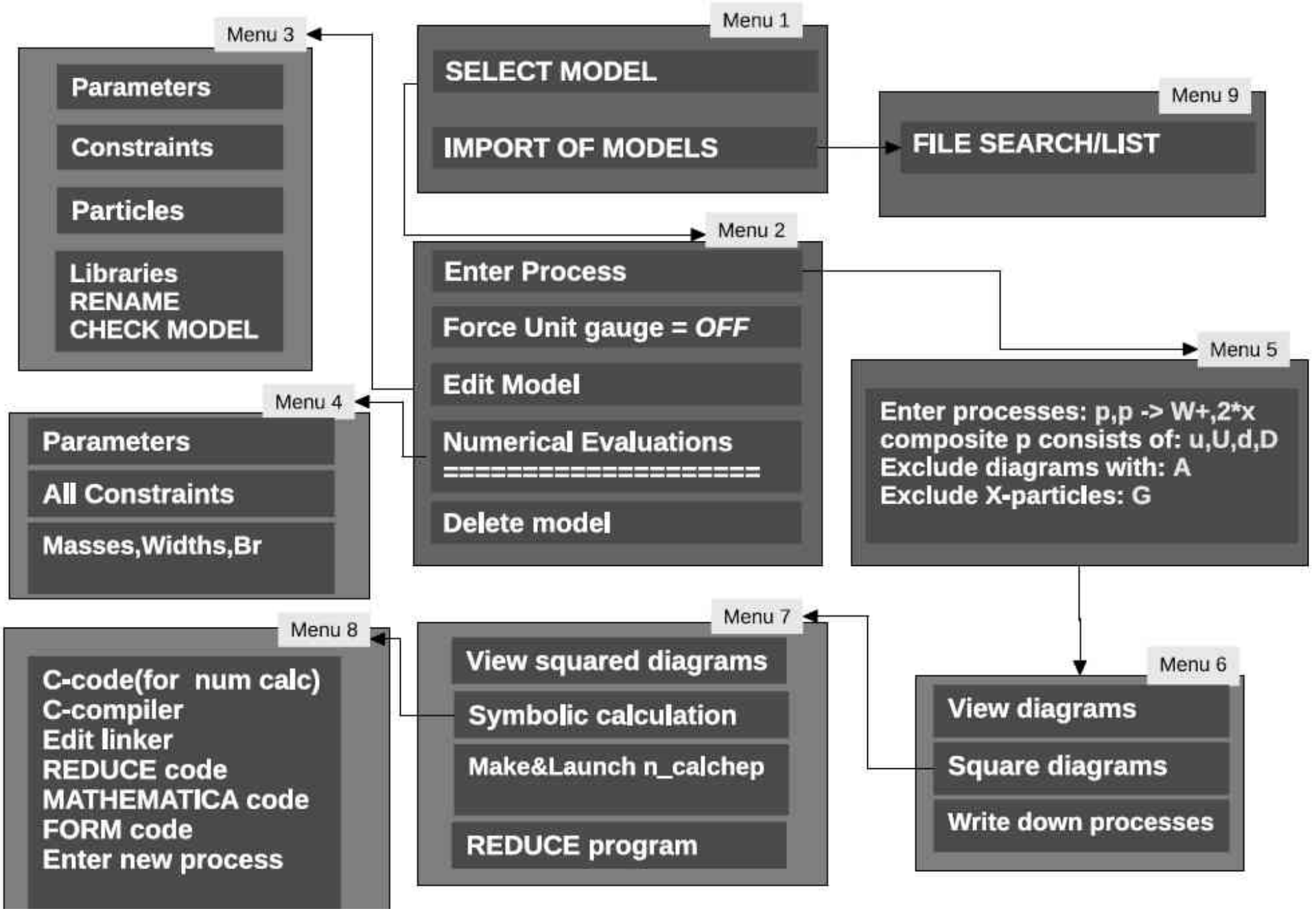
Help!

CalcHEP structure/modes

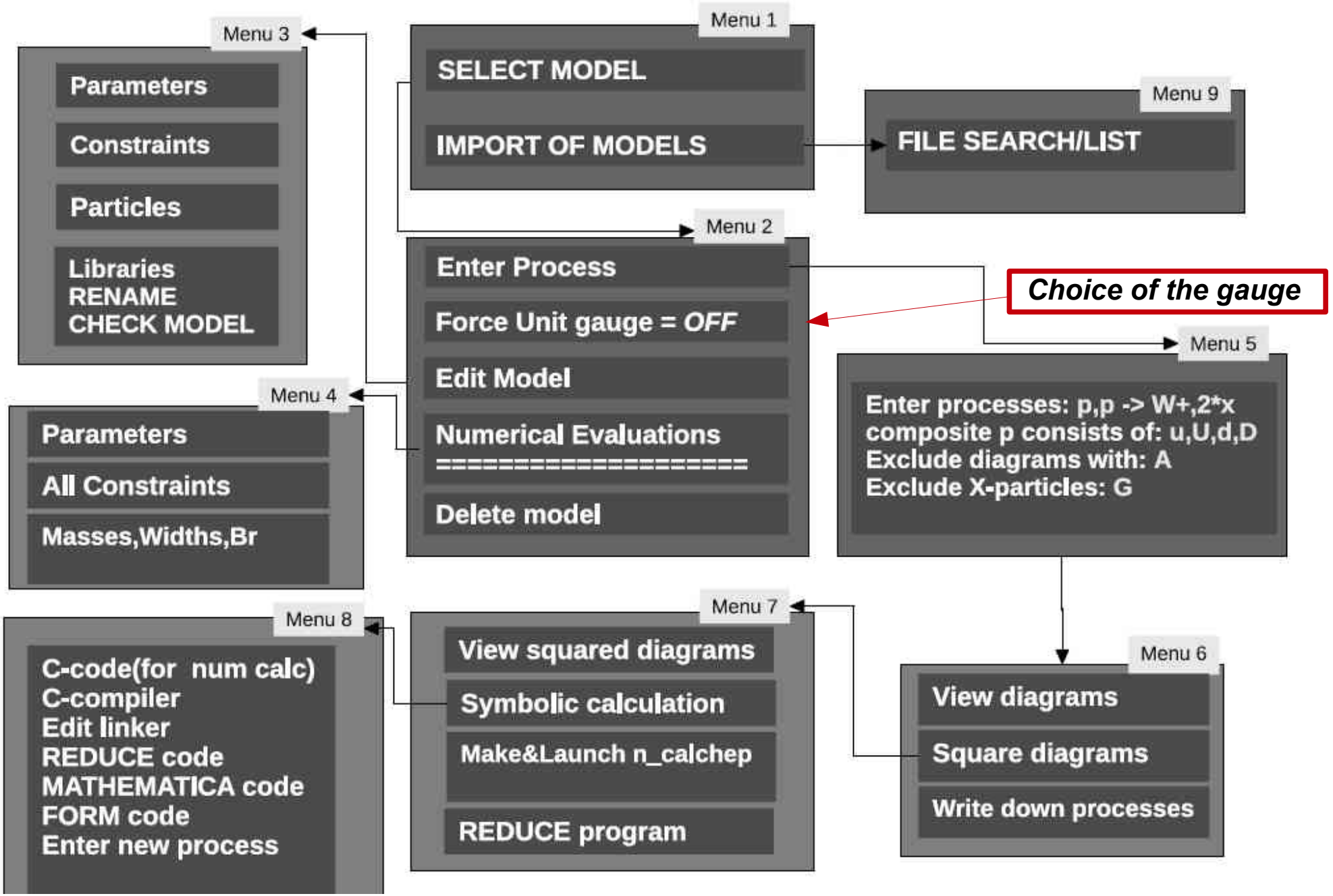
- ***Graphical mode***
  - **symbolic part**
  - **numerical part**
- ***Batch mode***

Starting CalcHEP

CalcHEP menu structure: symbolic part

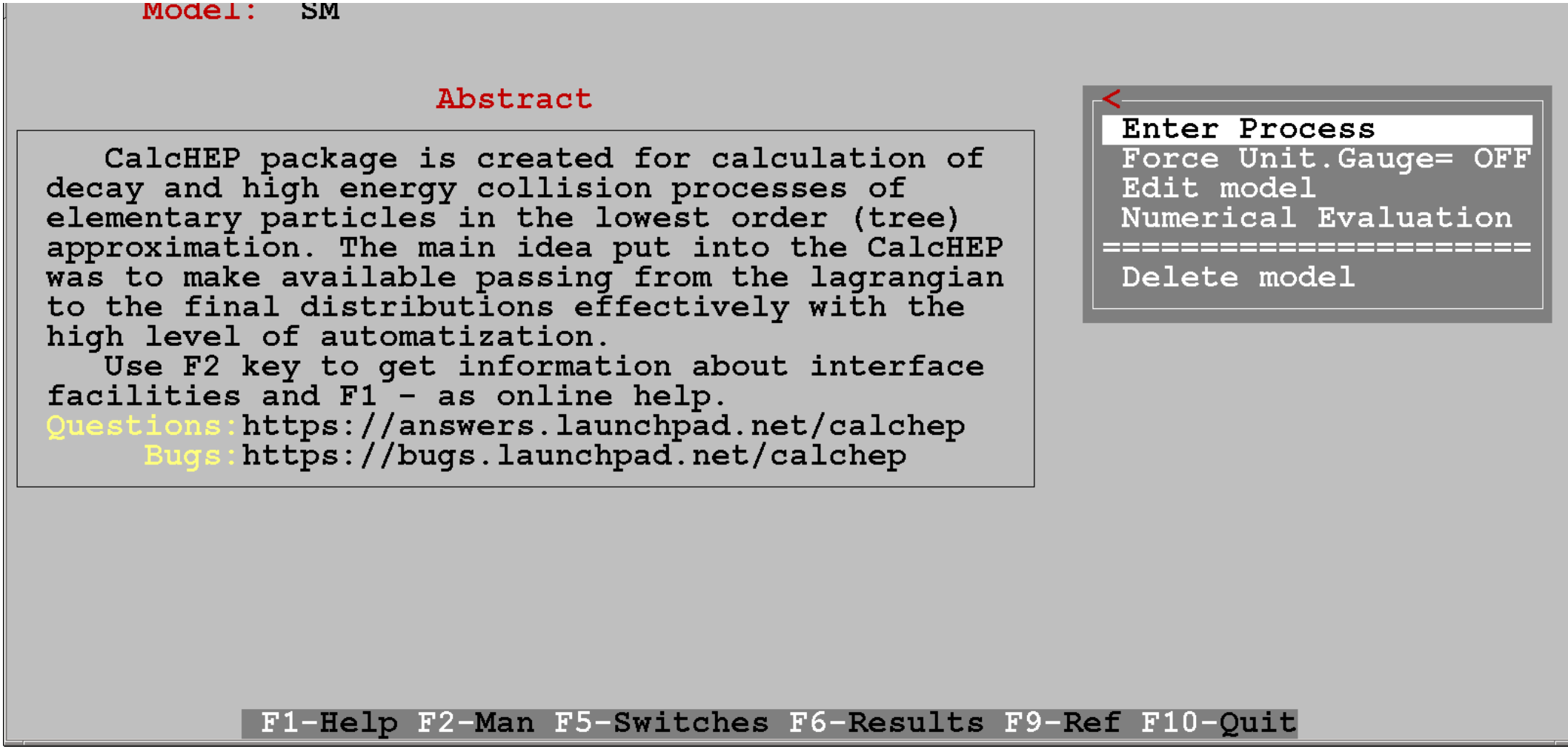


CalcHEP menu structure: symbolic part



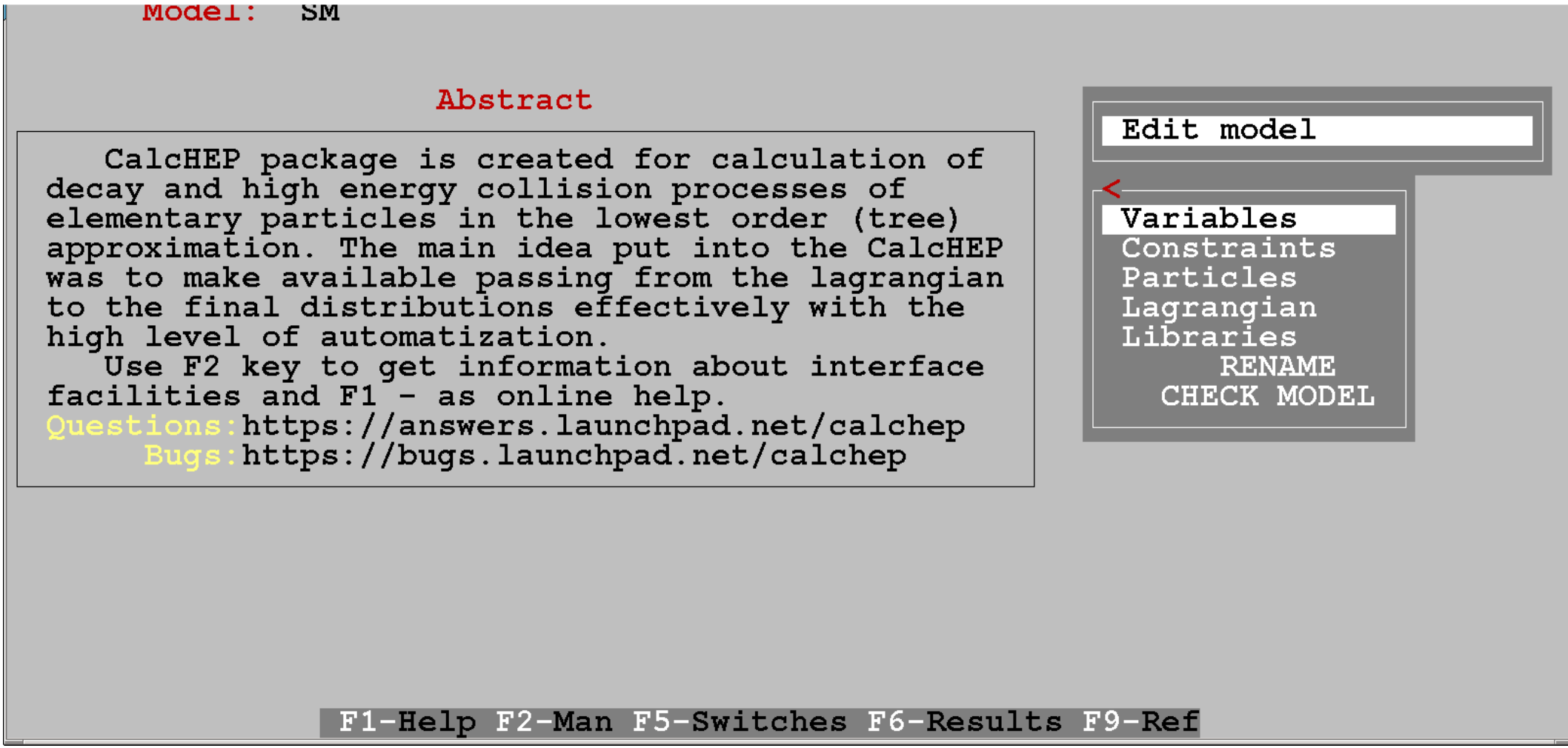
Model choice and Process input

Choose your gauge ***Enter Process***
Edit Model ***Numerical Evaluation***



The Model Structure

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



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

Particles

Clr Del Size Read ErrMes

Full name	A	A	PDG	2*spin	mass	width	color	aux	LaTex(A)	La
gluon	G	G	21	2	0	0	8	G	g	g
photon	A	A	22	2	0	0	1	G	\gamma	\ga
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	\ba
muon	m	M	13	1	Mm	0	1		\mu^-	\mu
m-neutrino	nm	Nm	14	1	0	0	1	L	\nu_\mu	\ba
tau-lepton	l	L	15	1	Ml	0	1		\tau^-	\ta
t-neutrino	nl	Nl	16	1	0	0	1	L	\nu_\tau	\ba
d-quark	d	D	1	1	0	0	3		d	\ba
u-quark	u	U	2	1	0	0	3		u	\ba
s-quark	s	S	3	1	0	0	3		s	\ba
c-quark	c	C	4	1	Mc	0	3		c	\ba
b-quark	b	B	5	1	Mb	0	3		b	\ba
t-quark	t	T	6	1	Mt	!wt	3		t	\ba

F1 F2 Xgoto Ygoto Find Write

Particles: prtcl*xx*.mdl

Particles

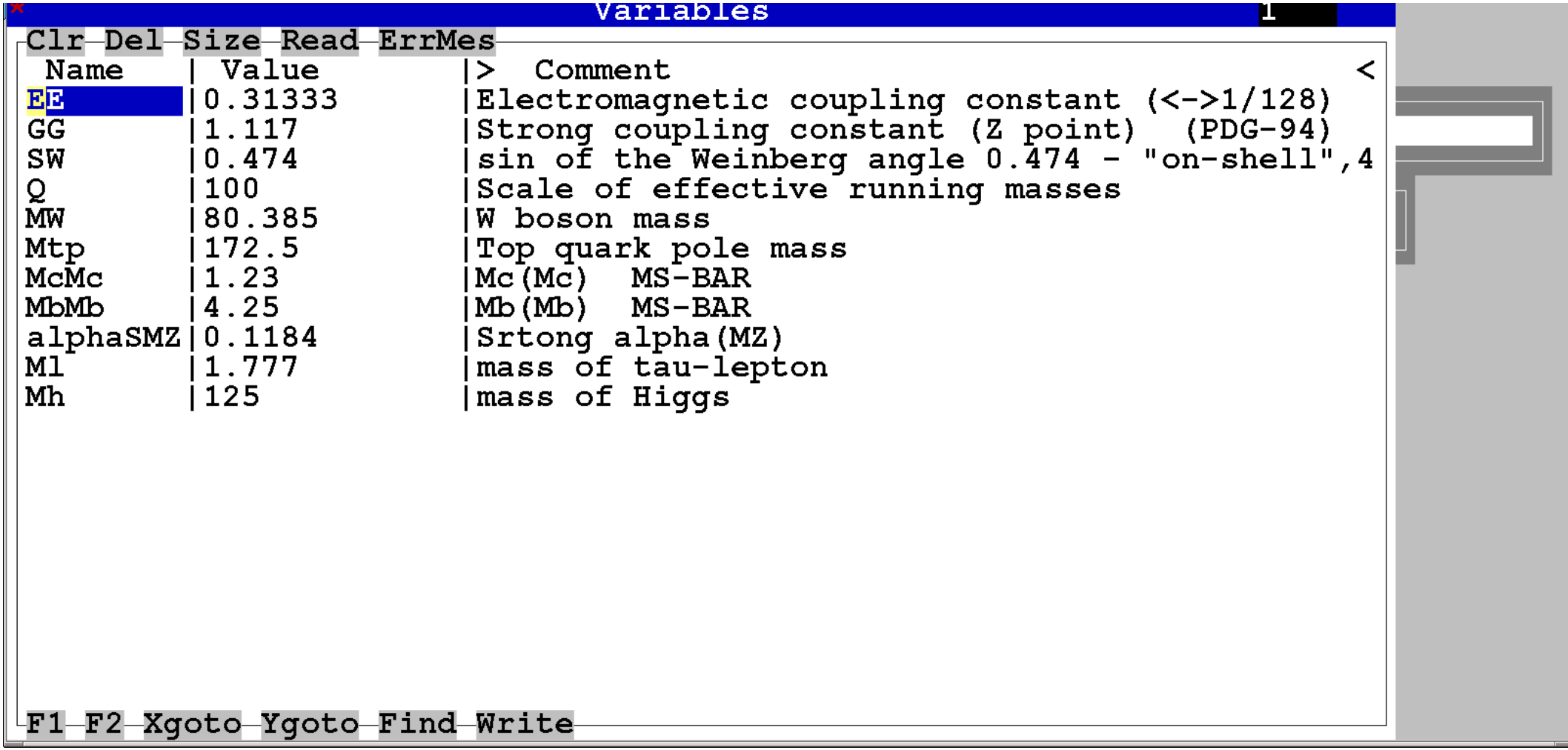
Clr Del Size Read ErrMes

Full name	A	A	PDG	2*spin	mass	width	color	aux	LaTex(A)	La
gluon	G	G	21	2	0	0	8	G	g	g
photon	A	A	22	2	0	0	1	G	\gamma	\ga
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	\ba
muon	m	M	13	1	Mm	0	1		\mu^-	\mu
m-neutrino	nm	Nm	14	1	0	0	1	L	\nu_\mu	\ba
tau-lepton	l	L	15	1	Ml	0	1		\tau^-	\ta
t-neutrino	nl	Nl	16	1	0	0	1	L	\nu_\tau	\ba
d-quark	d	D	1	1	0	0	3		d	\ba
u-quark	u	U	2	1	0	0	3		u	\ba
s-quark	s	S	3	1	0	0	3		s	\ba
c-quark	c	C	4	1	Mc	0	3		c	\ba
b-quark	b	B	5	1	Mb	0	3		b	\ba
t-quark	t	T	6	1	Mt	!wt	3		t	\ba

F1 F2 Xgoto Ygoto Find Write

Higgs boson width will be calculated `on the fly`

Independent parameters: varsxx.mdl



Dependent parameters(constraints): funcxx.mdl

Constraints

Clr Del Size Read ErrMes

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

F1 F2 Xgoto Ygoto Find Write

Feynman rules: lgrng*xx*.mdl

Lagrangian

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

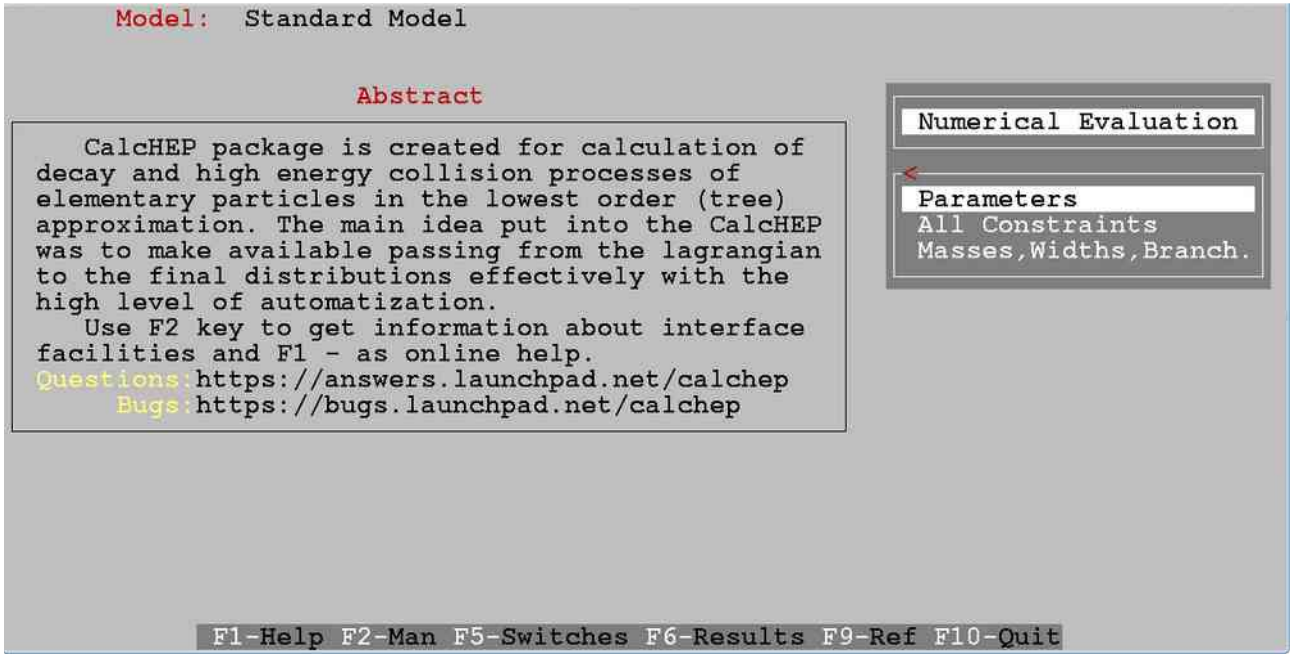
F1 F2 Xgoto Ygoto Find Write

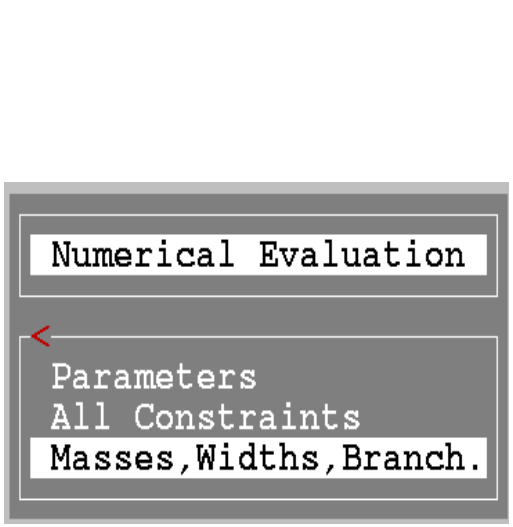
External Libraries: extlib*xx*.mdl

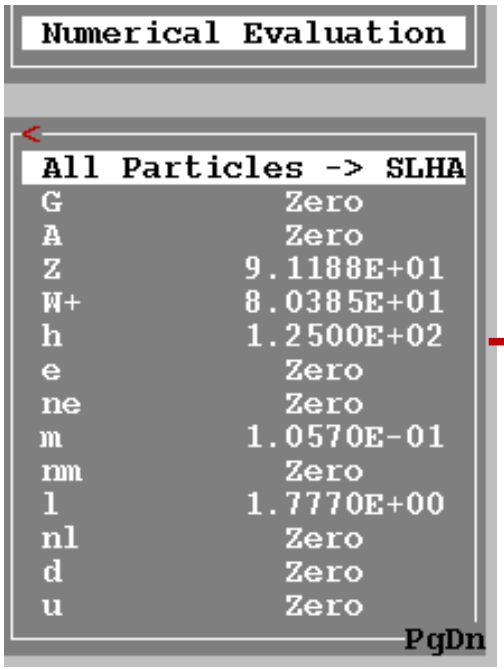
Typically is empty for simple models but can be used for any library which helps to build complicated model. E.g. mass spectra calculator for SUSY (involving RGE solutions etc)

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




F1 F2 Xgoto Ygoto Find Write
```

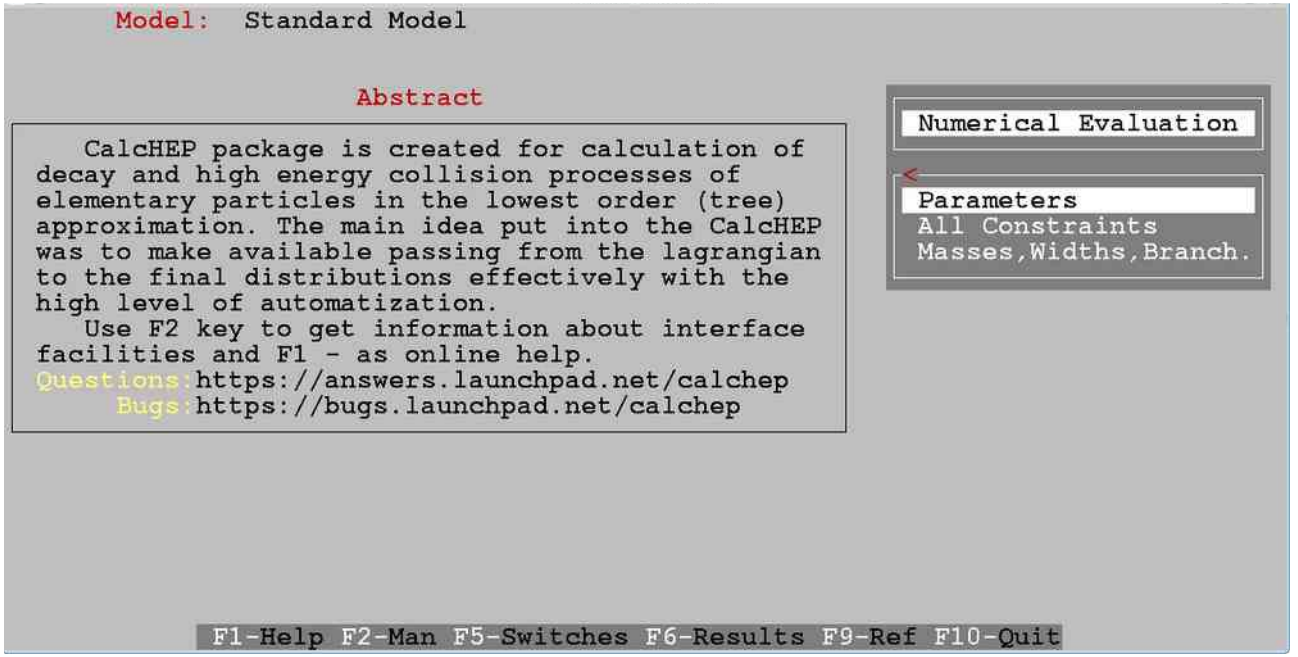
Numerical evaluation of masses & branchings

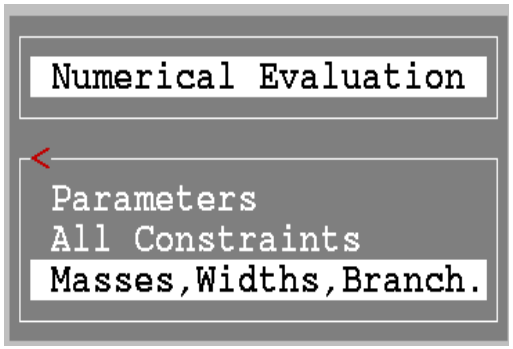


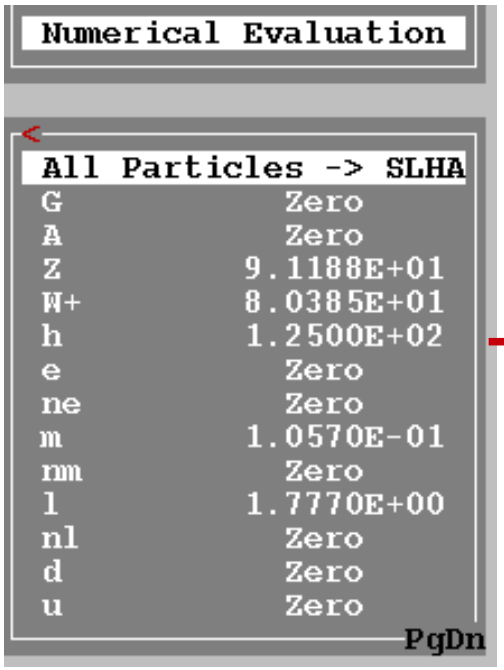




Numerical evaluation of masses & branchings







ex#2: Find the SM particles spectrum and Br ratios

Syntax for the process

- the input syntax: **P1**[**,P2**] **-> P3,P4** [**,,...,[N*x**]]

- hadron/composite particle scattering

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

  unknown particle are assumed to be composite,

  if you use **'p*'**, the **u,U,d,D,s,S,c,C,b,B,G** structure will be used automatically

- wild cards/names for outgoing particles

  'H -> 2*x'

- intermediate particles can be non-trivially excluded

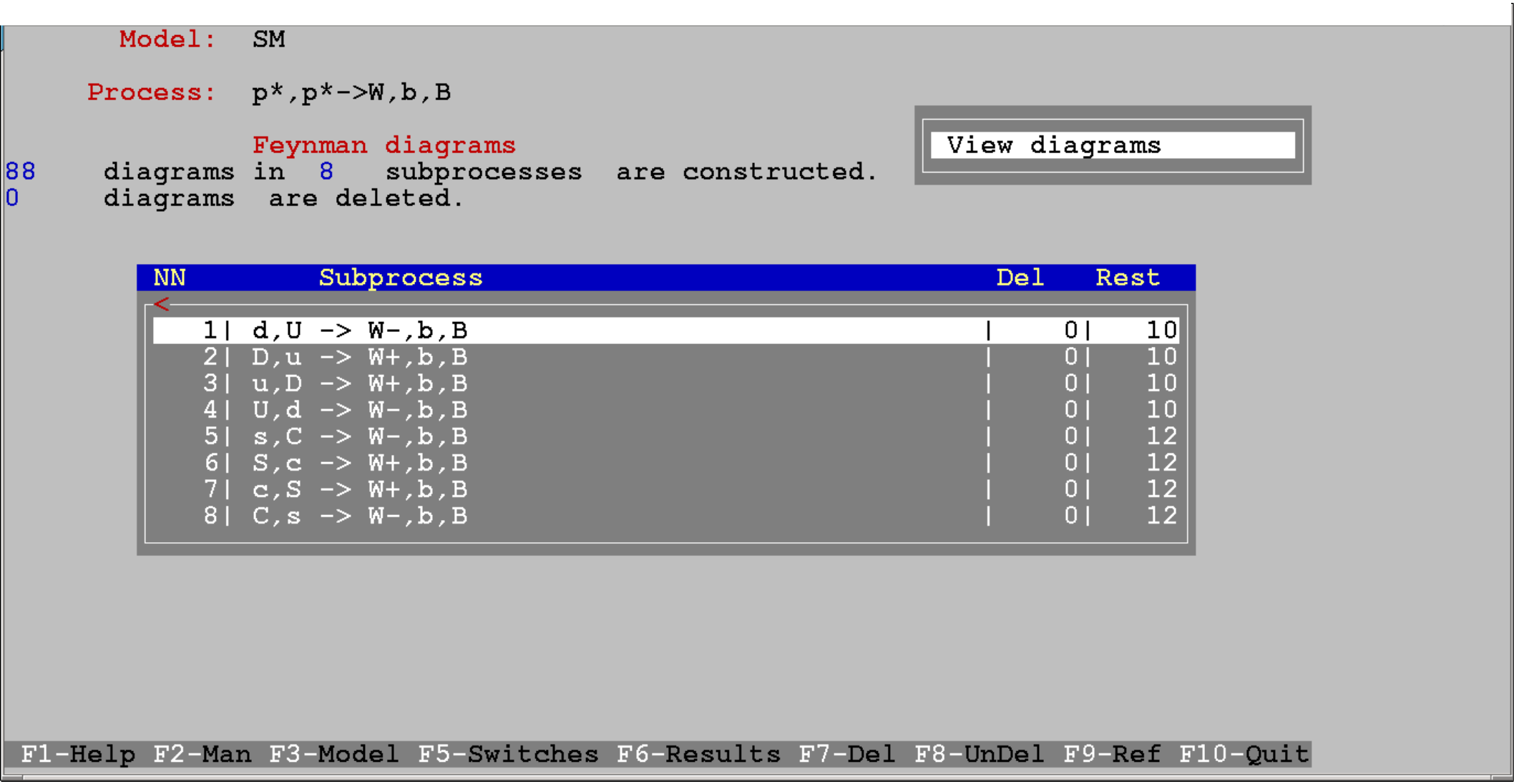
  'W+ > 2, A>1, Z>3'

ex#3: SM Higgs production cross section for e+e- → HZ process versus the collider energy for 0.5-1.0 TeV range, 10 GeV step

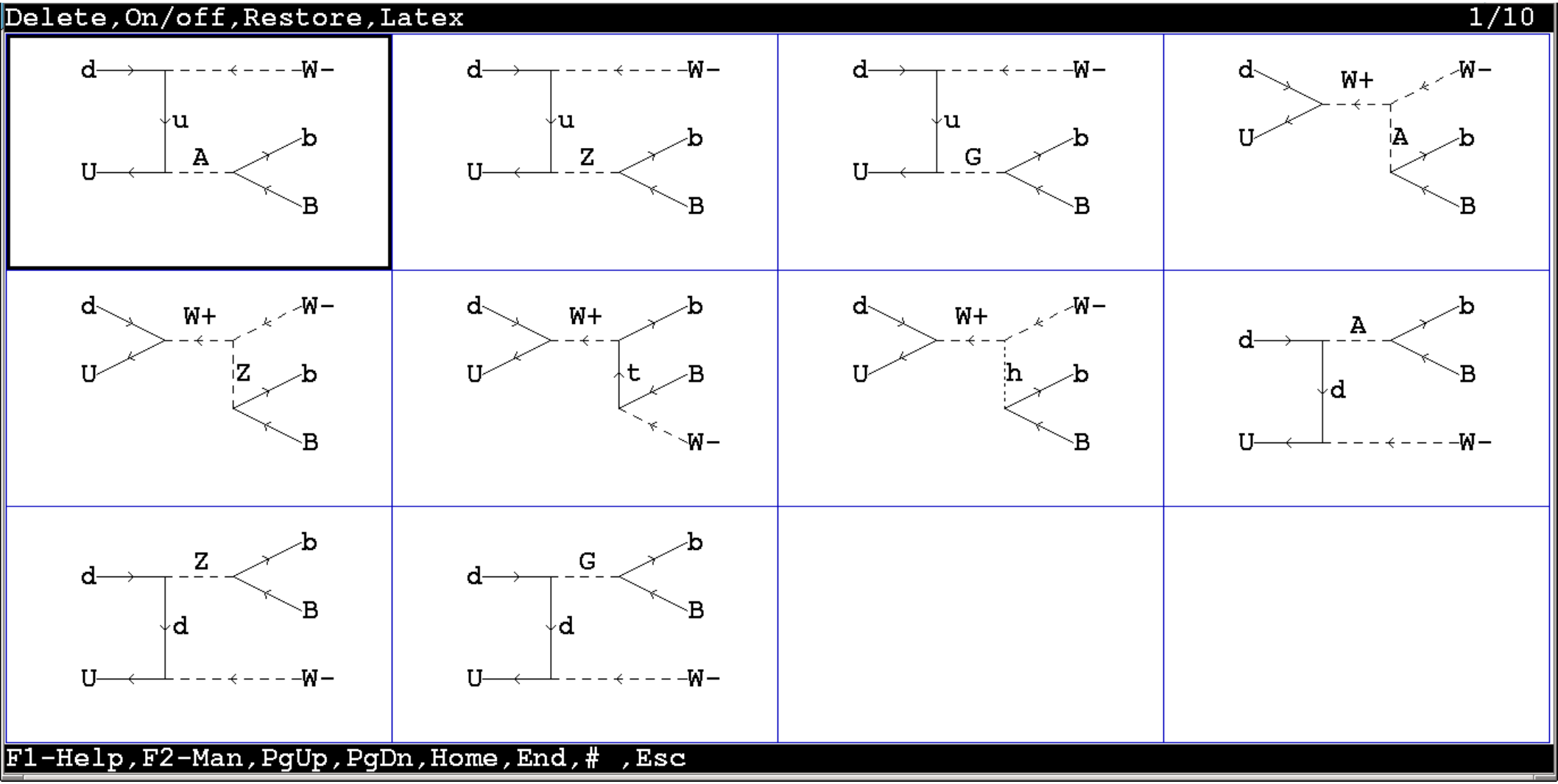
Symbolic session(1)

```
      Model:   SM

            List of particles (antiparticles)

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

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

Symbolic session (2)



Symbolic session (3)



Symbolic session (4)

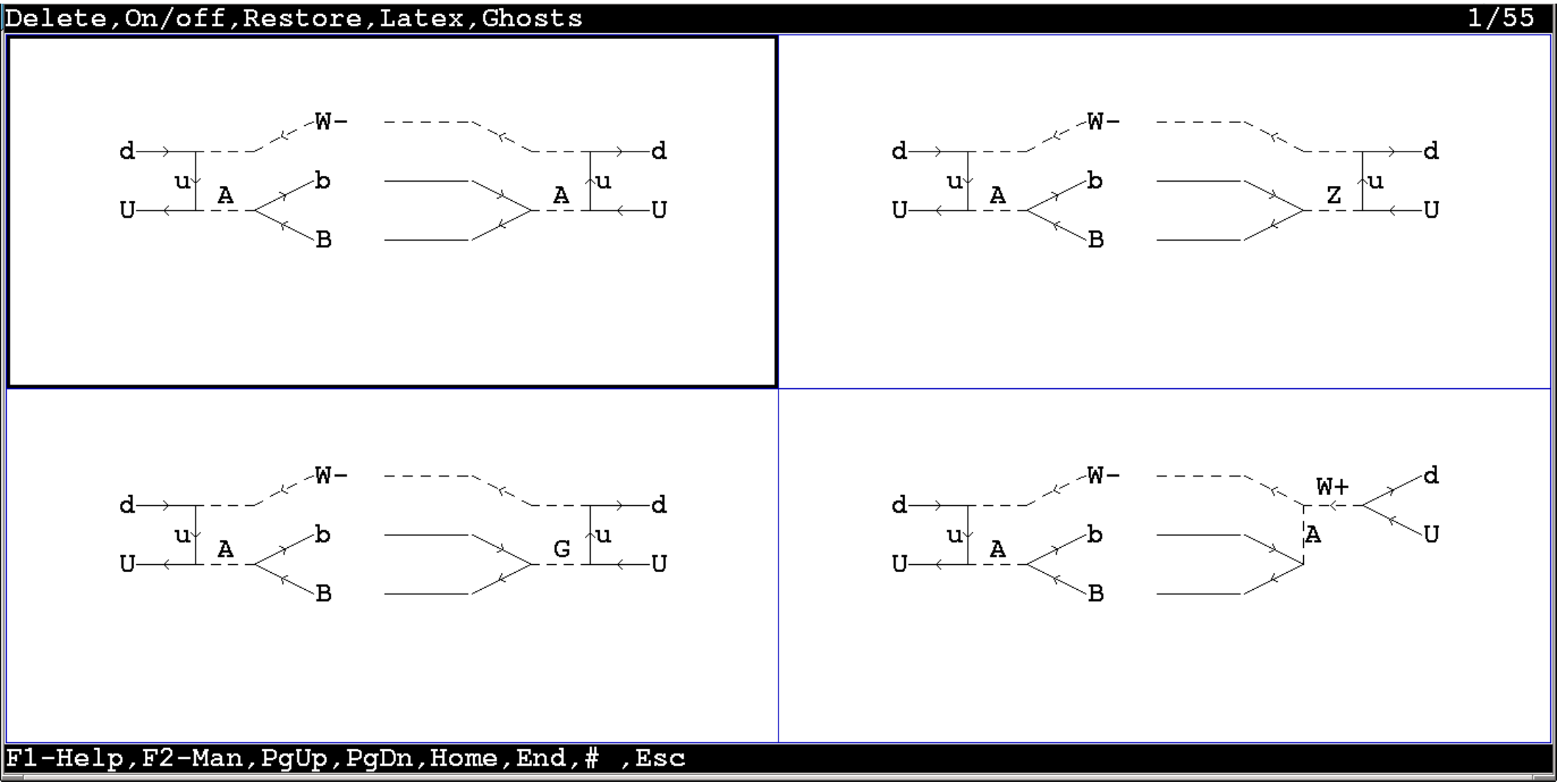
```
      Model:   SM

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

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

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

View squared diagrams

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

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

Symbolic session (5)



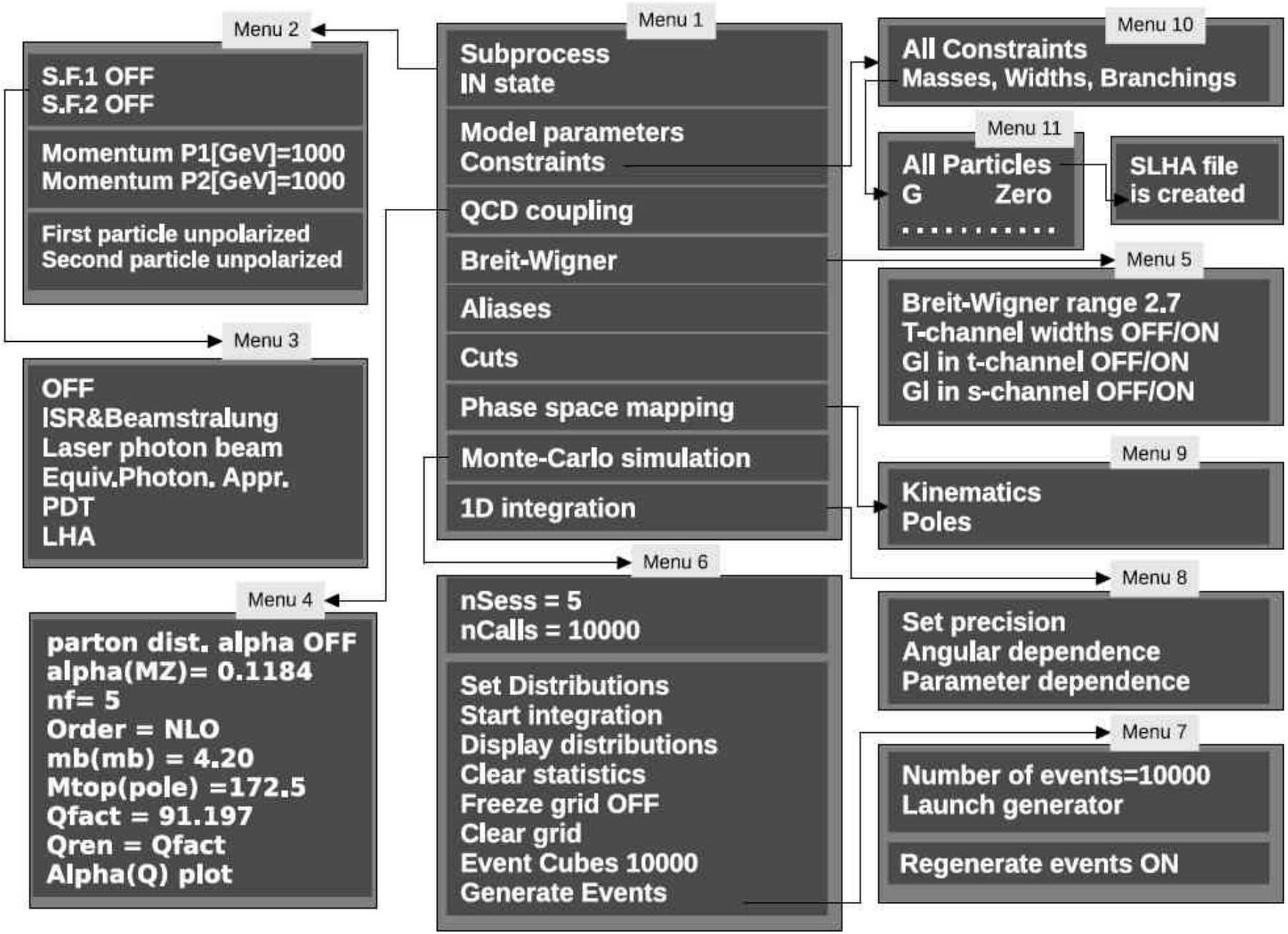
Symbolic session (6)

```
      Model:   SM

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

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

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

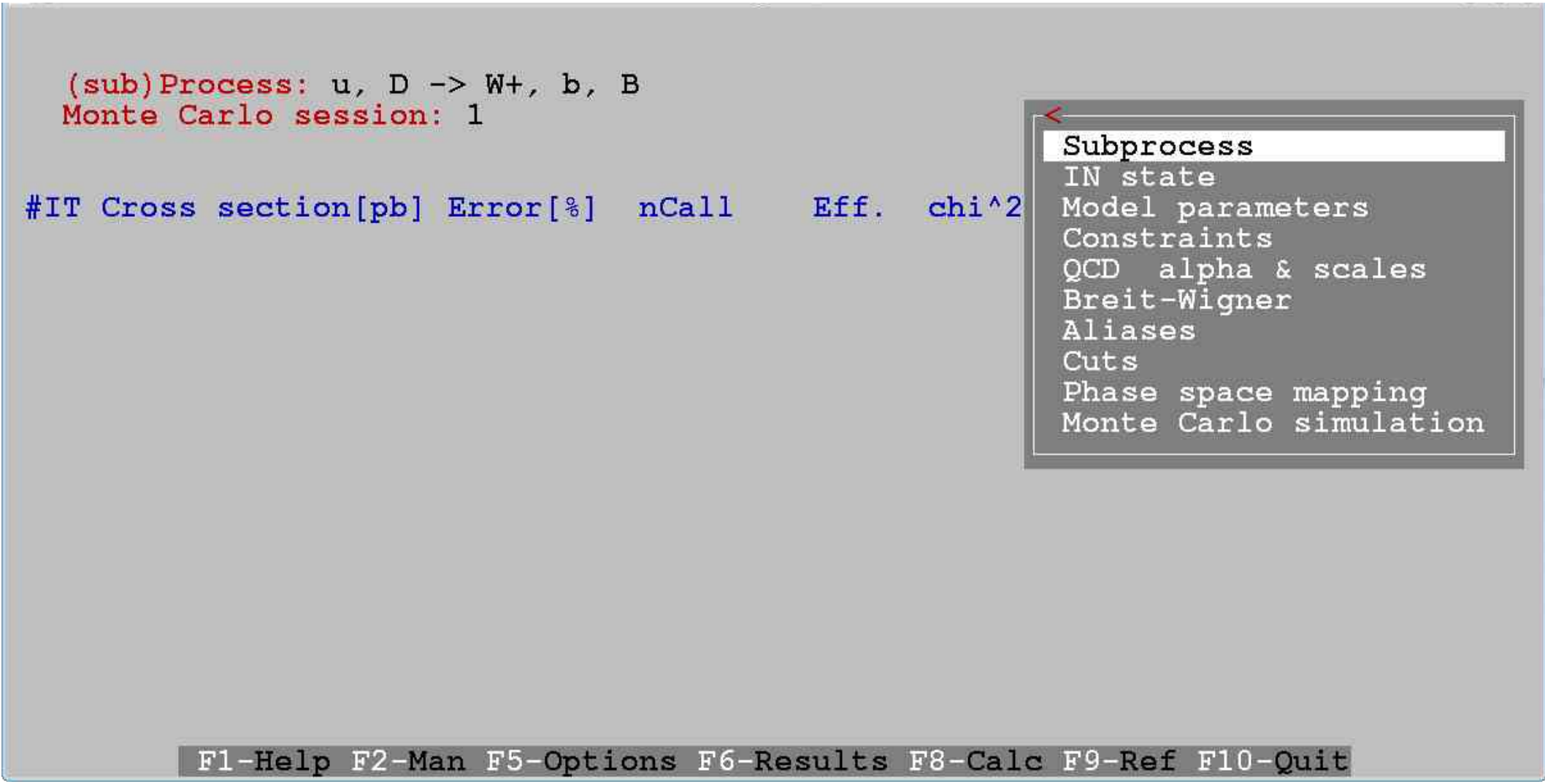
```
<
 C code
      C-compiler
      Edit Linker
 REDUCE code
 MATHEMATICA code
 FORM code
 Enter new process
```

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

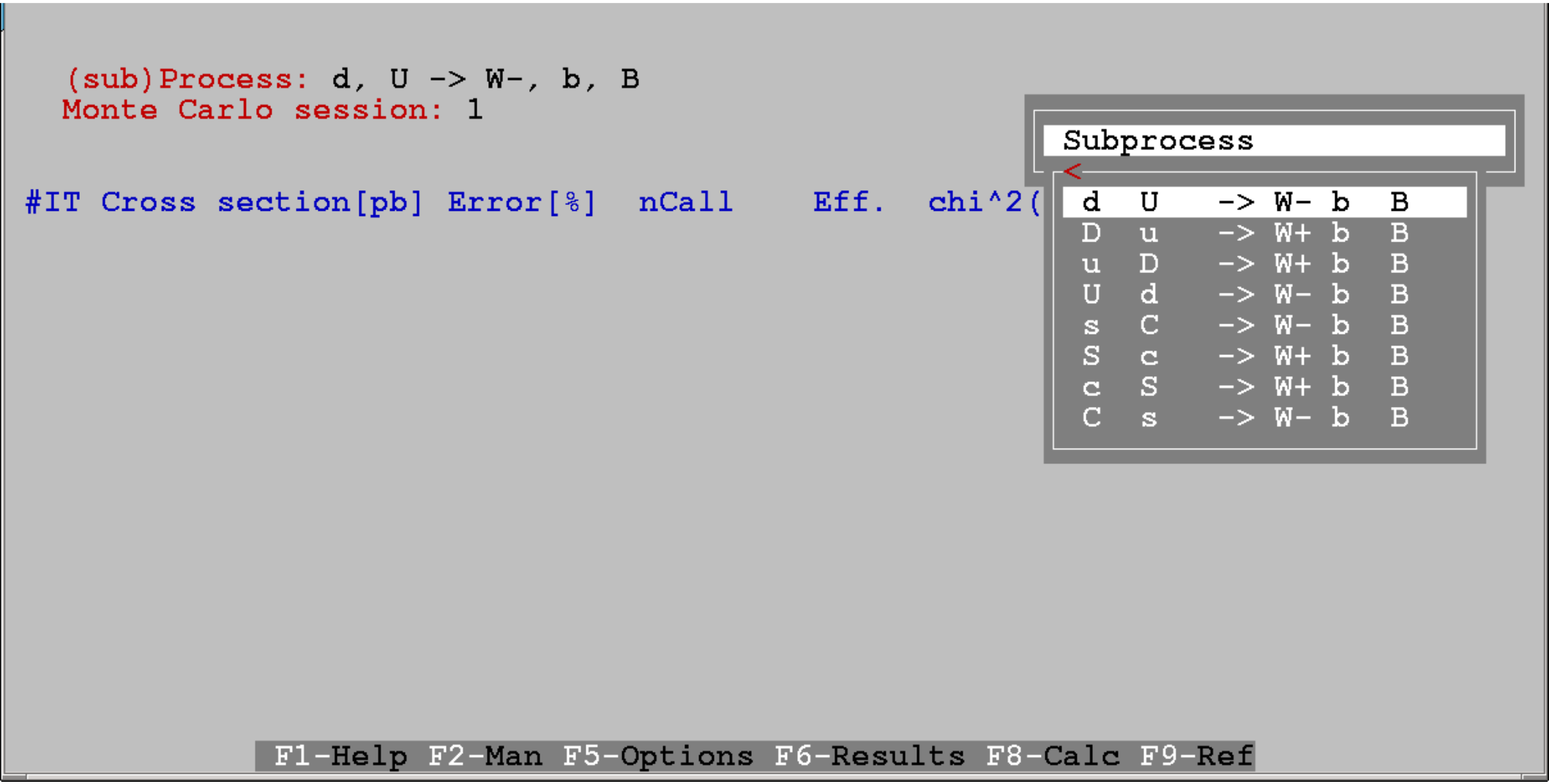
Menu structure of the numerical part



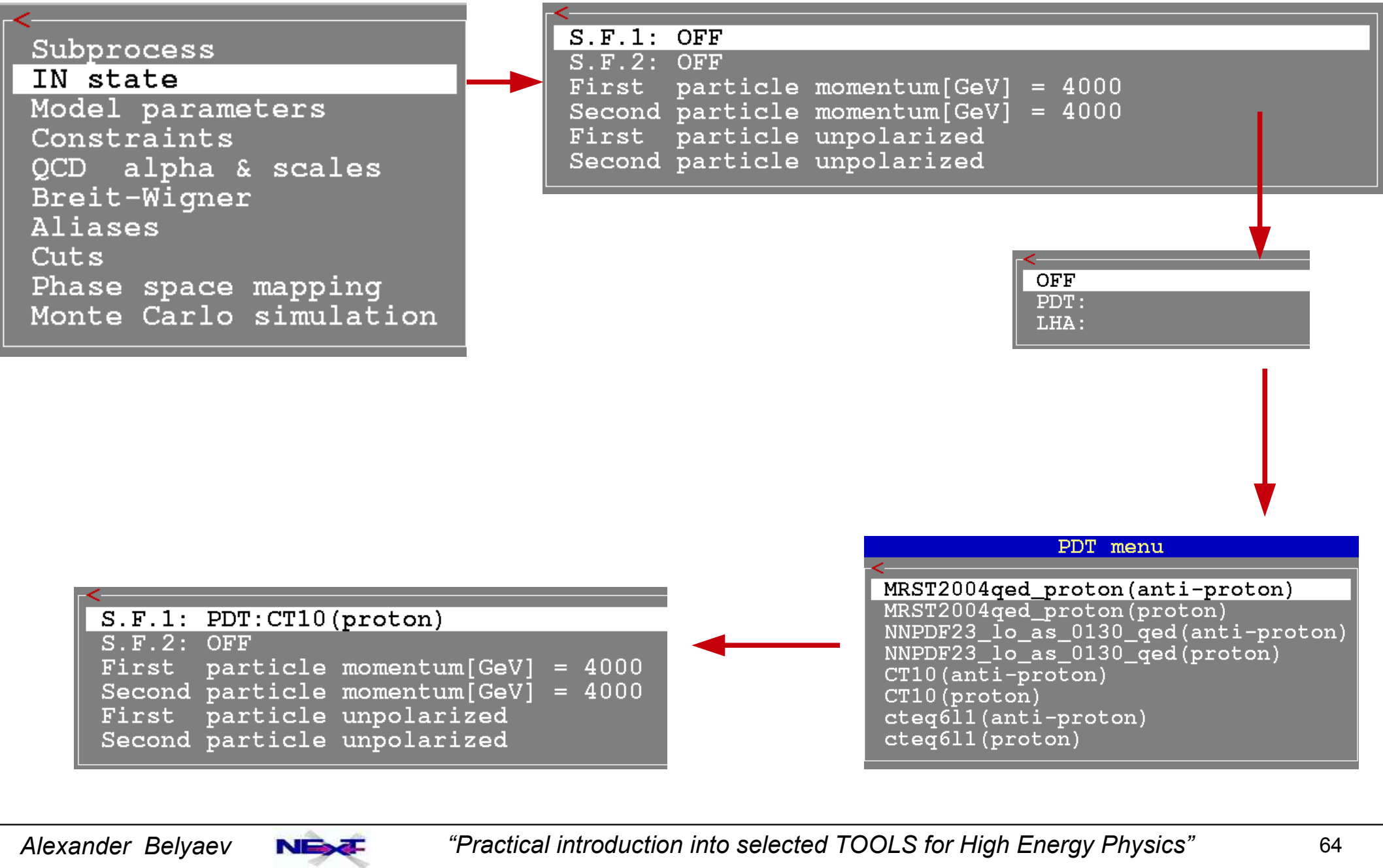
Numerical part(1)



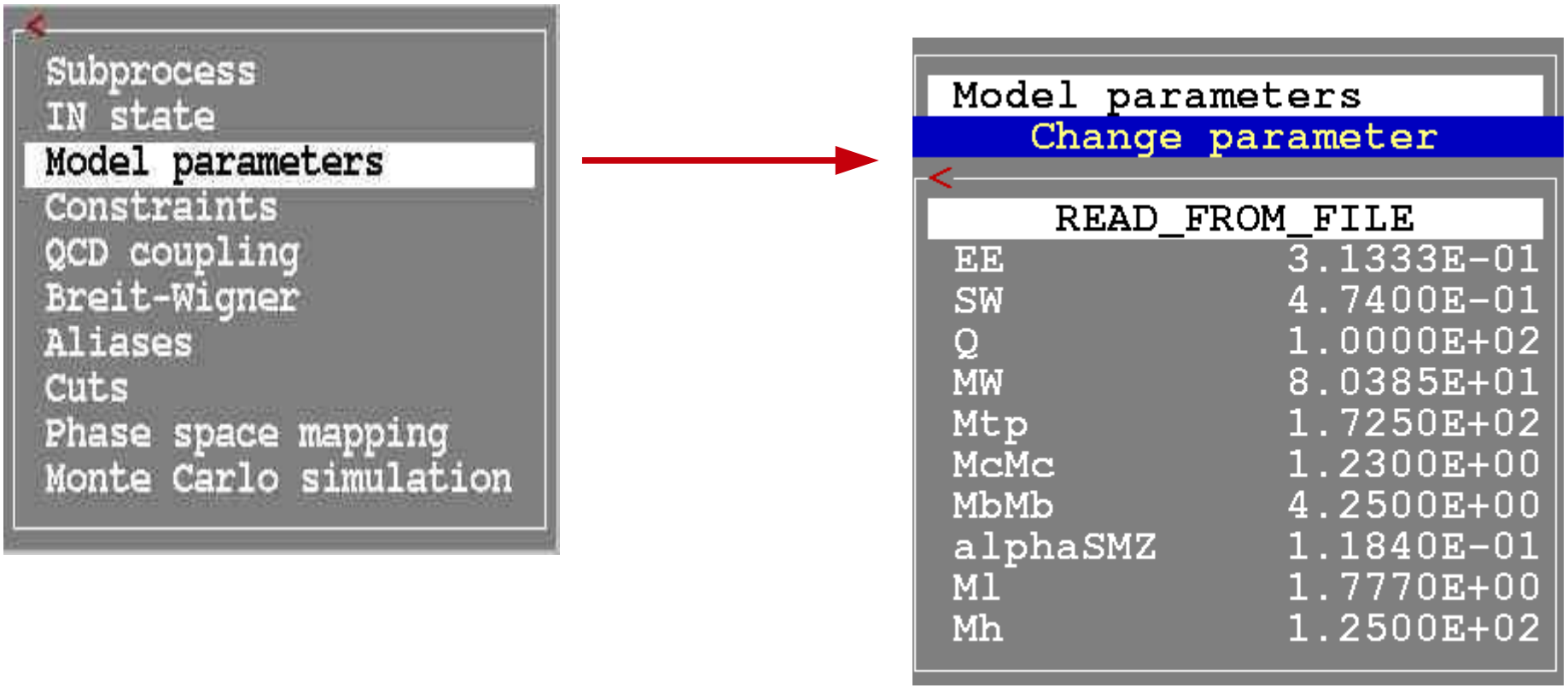
Numerical part(2)



control of the initial states and parton density functions



model parameters



dependent parameters (SM+ggH model)

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

Constraints

All Constraints
Masses,Widths,Branching

Constraints

Display dependence

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

Constraints

Display dependence

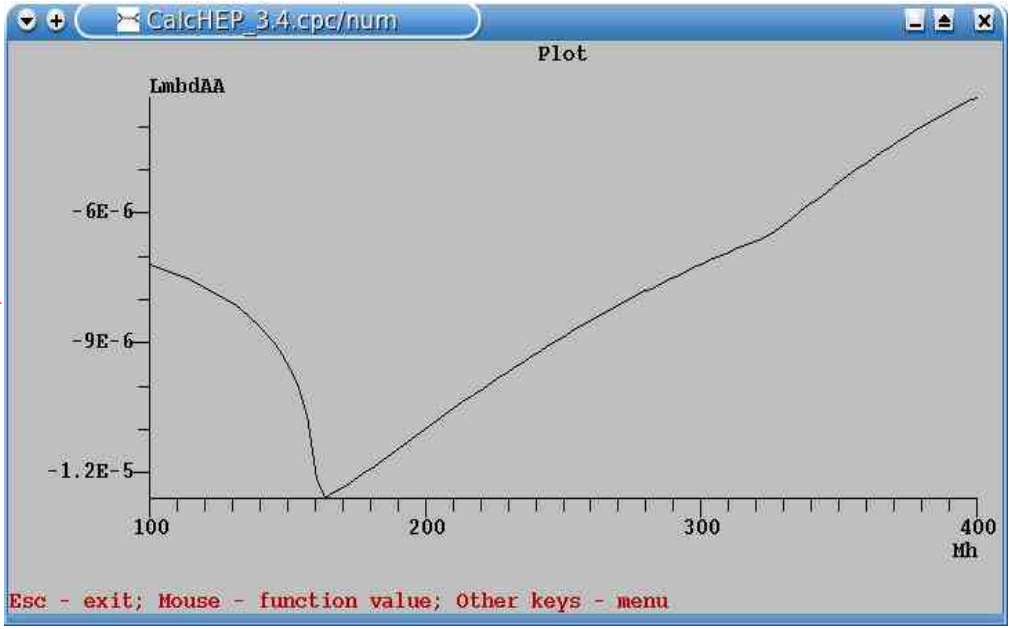
LmbdAA -7.8845E-06

on parameter

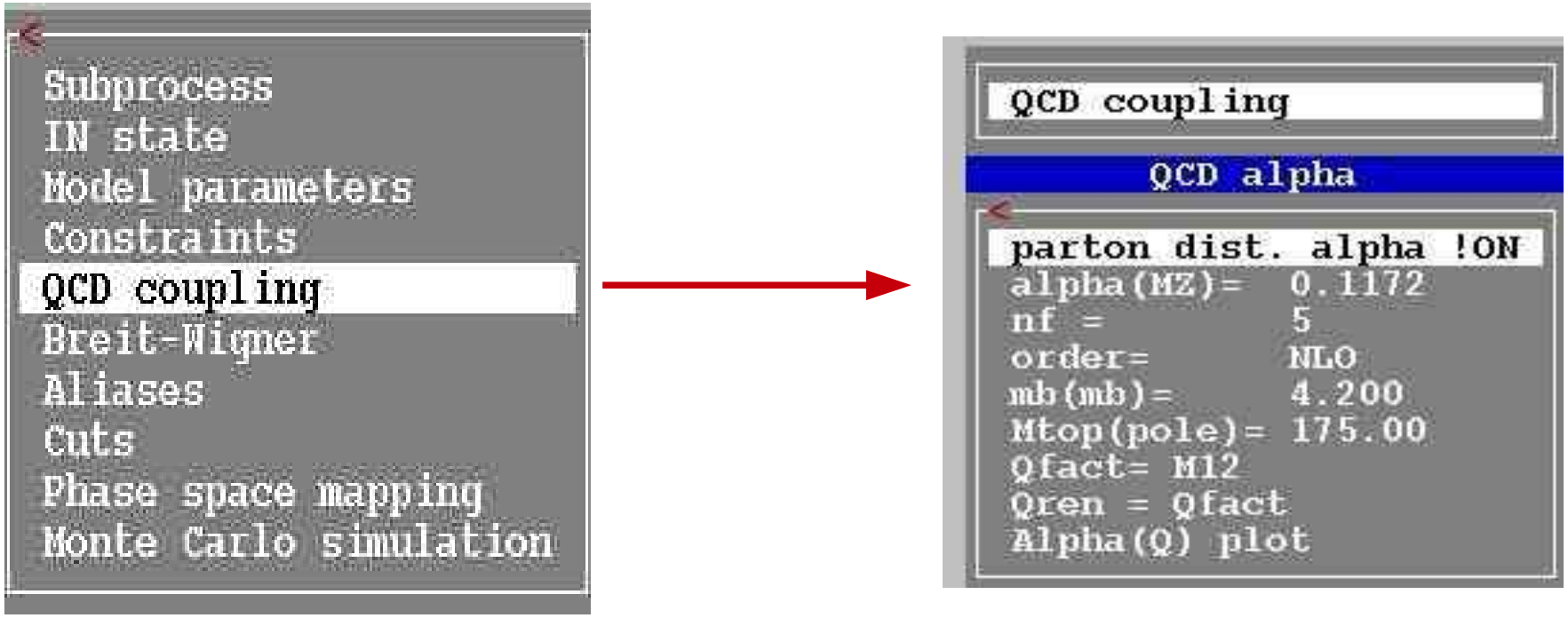
Mh 1.2500E+02

Plot

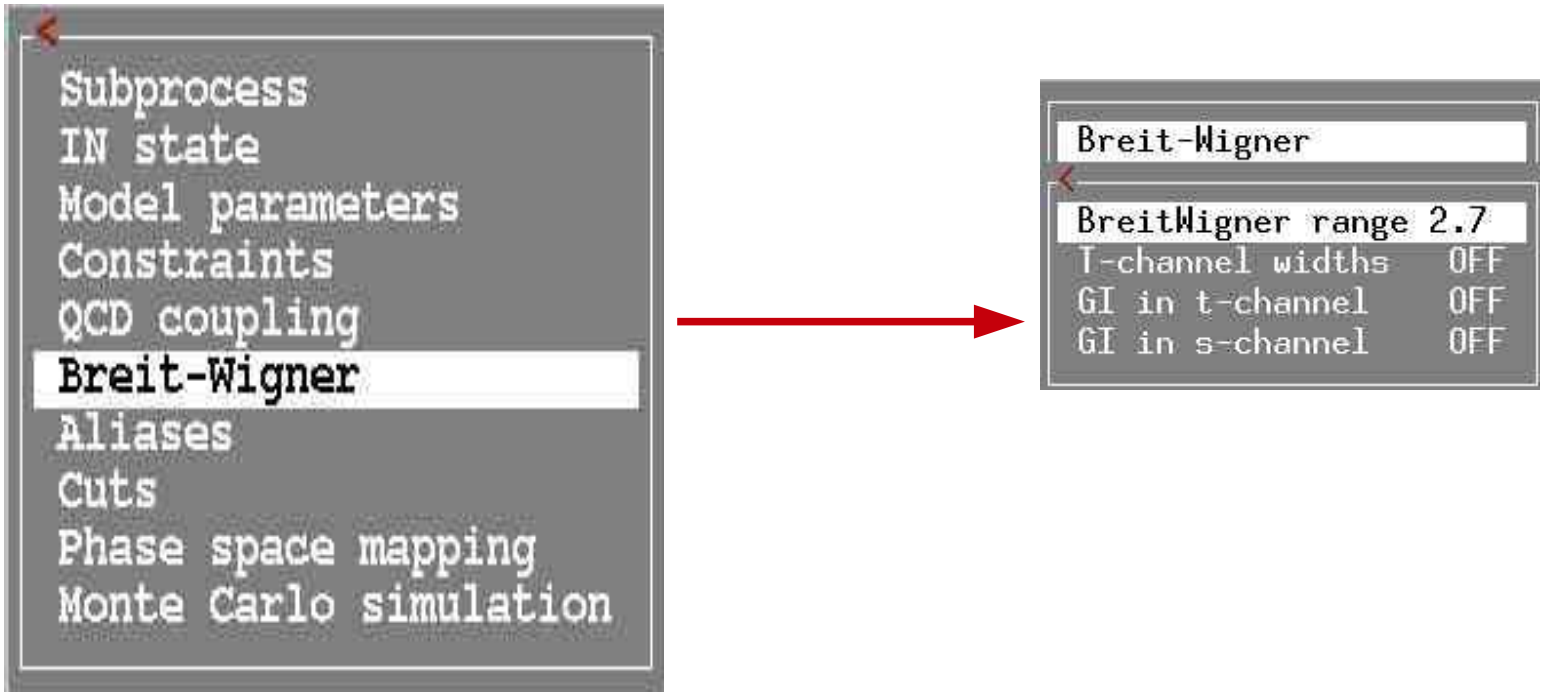
x-Min = 100
x-Max = 400
Npoints = 100
Display



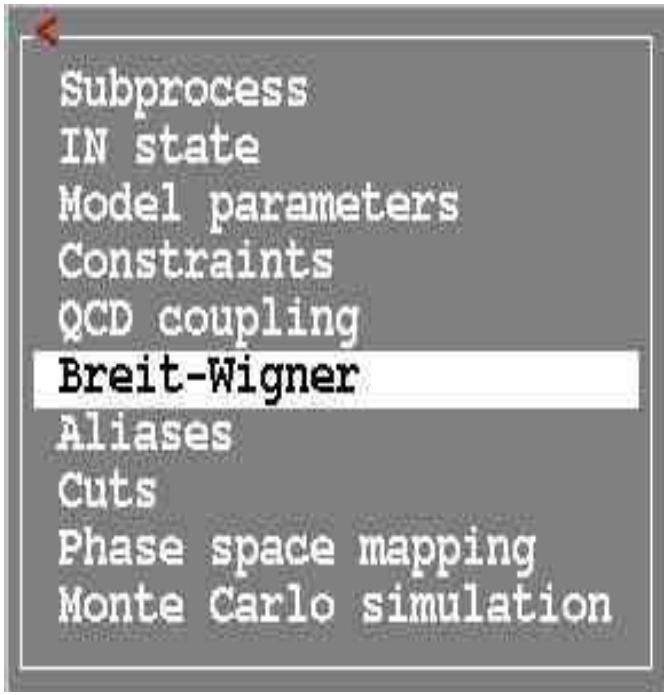
QCD coupling and the QCD scale



control of resonances



control of resonances



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

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

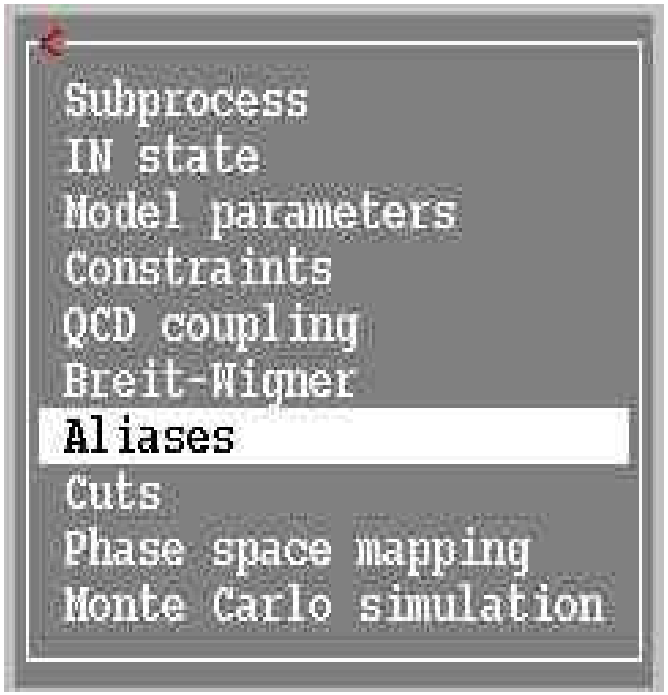
we use zero width propagator. In the intermediate region constant propagator interpolates both formulas.

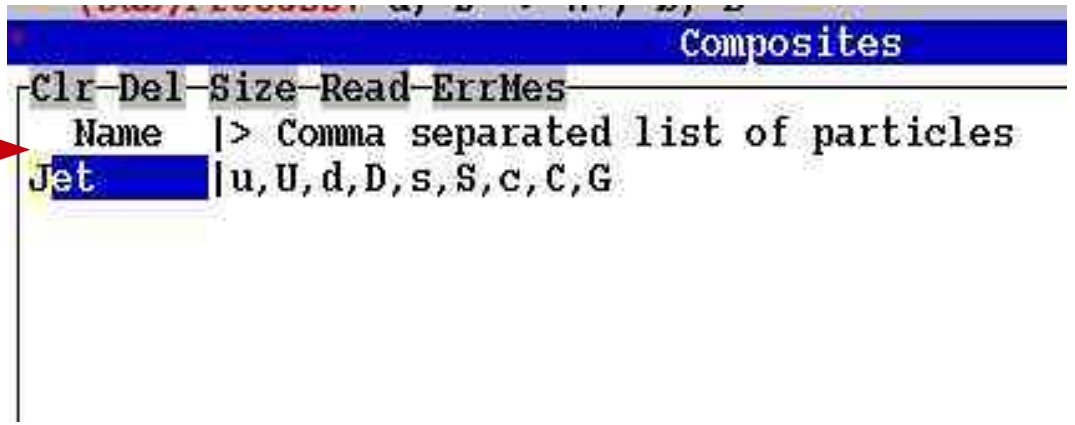
In general Breit-Wigner leads to breaking of gauge invariance. In its turn it can lead to the lost of diagram cancellation. From the other side just in the point $p^2=m^2$ the contribution of pole

diagram have to be gauge invariant. Thus at this

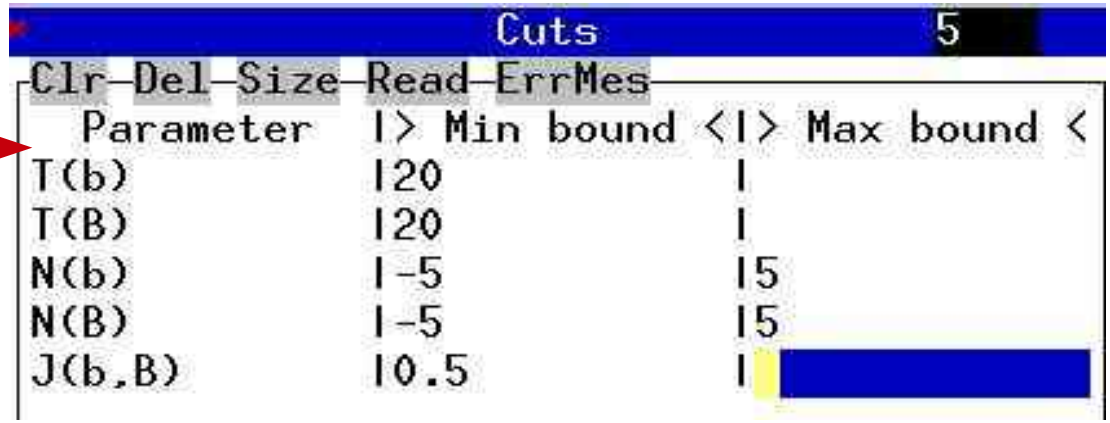
pont cancellation between pole and non-pole diagra ms
is not expected. We assume that close to pole the problem also is not so serious. But far from the p ole
we ignore width and restore gauge invariance.

Aliases

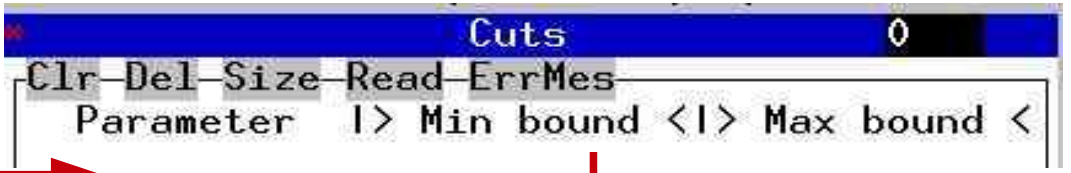

Subprocess
IN state
Model parameters
Constraints
QCD coupling
Breit-Wigner
Aliases
Cuts
Phase space mapping
Monte Carlo simulation


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

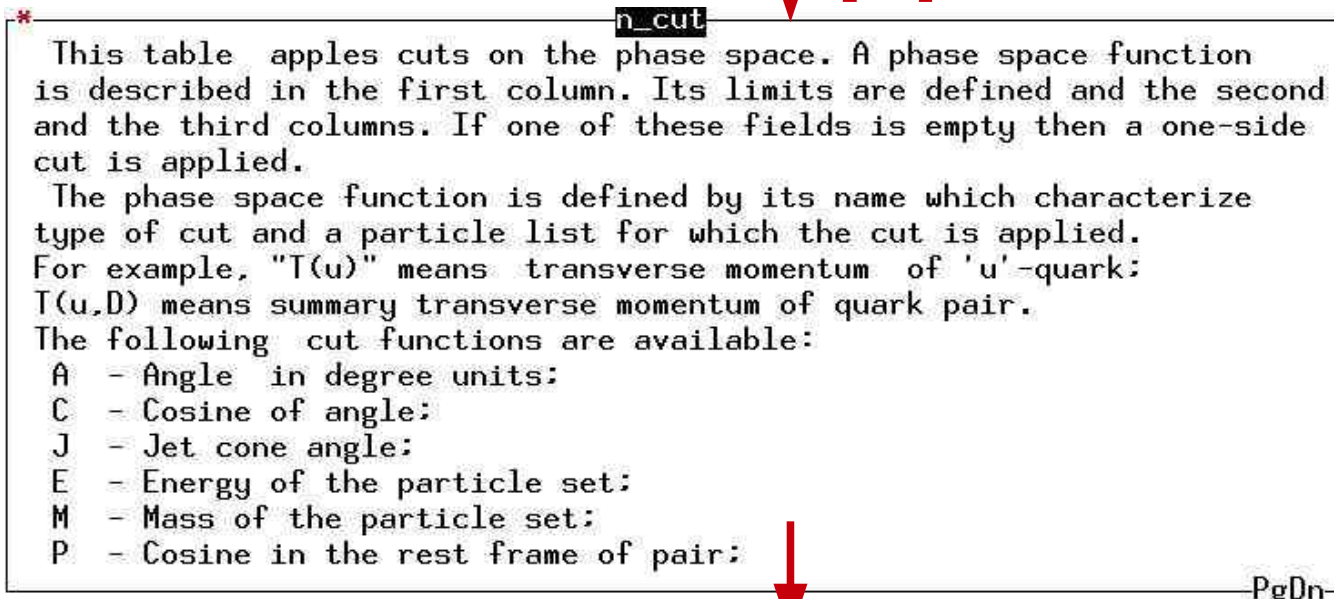
setting kinematical cuts



setting kinematical cuts

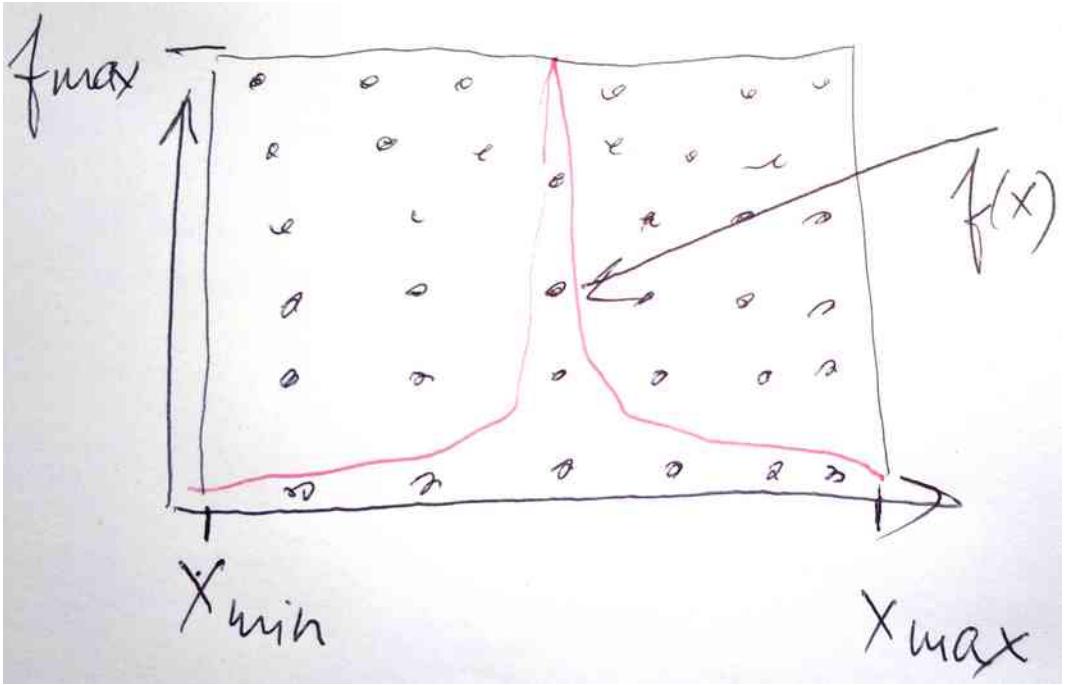


F1

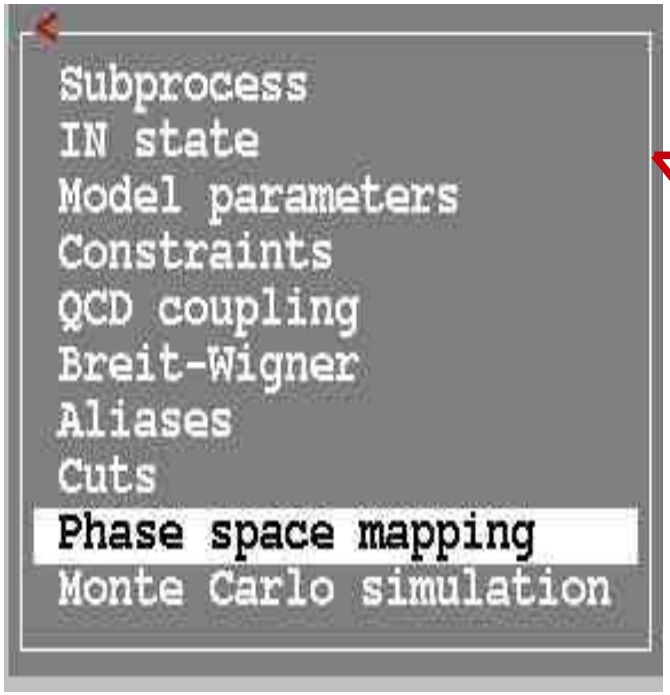


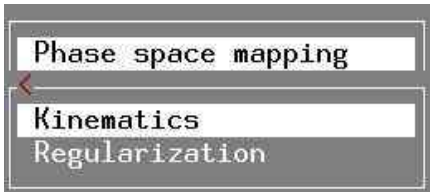
MC inegration and event generation is based on John von Neumann acceptance-rejection procedure

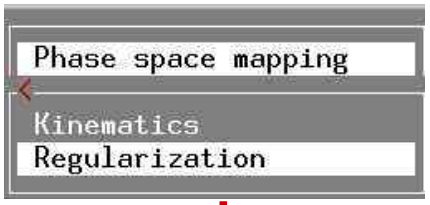
- The efficiency of the method strongly depends on the behavior of the function. Eventually it is equal to the ratio of the “useful” and total volume. And it can be very low in case of sharp resonances!

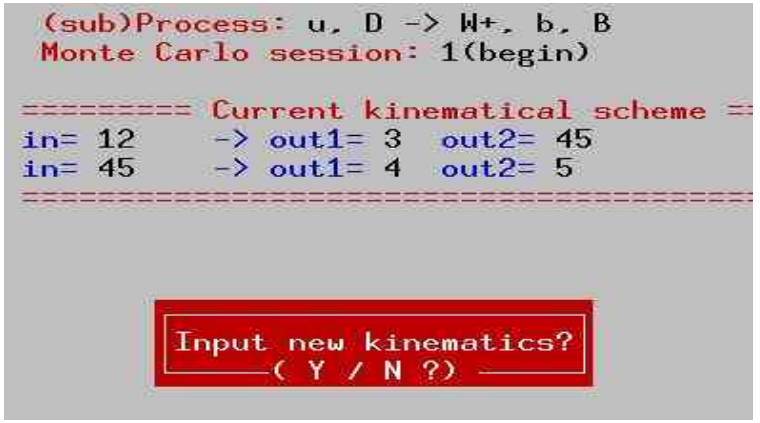


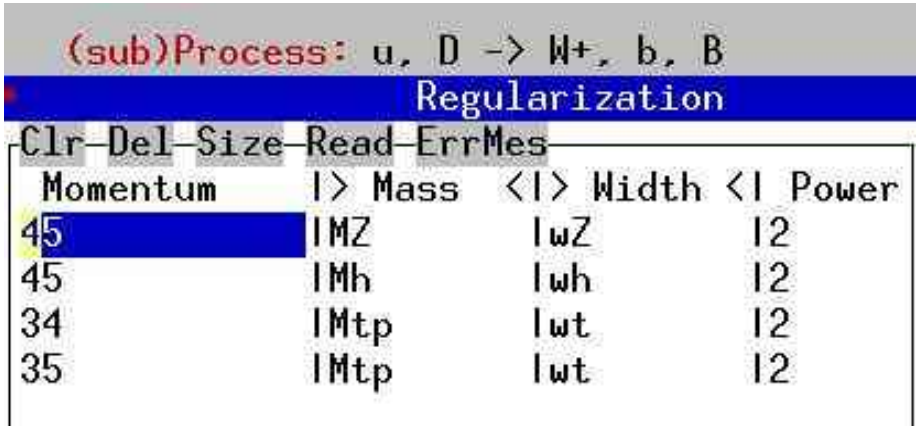
phase-space mapping











integration over the phase space

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

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

Distributions

Clr	Del	Size	Read	ErrMes

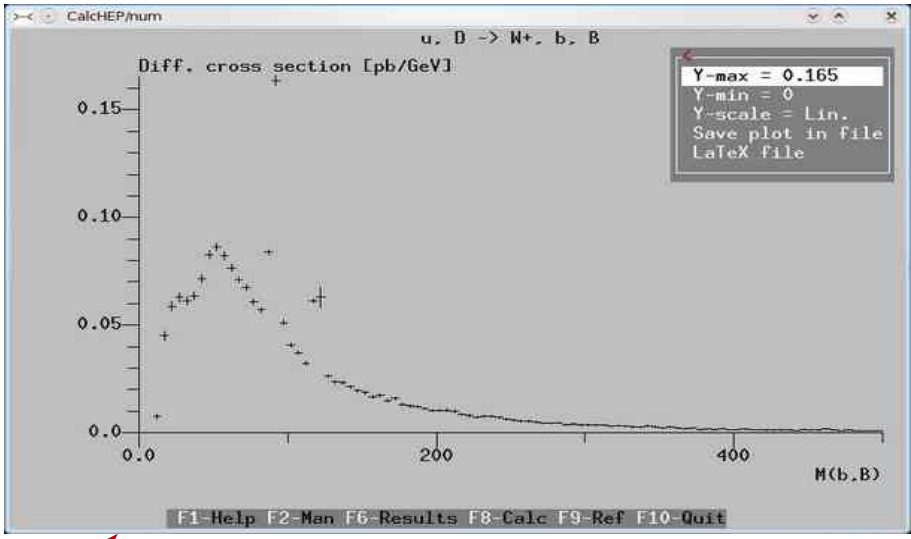
Parameter_1	|> Min_1	<|> Max_1	<|Parameter_2|> Min_2	<|> Max_2
T(b)	0	200		
T(B)	0	200		
N(b)	-5	5		
N(B)	-5	5		
M(b,B)	0	500		
M(W+,b)	0	500		
T(b)	0	500	M(b,B)	0 500

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

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

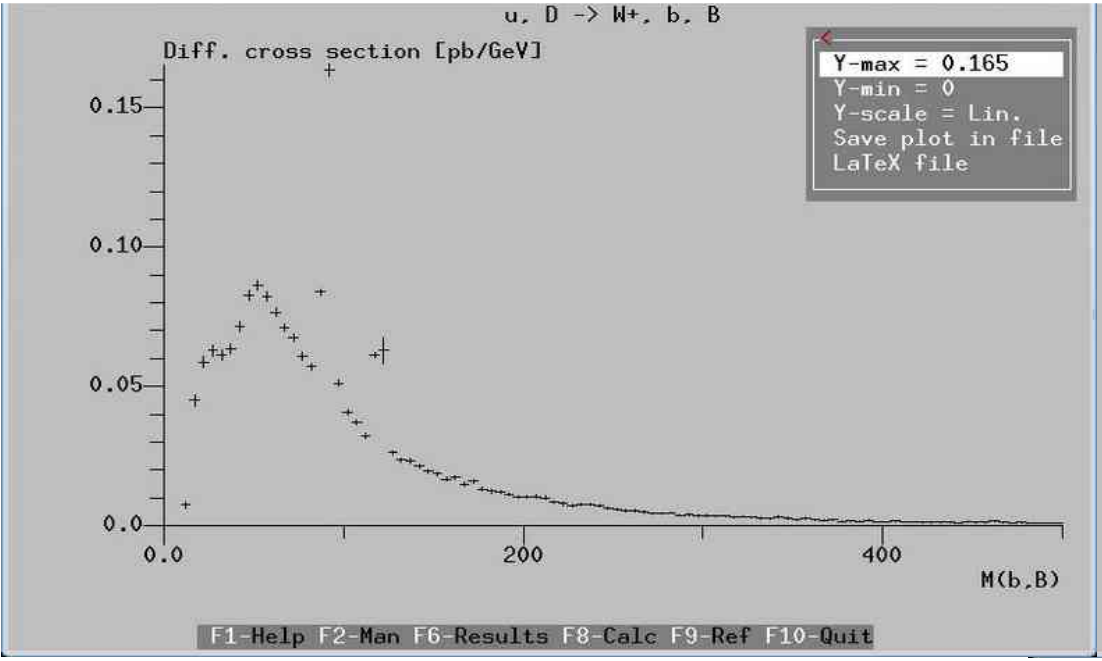
#IT	Cross section [pb]	Error %
6	9.5931E+00	7.10E-01
7	9.5686E+00	6.79E-01
8	9.5669E+00	6.82E-01
9	9.6892E+00	7.93E-01
10	9.6267E+00	7.51E-01
1	9.7757E+00	7.32E-01
clear statistics.		
2	9.6557E+00	6.82E-01
3	9.7464E+00	1.38E+00
4	9.6945E+00	1.05E+00
5	9.7032E+00	7.68E-01
< >	9.7095E+00	3.74E-01

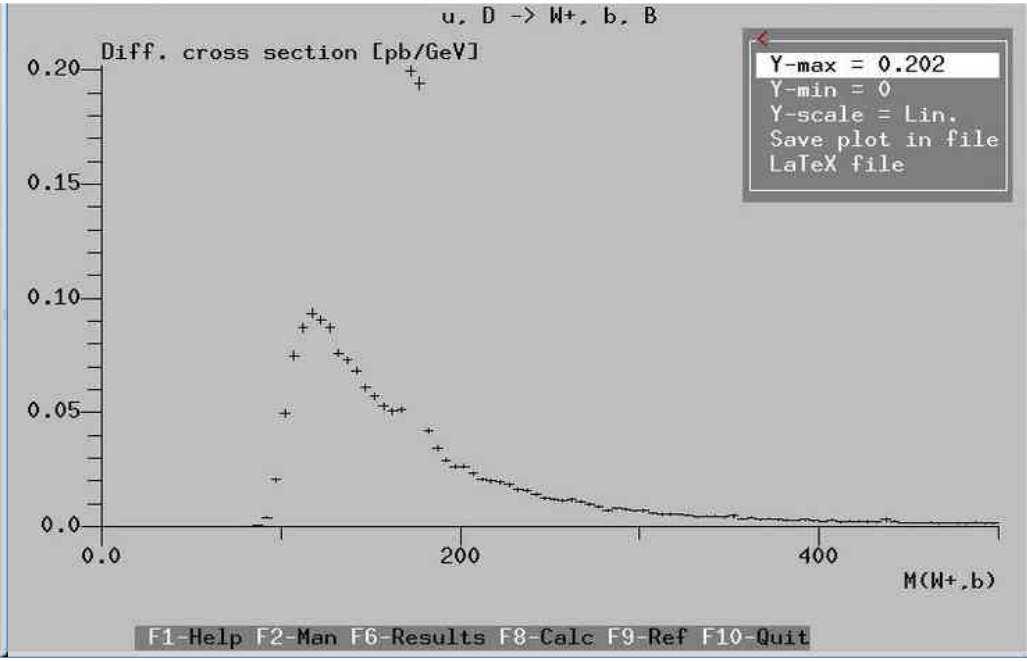
```
nSess  = 5
nCalls = 10000
Set  Distributions
*Start integration
Display Distributions
Clear statistic
Freeze grid          OFF
Clear  grid
Event Cubes 10000
Generate Events
```



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

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

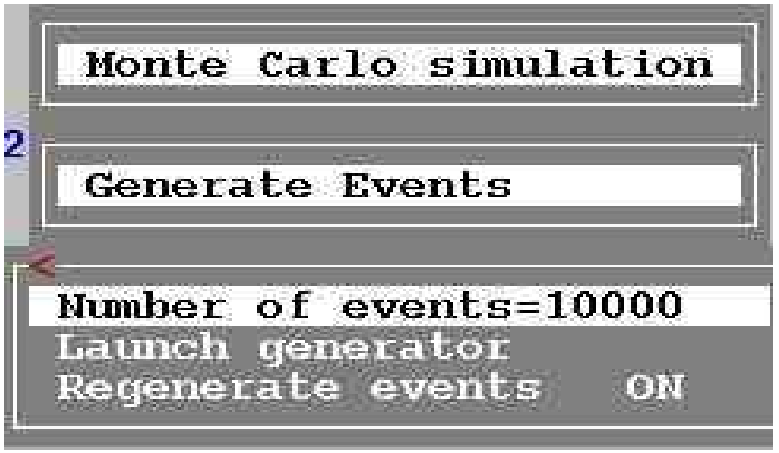


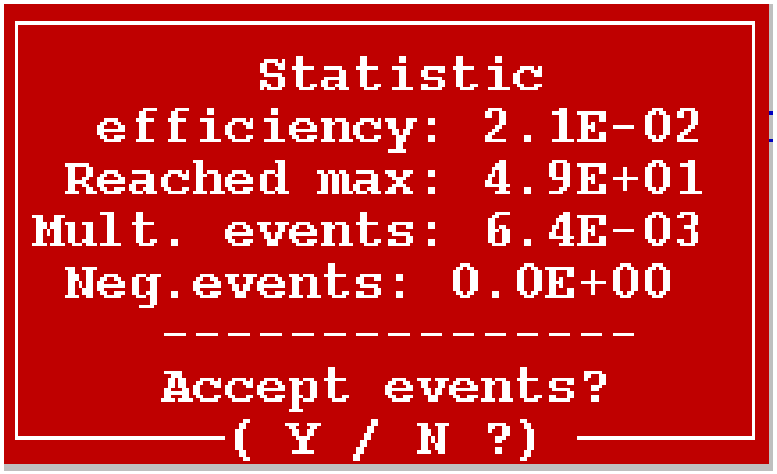


ex#4

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

events generations





File with events in the native CalcHEP format

```
#Type 2 -> 3
#Initial_state
  P1_3=4.000000E+03  P2_3=-4.000000E+03
  StrFun1="PDT:cteq6m(proton)" 2212
  StrFun2="PDT:cteq6m(proton)" 2212
#PROCESS   2(u) -1(D) -> 24(W+) 5(b) -5(B)
#MASSES  0.0000000000E+00 0.0000000000E+00 8.0385000000E+01 3.2414139578E+00 3.2414139578E+00
#Cross_section(Width) 6.473084E+01
#Number_of_events       1000
#Events       P1_3 [Gev]         P2_3 [Gev]         P3_1 [Gev]         P3_2 [Gev]         P3_3 [Gev]         P4
       1   7.0828325272E+02 -3.8182148276E+00 -5.8685533663E+00  2.4810106784E+00  6.8128552155E+02  1.995
       1   1.5237718262E+02 -2.5952742306E+01  1.1734367441E+01 -2.1669699291E+01  5.6645397996E+01  4.499
       1   7.2370755716E+02 -3.3186893665E+00 -3.4449322581E+00 -5.1815667765E+00  5.8508268207E+02 -3.584
       1   2.6295673814E+02 -1.1370528114E+01  8.9463043464E+00 -3.4258266547E+00  2.2732569389E+02 -9.675
       1   5.7099697940E+02 -3.3943984194E+01  7.2879879961E+00 -2.3531627752E+01  1.9857446272E+01 -8.750
       1   3.6709401207E+02 -2.4124155464E+01 -4.8101350483E+00  6.6698730251E+01  2.0295672218E+02 -4.597
       1   3.7196555447E+01 -4.1553021555E+02 -3.1735918986E+00  2.8330641675E-01 -6.6745521993E+00  4.343
       1   4.0543944850E+01 -1.1104274125E+02 -8.2903700266E+00 -4.3292277920E+00 -9.0241583360E-01  6.562
       1   4.0084952687E+02 -1.0215920577E+01  1.1427574950E+01  2.6016502364E+00  3.8645254998E+02 -4.666
       1   2.2620009412E+01 -1.2387066011E+02 -5.0869818859E+00  1.1389105773E+01 -7.1200204784E+01  1.176
       1   7.2046251695E+02 -2.1091178466E+01 -1.4887347954E+01  8.1292985197E+01  5.8742582956E+02 -5.134
       1   6.8661185459E+01 -8.3534206530E+01 -5.5091602956E+00 -1.7099072377E+01  4.1559702536E+01  2.604
       1   1.5145483971E+03 -3.1164597600E+00 -7.8325298677E+00  3.6606202670E+01  1.2782056265E+03  1.074
```

GUI: full control of details of the process

scripts: automate calculation/generation/analysis

batch: does everything (sym,num,plots,…) in one run

Script example:

- **$CALCHEP/bin/subproc_cycle** ***nmax lumi***

  e.g.

  ../bin/subproc_cycle 1000 100000

  You should run it from results dir where the n_calchep binary is!

  Will evaluate cross section and generate events

- **$CALCHEP/bin/event_mixer Luminosity[1/fb] nevents event_dirs**

  mixes subprocesses and connects production and decay events

useful scripts for numerical session

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

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

ex#5
produce LHE file
and use lhe2tab
to produce
distributions from ex#4

running subproc_cycle for SM model

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

1000 events are requested
Number of enents limited by flux 40 [1/fb]

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

3.045E+01  -total cross section[pb]
3690       -maximum number of events
 1000 events are generated
Events in LHE format: events_9_16.lhe
Total Cross Section 3.046E+01 [pb] (5.685E-01%)
See details in directory 9_16
```

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

- **bin/event_mixer** ***Luminosity[1/fb] nevents event_dirs***

mixes subprocesses and connects production and decay events

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

- ***the output is*** **event_mixer.lhe** ***file***

```
<LesHouchesEvents version="1.0">
<!--
File generated with CalcHEP-PYTHIA interface
-->
<header>
<slha>
</slha>
</header>
<init>
  2212   2212   7.00000006860E+03   7.00000006860E+03     -1     -1     -1     -1      3      1
  1.16593335502E+01   0.00000000000E+00   1.00000000000E+00    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>
```

Accessing all your results

- results are stored in “results” directory
- output files:
  - n_calchep — numerical module
  - prt_nn — protocol
  - distr_nn_mm — summed distributions
  - distr_nn — individual distribution
  - events_nn.txt — events file
  - list_prc.txt — list of processes
  - qnumbers — 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
.........................................
.........................................
```

scripts for numerical session

- events2tab

Parameters:
1- name of variable,
2- minimum limit,
3- maximum limit,
4- number of bins(<=300).
File with events must be passed to input.

../bin/events2tab “T(b)” 1 100 200 < events_1.txt >tab.txt
../bin/tab_view < tab.txt

- name_cycle

1: Name of parameter
2: Initial value
3: Step
4: Number of steps

../bin/name_cycle Mh 100 10 11

scripts above became a part of calchep_batch interface – will be discussed below

the most general scan with

par_scan

- Usage:
  $CALCHEP/bin/par_scan < data_file

- Data file structure:

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

- where par_name_i present free parameters of the models. Among them one also can write momenta of incoming particles as momentum1 and momentum2.
- fun_name_i is the name of constrained parameter which will be presented in output file
- Output file has the same structure as input plus calculated numerical values for constrained parameters, and an additional column for evaluated cross section with statistical error
- If you are not interested in the prt_# files you can clean it using
  $CALCHEP/bin/par_scan clean < data_file

CalcHEP batch interface

https://hepmdb.soton.ac.uk/wiki/index.php/CalcHEP_tutorial

CalcHEP batch interface: all results in one shot

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

```
Kinematics :       12 -> 3, 45
Kinematics :       45 -> 4 , 5
Regularization momentum:1:  45
Regularization mass:1:      Mh
Regularization width:1:     wh
Regularization power:1:     2
########################################
Dist parameter:     M(b,B)
Dist min:           100
Dist max:           200
Dist n bins:        100
Dist title:         p,p->W,b,B
Dist x-title:       M(b,B) (GeV)

Dist parameter:     M(W,jet)
Dist min:           100
Dist max:           200
Dist n bins:        100
Dist title:         p,p->W,b,B
Dist x-title:       M(W,jet) (GeV)
########################################
Number of events (per run step): 10000
Filename:                        pp_Wbb
########################################
Parallelization method:       local
Max number of nodes:    8
Max number of processes per node: 1
########################################
nSess_1:    5
nCalls_1:   100000
nSess_2:    5
nCalls_2:   100000
```

CalcHEP batch interface: running and monitoring

$CALCHEP= path to calchep installation

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

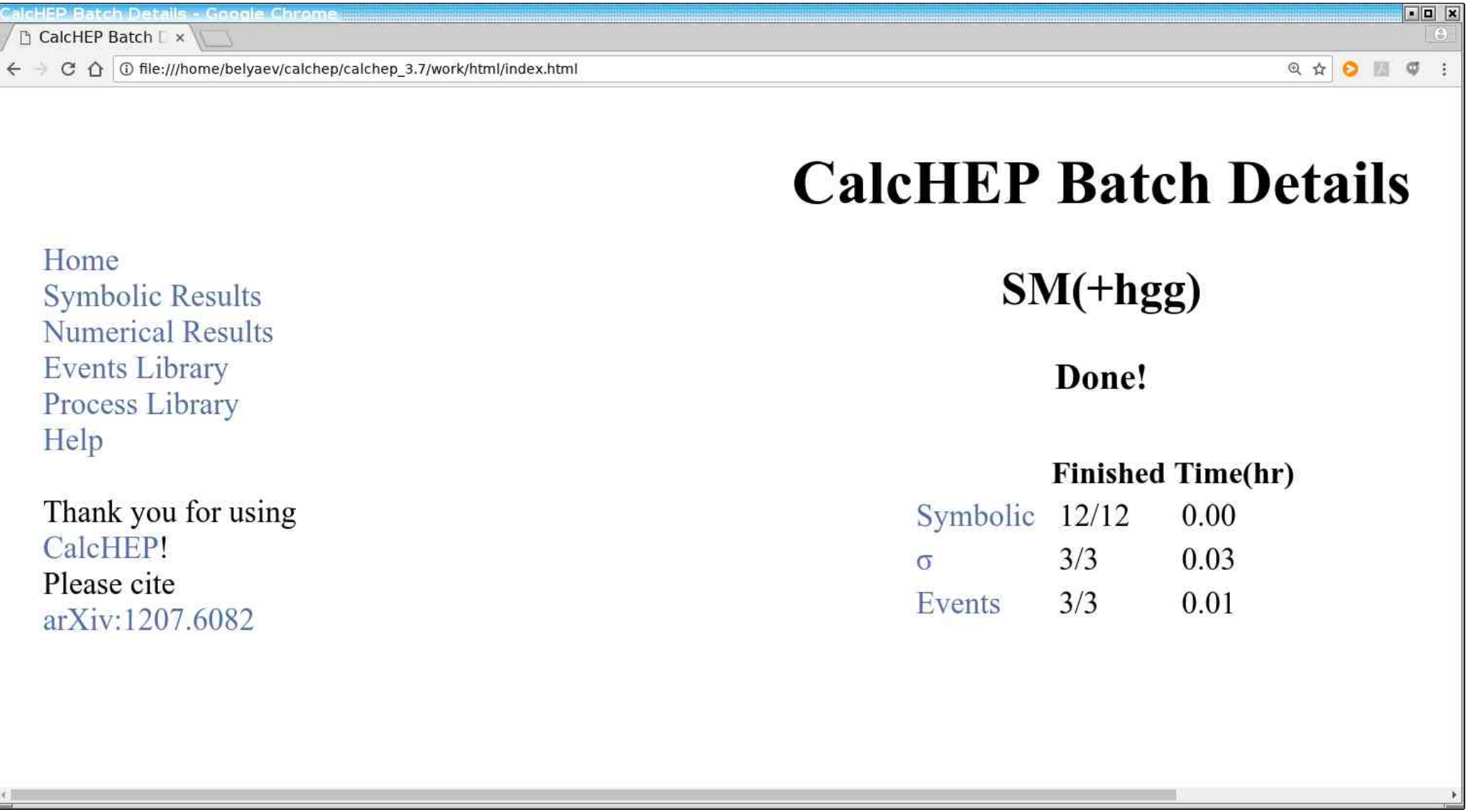
CALCHEP= /home/belyaev/calchep/calchep_x.y.z

calchep_batch version x.yz

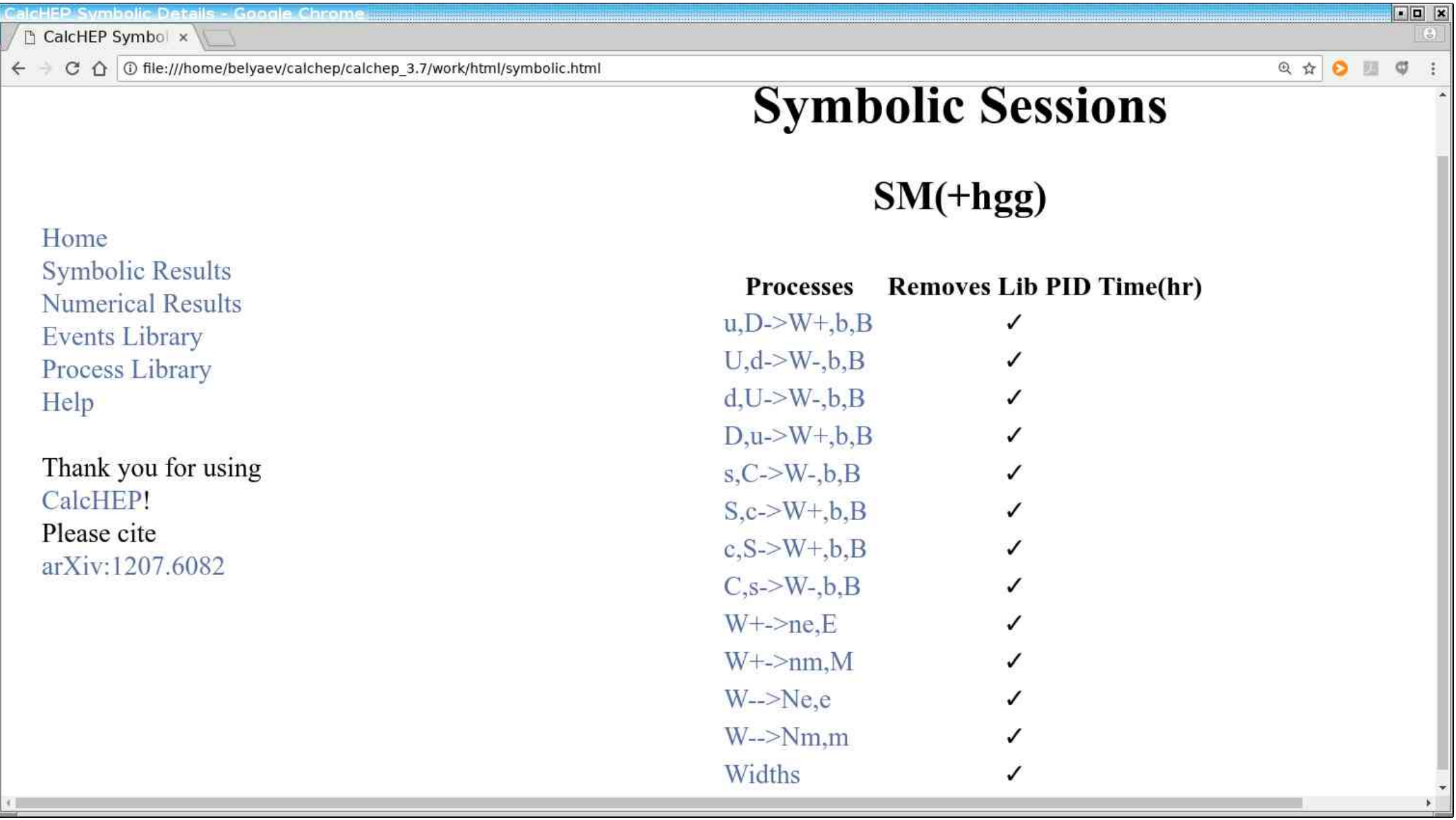
Processing batch:
Progress information can be found in the html directory.
Simply open the following link in your browser:
file:///.../calchep_x.y.z/work/html/index.html

You can also view textual progress reports in
.../calchep_x.y.z/work/html/ and the other .txt files in the html directory.
Events will be stored in the batch_results directory.

CalcHEP batch interface: running and monitoring



CalcHEP batch interface: running and monitoring



CalcHEP batch interface: running and monitoring

CalcHEP Numerical Details - Google Chrome

CalcHEP Numeri ×

file:///home/belyaev/calchep/calchep_3.7/work/html/numerical.html

Numerical Sessions

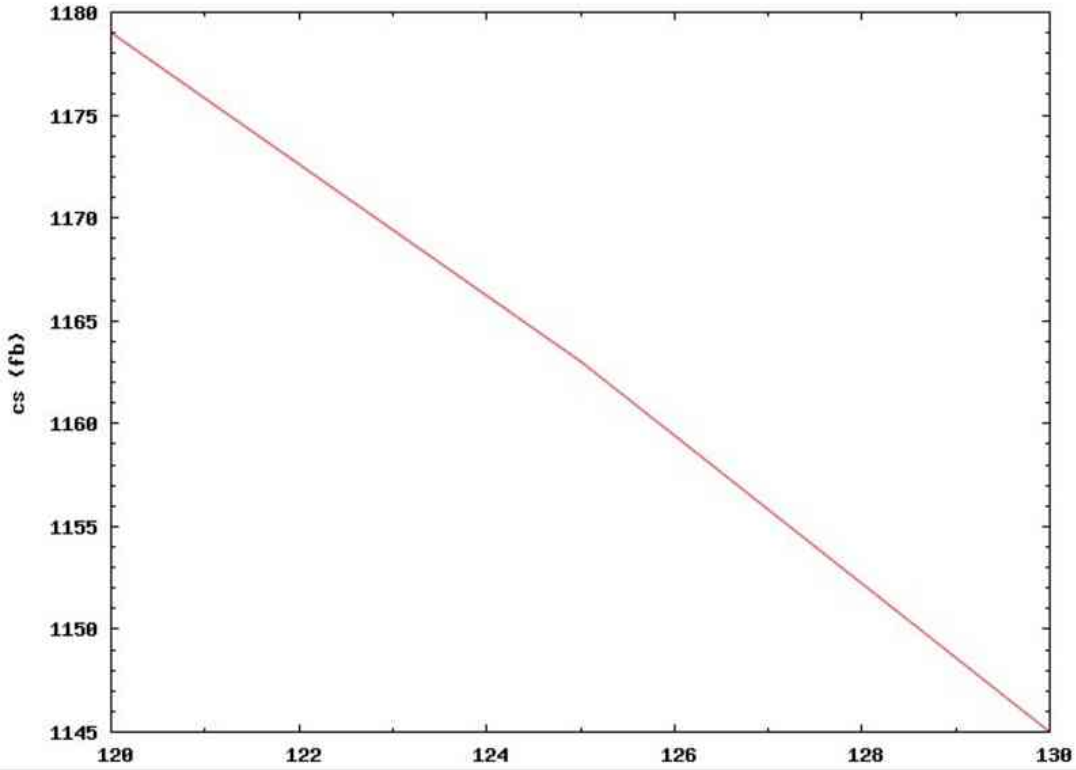
SM(+hgg)

Done!

Home
Symbolic Results
Numerical Results
Events Library
Process Library
Help

Thank you for using CalcHEP!
Please cite
arXiv:1207.6082

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



CalcHEP batch interface: running and monitoring

Home
Symbolic Results
Numerical Results
Events Library
Process Library
Help

Thank you for using CalcHEP!
Please cite
arXiv:1207.6082

Numerical Sessions

SM(+hgg)

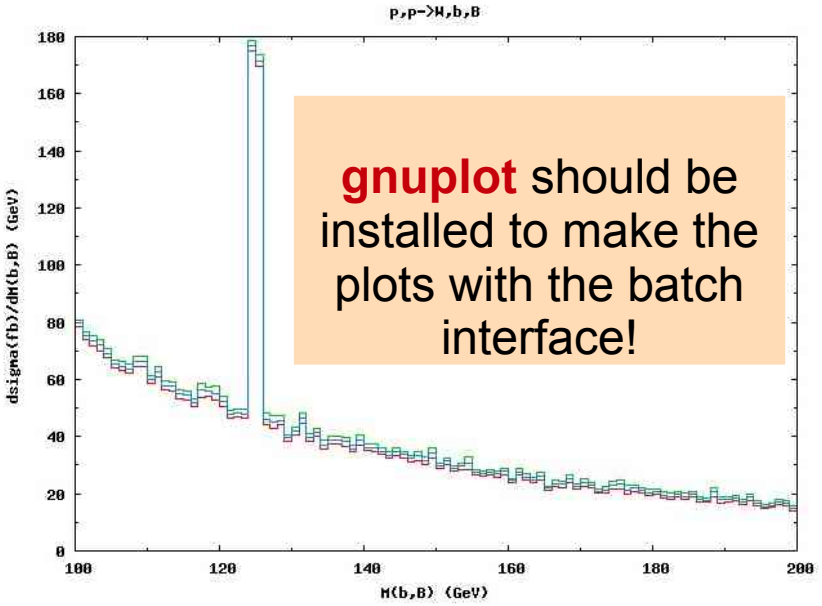
Done!

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

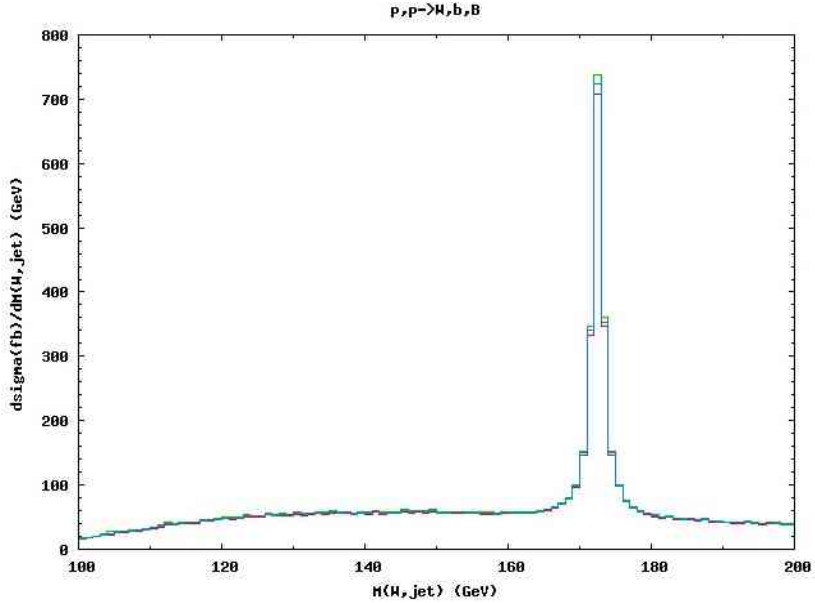
Decays	Γ (GeV)	ΔΓ (%)	PID	Time (hr)	N events	Details
W+->ne,E	0.23293	0	29129	0.00	5099/5100	prt_1 session.dat
W+->nm,M	0.23293	0	29135	0.00	5099/5100	prt_1 session.dat
W-->Ne,e	0.23293	0	29142	0.00	5099/5100	prt_1 session.dat
W-->Nm,m	0.23293	0	29324	0.00	5099/5100	prt_1 session.dat

Widths		PID	Time (hr)		Details
Widths		29328	0.00		session.dat
Total	1163		0.01	1000/1000	

Distributions



gnuplot should be installed to make the plots with the batch interface!



ex#6: *using calchep_batch evaluate complete cross section for pp-> Wbb process with the same cuts as for ex#4*

CalcHEP batch results

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

see https://answers.launchpad.net/calchep for many “tricky” questions/answers

CalcHEP batch interface:
some additional features/tricks

- see https://answers.launchpad.net/calchep
  for many “tricky” questions/answers
- scanning over the collider energy
  Run parameter: rtS
  Run begin: 7
  Run step size: 1
  Run n steps: 2

  p1: 1000*rtS/2
  p2: 1000*rtS/2
  rtS here is some “fake” parameter
- you can use “fake” parameter only if you define it as a loop parameter
  - It can be used in the cut statement (assigning cut to the symbol)
  - It can be assigned to the parameter model – this way you can run use complicated scan

CalcHEP batch interface:
Scanning with 'fake' parameters

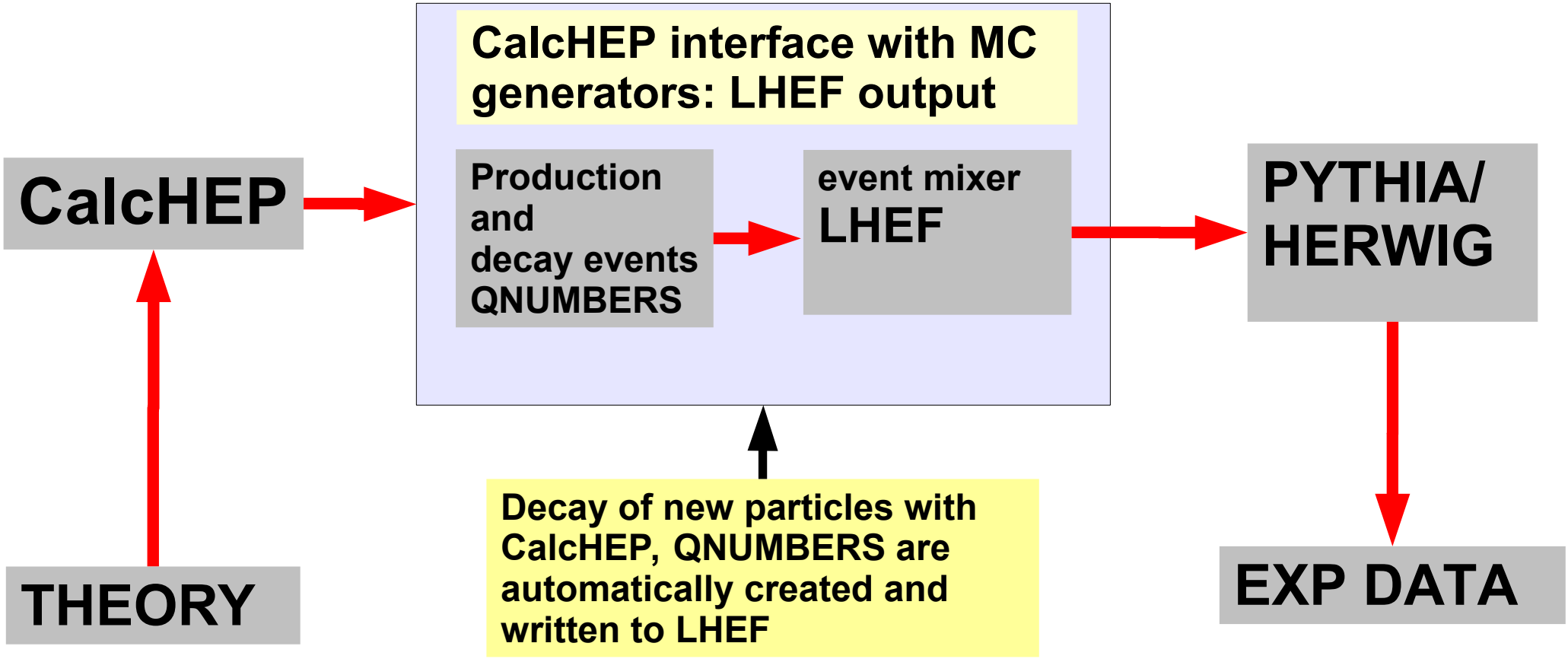
an example:

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

```
########################################
#  Run Info                            #
#  Masses and Energies are in GeV      #
#  More than one run can be specified at #
#    the same time.                    #
########################################
Run parameter: MASS
Run begin:     500
Run step size: 500
Run n steps:   6
```

```
########################################
#  Cut Info                            #
#  Must be in terms of the (production mode) #
#    final state particles.            #
#    :n: specifies which process.      #
#    : means to apply to all processes. #
########################################

Cut parameter:    M(e,E)
Cut invert:       False
Cut min:          MASS-400
Cut max:          MASS+400
```

CalcHEP interface to MC generators via Events in the LHE format



Lecture II

LanHEP

Introduction to LanHEP package

author: ***Andrei Semenov***

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

- 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 CalcHEP/CompHEP/FeynArts/UFO formats 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
- user can write Lagrangian terms with Lorentz and multiplet indices explicitly or omit indices (all or some of them)
- LanHEP performs explicit summation over the indices in Lagrangian terms, if the corresponding components for multiplets and matrices are introduced
- it also 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, …

QCD as an example

- **Gauge interactions** $L_{YM} = -\frac{1}{4} F^{a\mu\nu} F^a_{\mu\nu},$

where $F^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g_s f^{abc} G^b_\mu G^c_\nu,\ G^a_\mu(x)$

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

- **Gauge fixing term and Fadeev-Popov ghost term**

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

- **LanHEP model file (qcd.mdl):**

```
model      QCD/2.
parameter  gg= 1.13 : 'Strong coupling'.
vector     G/G: (gluon, color c8, gauge).
spinor     q:(quark, color c3, mass Mq=0.02).
lterm      i*gg*f_SU3*ccghost(G)*G*deriv*ghost(G).
lterm      Q*gamma*(i*deriv + gg*lambda*G)*q.
lterm       -F**2/4  where
           F=deriv^mu*G^nu^a-deriv^nu*G^mu^a+
           i*gg*f_SU3^a^b^c*G^mu^b*G^nu^c.
```

../lhep -tex qcd.mdl

will produce: vars2.tex, prtcls2.tex, lgrng2.tex

lgrng2.tex

QCD Feynman rules generated by LanHEP in LaTeX format

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

Model implementation in CalcHEP

using LanHEP (*Andrei Semenov*)

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

- **To install**
  wget https://theory.sinp.msu.ru/~semenov/lhep400.tgz
  tar -zxvf lhep*xxx*.tgz
  cd lanhep*xxx*
  make

- **To Run**
  cd mdl
  ../lhep -ca stand.mdl

  File sm_tex processed, 0 sec.
  File stand.mdl processed, 0 sec.

- **Also you can do**
  ../lhep -ufo stand.mdl
  ../lhep -tex stand.mdl

  to produce model in UFO format and get Feynman rules in the LaTeX format respectively

ex#7
install LanHEP

Default options are in calchep.rc file

```
% Definitions specific for CalcHEP format of Feynman rules.

external_func(creal,1).
external_func(cimag,1).
external_func(cabs,1).

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

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

Some Format Options for LanHEP output

```
model qed/1.
parameter ee = 0.3133: 'Electric charge'.

prtcformat fullname:
'Full Name   ', name:' p ', aname:' ap', pdg:'  PDG ID',
spin2:'2*spin', mass:' mass ',width:'width ',
color, aux, texname:'>LaTeX(A)<', atexname:'>LaTeX(A+)< ' .

vector A/A:(photon, pdg 22).
spinor e1:(electron, mass me=0.000511, pdg 11).

let F^mu^nu=deriv^mu*A^nu-deriv^nu*A^mu.
lterm -1/4*F**2 + ee*E1*gamma*A*e1.
```

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 matrice*** `OrthMatrix(` $\{\{a_{11}, a_{12}\}, \{a_{21}, a_{22}\}\}$ `)`.

- ***Including files*** `read` *file*. or `use` *file*. (no multiple reading)

- ***Checking electric charge conservation*** `SetEM(`*photon*, *param*`)`.

- ***Running LanHEP*** `lhep` *filename options*

  `-OutDir` *directory* Set the directory for output files

  `-InDir` *directory* Set the directory where to search files

  `-tex` LanHEP generates LaTeX files

  `-frc` If `-tex` option is set, forces LanHEP to split 4-fermion and 4-color vertices just as it is made for CompHEP files.

  `-texLines` *num* Set number of lines in LaTeX tables

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

Default groups and specials in LanHEP

- ***See*** mdl/lhep.rc

```
special gamma:(spinor,cspinor,vector).
special gamma5:(spinor,cspinor).
special '(1+gamma5)/2':(spinor,cspinor), '(1-gamma5)/2':
(spinor,cspinor).
special moment:(vector).
special '__moment__start__':(vector), '__moment__end__'.
special epsv:(vector,vector,vector,vector).
group color:SU(3).
repres color:(c3/c3b,c8).
SetDefIndex(spinor,color c3, color c8, vector).
special lambda:(color c3, color c3b, color c8).
special f_SU3:(color c8, color c8, color c8).
special d_SU3:(color c8, color c8, color c8).
special eps_c3: (color c3,  color c3,  color c3),
        eps_c3b:(color c3b, color c3b, color c3b).
let deriv=-i*moment.
let tau1={{0,1},{1,0}}, tau2={{0,i},{-i,0}}, tau3={{1,0},
{0,-1}}.
```

user-defined model

$$\bar{b}_{ap} \quad t_{bq} \quad W^{-}{}_{\mu} \qquad \Big| \; -\frac{1}{4}\frac{e\cdot\sqrt{2}\cdot Vtb}{s_w}\cdot(1-\gamma^5)_{cb}\delta_{pq}\gamma^{\mu}_{ac}$$

- ***Let us add left and right anomalous couplings to WtB interaction: Ar and Al***

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% anomalous WtB interactions Ar and Al
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

parameter Ar,Al.
let PR=(1+gamma5)/2, PL=(1-gamma5)/2.

lterm   -g/Sqrt2*
         (Ar*anti(t)*'W+'*gamma*PR*b  + Al*anti(t)*'W+'*gamma*PL*b)
       + AddHermConj.
```

$$-\frac{1}{4}\frac{e\cdot\sqrt{2}}{s_w}\delta_{pq}\gamma^{\mu}_{ac}(Vtb\cdot(1-\gamma^5)_{cb}+Ar\cdot(1+\gamma^5)_{cb}+Al\cdot(1-\gamma^5)_{cb})$$

ex#8
implement $\sigma^{\mu\nu}$ anomalous terms B_l, B_r

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:***

$$W = \mu\epsilon_{ij}H_i^1H_j^2 + \epsilon_{ij}Y_l^{IJ}H_i^1L_j^IR^J + \epsilon_{ij}Y_d^{IJ}H_i^1Q_j^ID^J + \epsilon_{ij}Y_u^{IJ}H_i^2Q_j^IU^J$$

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***

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

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) - ....
```

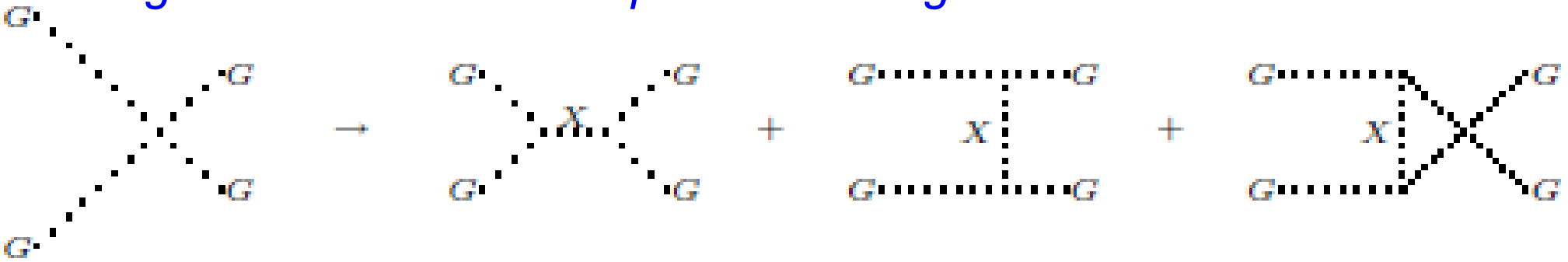
where dfdfc(W,H1) **function** ***evaluates the variational derivative, multiplies it by the conjugate expression and returns the result***

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^1_p and A^2_q
  - λ^r_{pq} for three particles, which are color triplet, antitriplet and octet
  - f^{pqr} for three color octets $\quad f^{pqr} G^p_\mu G^q_\nu G^r_\lambda$
  - ***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*

Implementation of SM Lagrangian(1)

Location of LanHEP model files:

mdl/stand.mdl

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

keys gauge_fixing=Feynman.

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

Implementation of SM Lagrangian(2)

- ***Parameters definition***

```
let g5=gamma5.
use sm_tex.

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

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

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

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

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

Implementation of SM Lagrangian(4)

- ***Definition of mixings and doublets***

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

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

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

do_if gauge_fixing==Feynman.

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

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

end_if.

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

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

Implementation of SM Lagrangian(5)

```
% Self-interaction of gauge bosons


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

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

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

Implementation of SM Lagrangian(6)

```
% left fermion interaction with gauge fields


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

% right fermion interaction with gauge fields

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


% quark-gluon interaction

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

$H\gamma\gamma, Hgg$ Effective vertices in CalcHEP

- **Model sources in CalcHEP**
  cd $CALCHEP/model_src
  ls
  sm.inc, sm.lhep, idm.lhep

  $LANHEP/lhep -ca sm
  $LANHEP/lhep -ca idm
  will produce SM and IDM models for CalcHEP

- **The sm.inc contains the $H\gamma\gamma$ implementation**

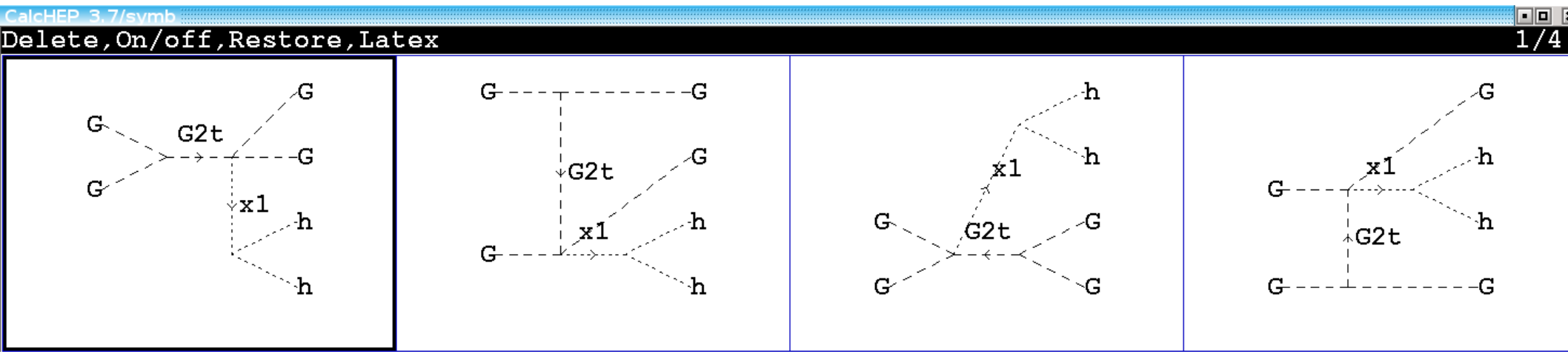
```
let shd = {  i*'W+.f',  (vev(vevh)+h-i*'Z.f')/Sqrt2 }.
external_func(lAAhiggs,2).
parameter LAAh=-cabs(lAAhiggs(Mh,str(h))).
lterm  LAAh*(shd*anti(shd)-vevh**2/2)/vevh*F**2  where
         F=deriv^mu*A^nu-deriv^nu*A^mu.
```

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

Introducing auxiliary particles in CalcHEP

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

```
vector  G2t/G2T: (G2T, mass Maux, color c8, aux ('!*')).
scalar  x1/X1:   (x1,  mass Maux, aux ("!*")).

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

lterm   1/vevh*LGGh*RQCDh*(shd*anti(shd)-vevh**2/2-vevh*h)*x1*Maux.
lterm   (GG/2*f_SU3^a^b^c*G^n^a*G^m^b*'G2t.t'^m^n^c)*(X1*Maux).
lterm    GG/2*f_SU3^a^b^c*G^n^a*G^m^b*'G2T.t'^m^n^c.
```



micrOMEGAs

Cold DM density in Universe.

DM density is known from measurements of CMB temperature fluctuations in WMAP and Planck spacecraft experiments: Assuming that DM is a non-relativistic particle at temperatures of CMB formation (Mdm > 10KeV) they get

$$\Omega h^2 = h^2 \rho_{dm}/\rho_{cr} = 0.1198(26)$$

Here ρ_{cr} is critical density of Universe defined via gravitation constant G and Hubble rate H

$$\rho_{cr} = \frac{3H^2}{8\pi G}$$

H=h*100km/s/Mpc where h=0.73(3) is a present day Hubble rate

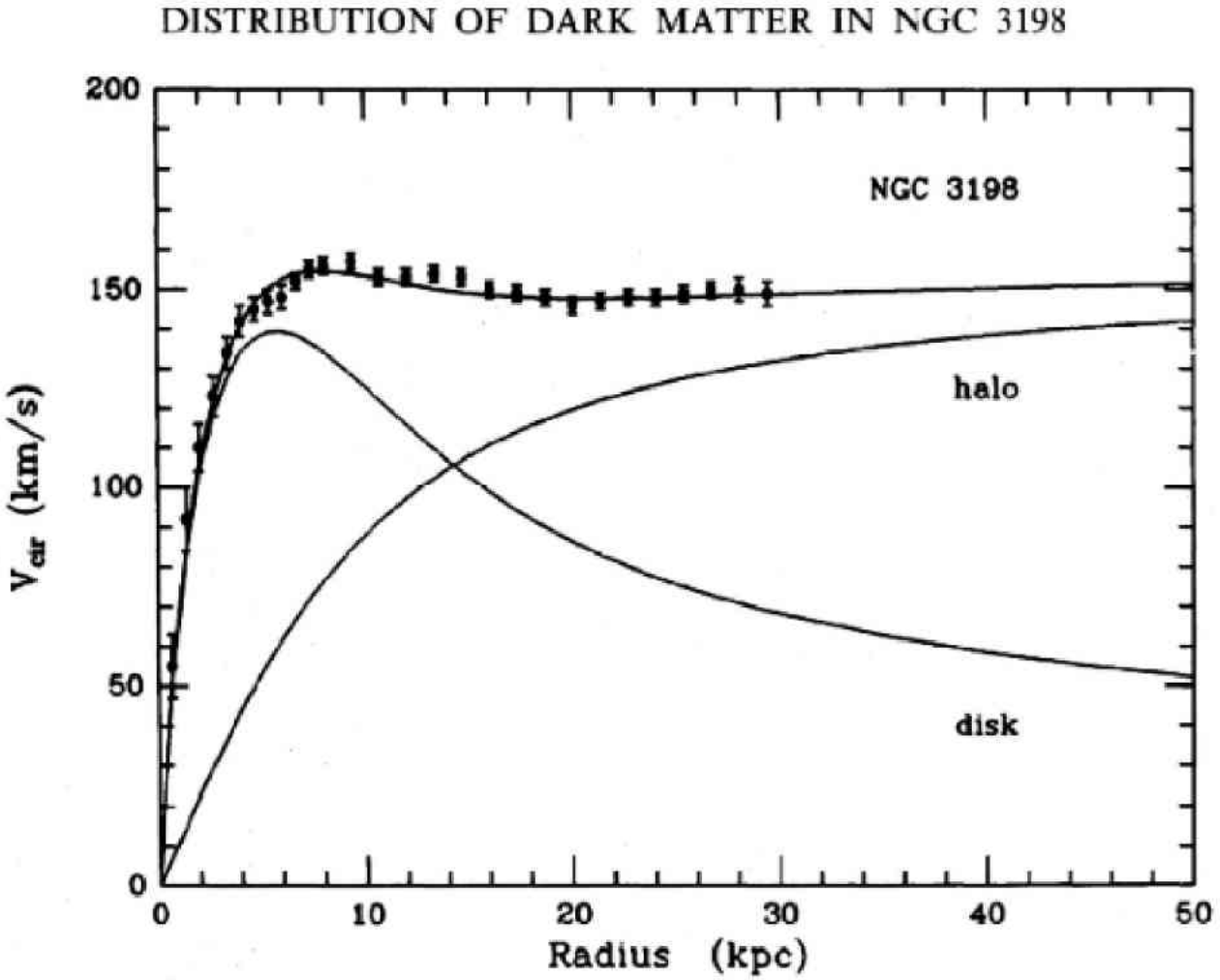
ρ(rc)=10.537h^2 GeV/m^3 so ρ(dm)= 1.11 GeV/m^3

$$\Omega = 0.12/0.73^2 = 0.23$$

Such value of Ω is in good agreement with simulation of galaxies formation and with requirement on expansion rate in time of primordial nucleosynthesis (MeV temperatures).

Dark mater in spiral galaxies.

Dark matter density in spiral galaxies is detected via rotation curve - dependence of velocity rotation on distance from galactic center. It is defined via Doppler shift of 21-cm hydrogen radiation.



Flat rotation curve corresponds to DM density profile

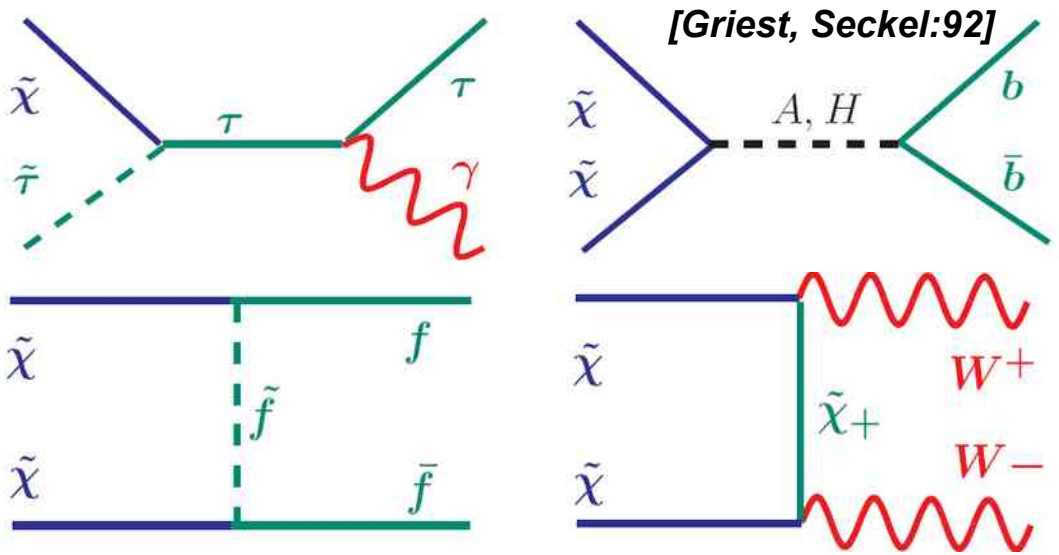
$$\rho(r) \approx 1/r^2$$

Typical DM profile Navaro, Frenk, and White

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

Evolution of neutralino relic density

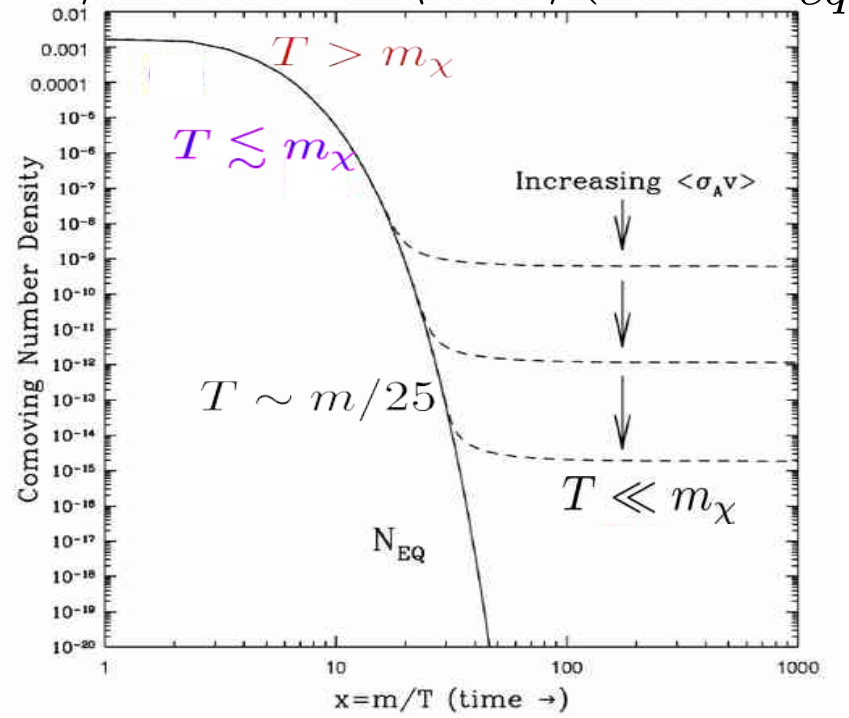
The challenge is to evaluate thousands annihilation/co-annihilation diagrams



relic density depends crucially on $\langle \sigma_A v \rangle$

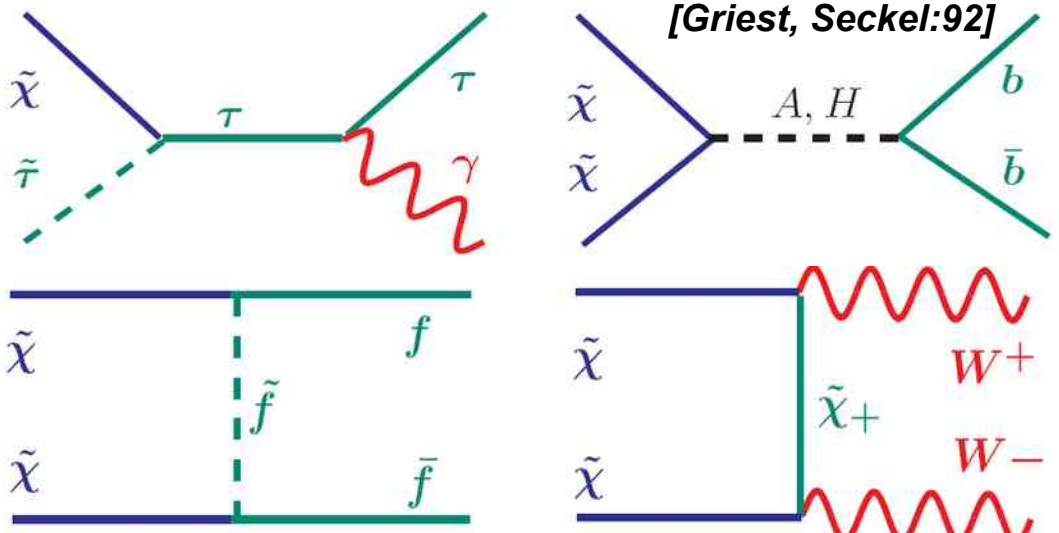
time evolution of number density is given by Boltzmann equation

$$dn/dt = -3Hn - \langle \sigma_A v \rangle (n^2 - n_{eq}^2)$$



Evolution of neutralino relic density

The challenge is to evaluate thousands annihilation/co-annihilation diagrams



[Griest, Seckel:92]

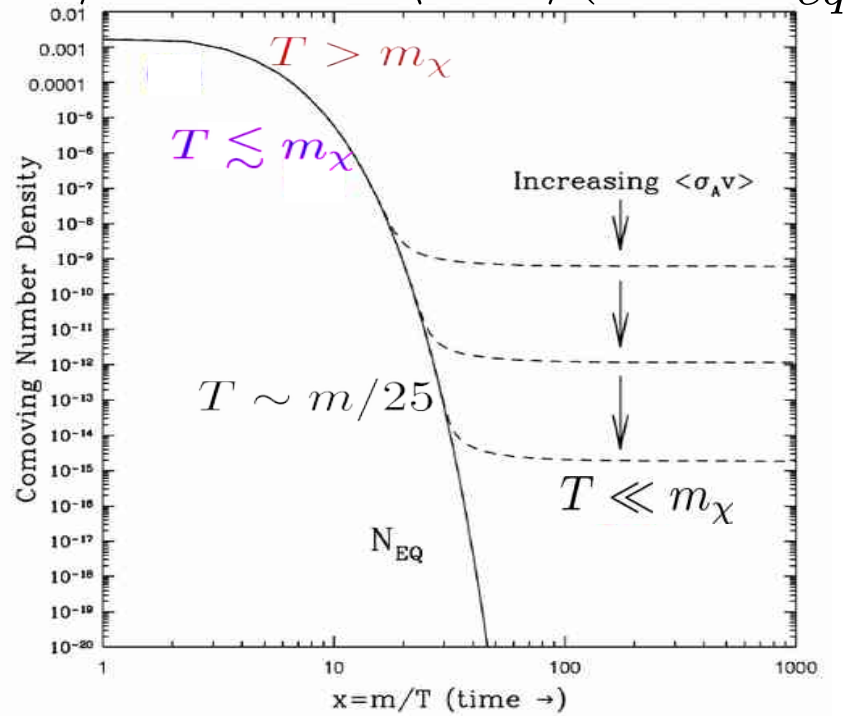
relic density depends crucially on thermal equilibrium stage:

$$\langle \sigma_A v \rangle$$

$$T > m_\chi, \quad \chi\chi \leftrightarrow f$$

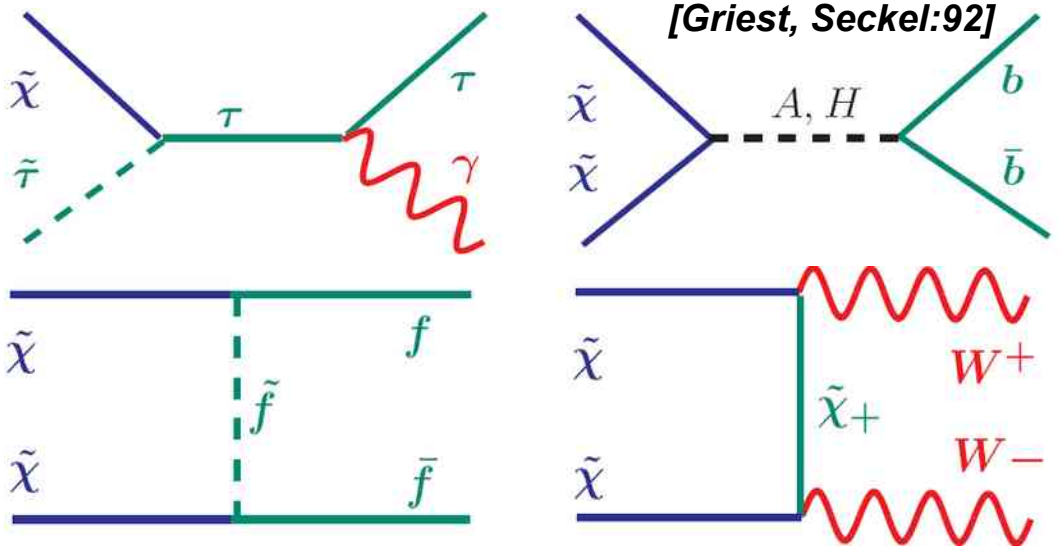
time evolution of number density is given by Boltzmann equation

$$dn/dt = -3Hn - \langle \sigma_A v \rangle (n^2 - n_{eq}^2)$$



Evolution of neutralino relic density

The challenge is to evaluate thousands annihilation/co-annihilation diagrams



relic density depends crucially on

$$\langle \sigma_A v \rangle$$

thermal equilibrium stage:

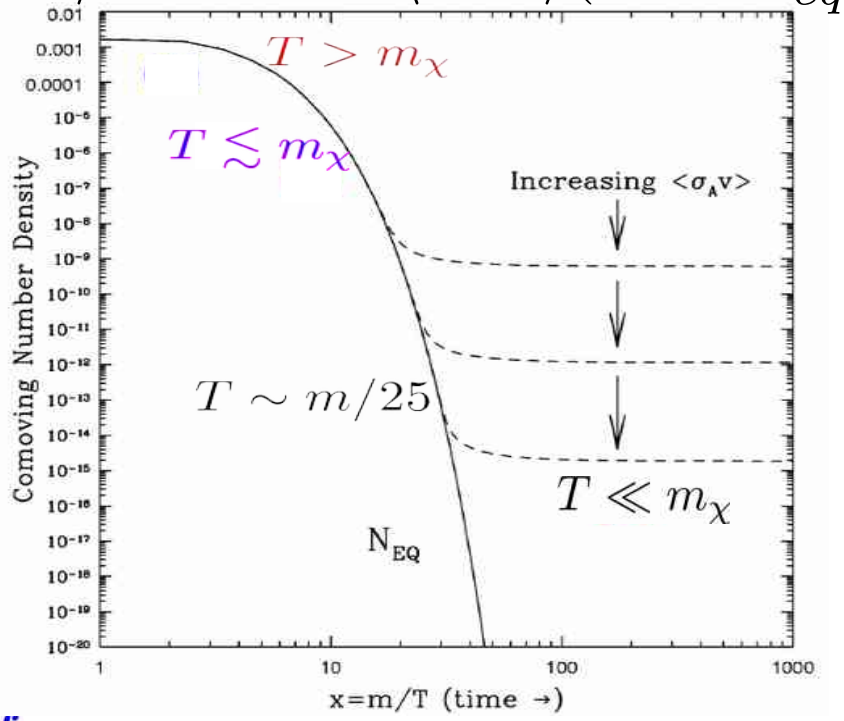
$$T > m_\chi, \quad \chi\chi \leftrightarrow f$$

universe cools:
$n = n_{eq} \sim e^{-m/T}$

$$T \lesssim m_\chi, \quad \chi\chi \not\leftrightarrow f\bar{f}$$

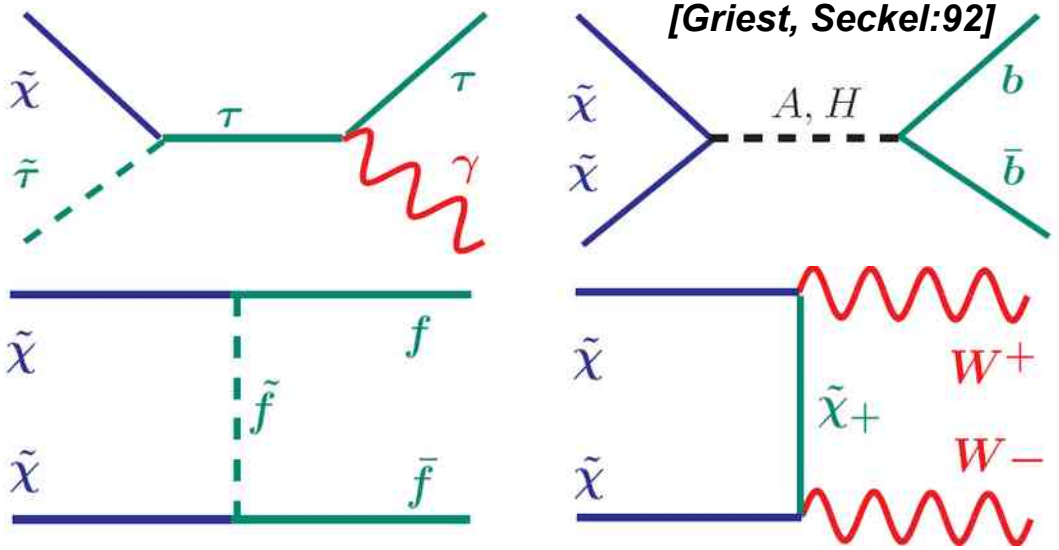
time evolution of number density is given by Boltzmann equation

$$dn/dt = -3Hn - \langle \sigma_A v \rangle (n^2 - n_{eq}^2)$$



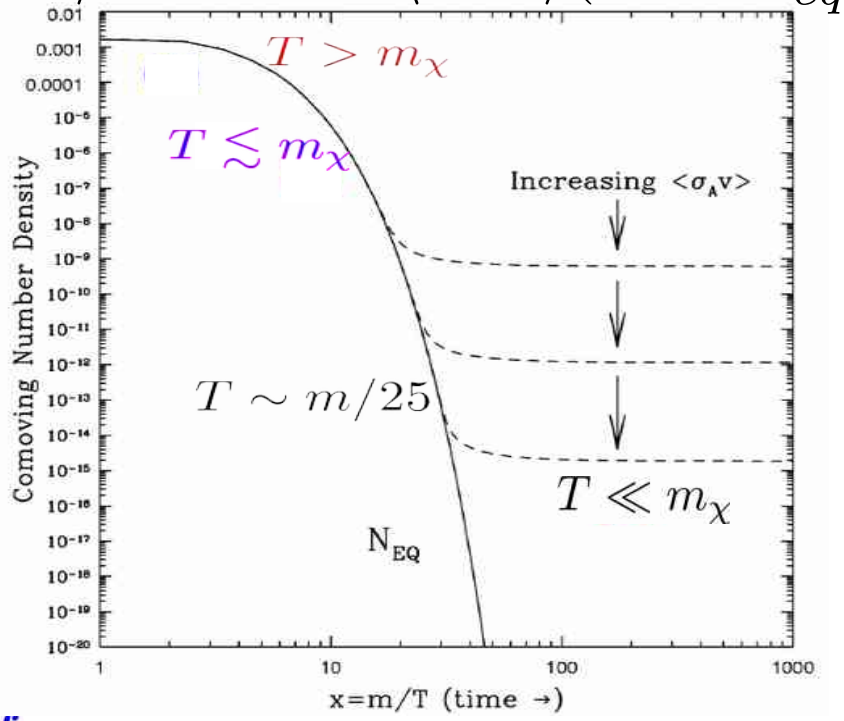
Evolution of neutralino relic density

The challenge is to evaluate thousands annihilation/co-annihilation diagrams



time evolution of number density is given by Boltzmann equation

$$dn/dt = -3Hn - \langle \sigma_A v \rangle (n^2 - n_{eq}^2)$$



relic density depends crucially on

$$\langle \sigma_A v \rangle$$

thermal equilibrium stage:

$$T > m_\chi, \quad \chi\chi \leftrightarrow f$$

universe cools:
$n = n_{eq} \sim e^{-m/T}$

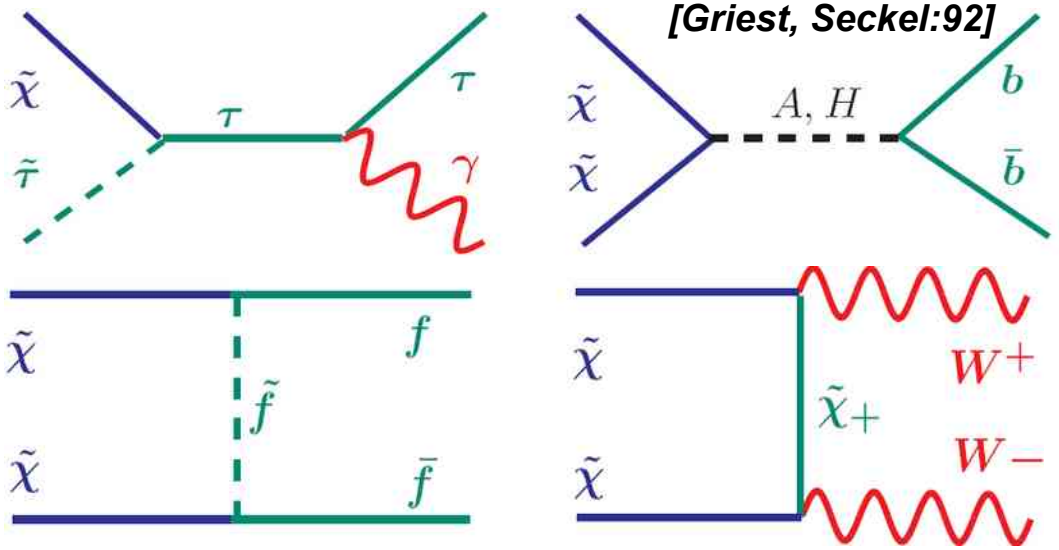
$$T \lesssim m_\chi, \quad \chi\chi \not\leftrightarrow f\bar{f}$$

neutralinos "freeze-out" at

$$T_F \sim m/25$$

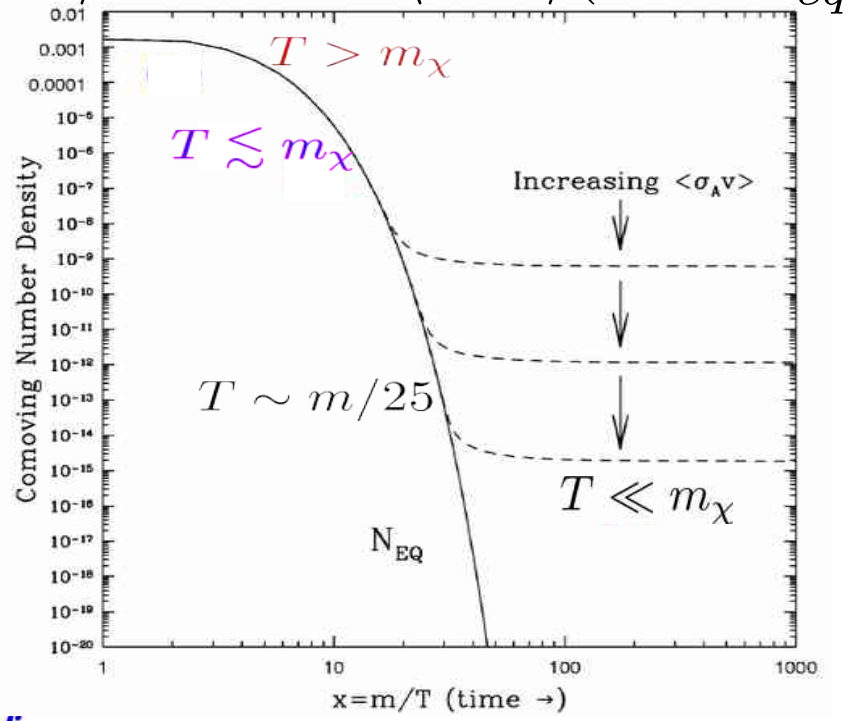
Evolution of neutralino relic density

The challenge is to evaluate thousands annihilation/co-annihilation diagrams



time evolution of number density is given by Boltzmann equation

$$dn/dt = -3Hn - \langle \sigma_A v \rangle (n^2 - n_{eq}^2)$$



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$$\langle \sigma_A v \rangle$$

thermal equilibrium stage:

$$T > m_\chi, \quad \chi\chi \leftrightarrow f$$

universe cools:
$n = n_{eq} \sim e^{-m/T}$

$$T \lesssim m_\chi, \quad \chi\chi \not\leftrightarrow f\bar{f}$$

neutralinos "freeze-out" at

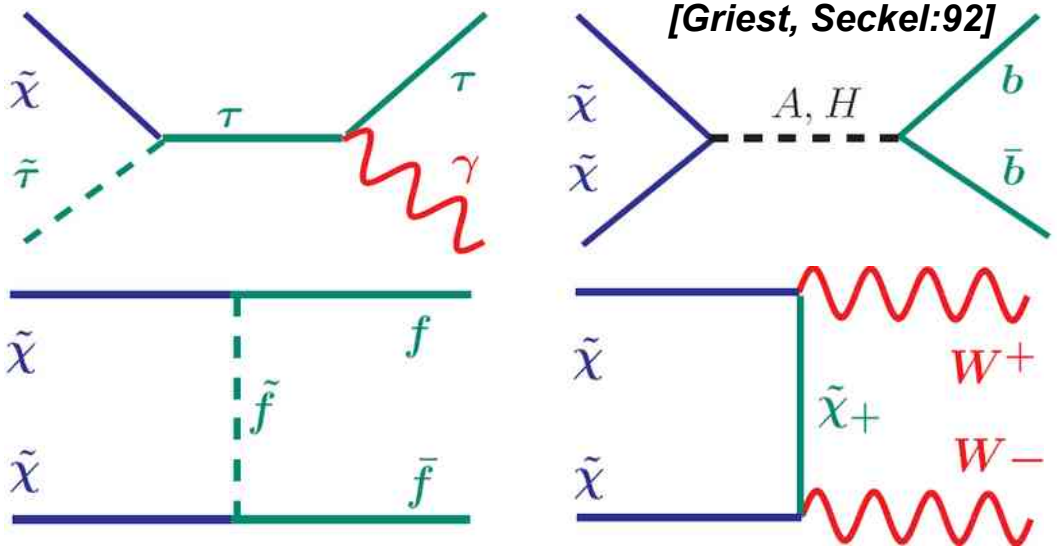
$$T_F \sim m/25$$

$$\Omega_\chi = 0.112$$

Packages:
MicrOMEGAs (Pukhov et al), DarkSusy, ISARED

Evolution of neutralino relic density

The challenge is to evaluate thousands annihilation/co-annihilation diagrams



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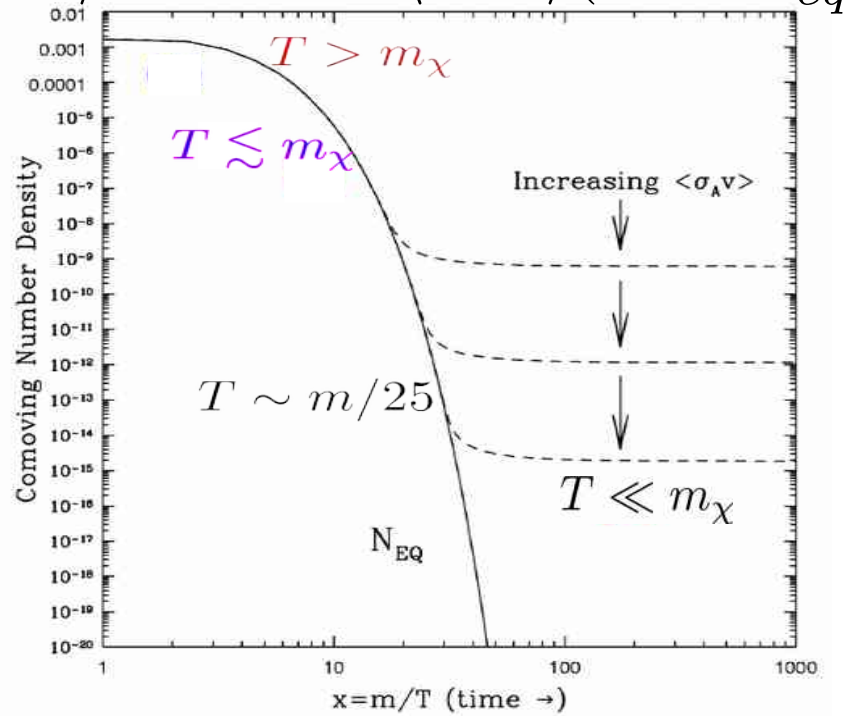

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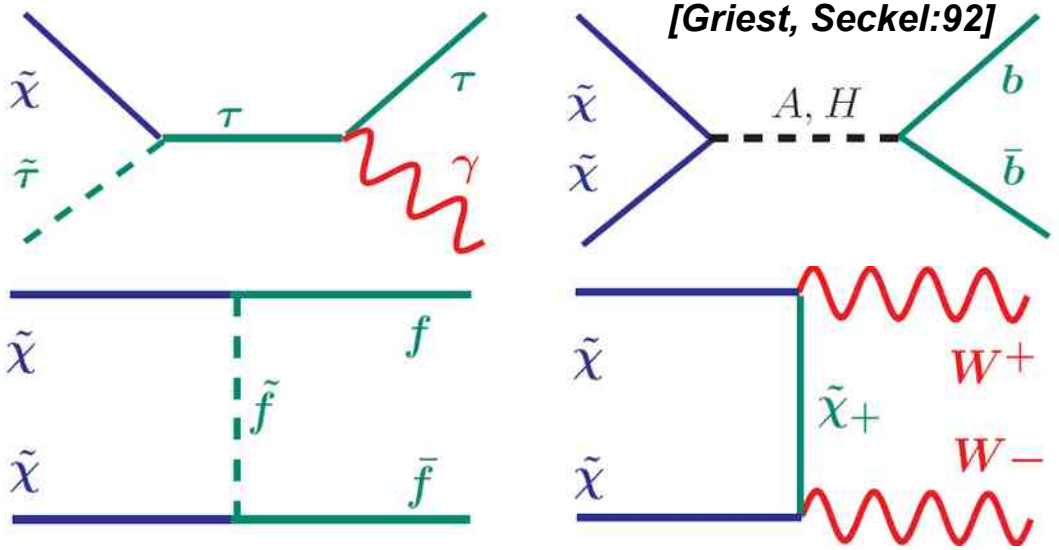

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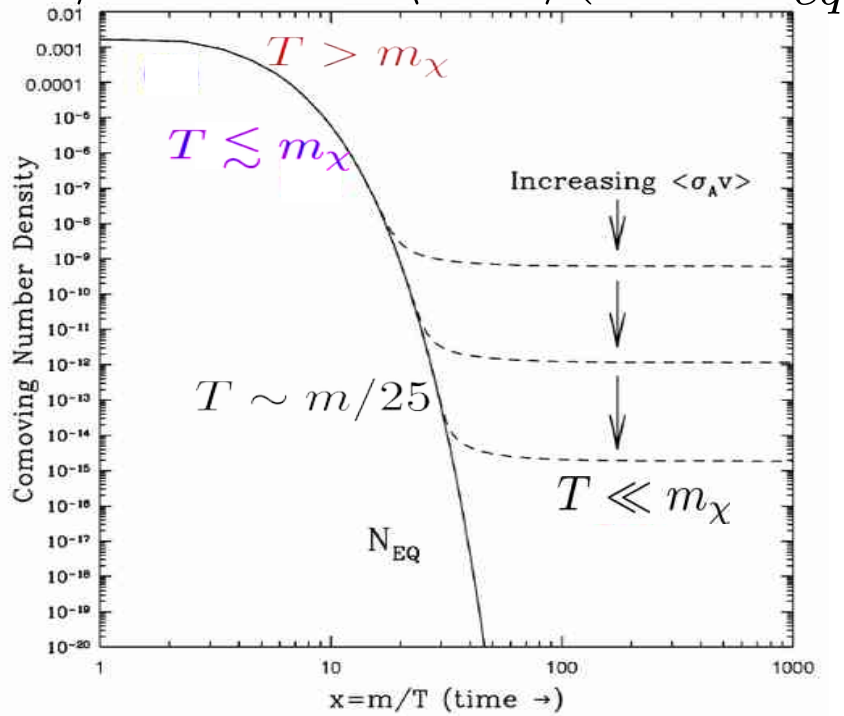

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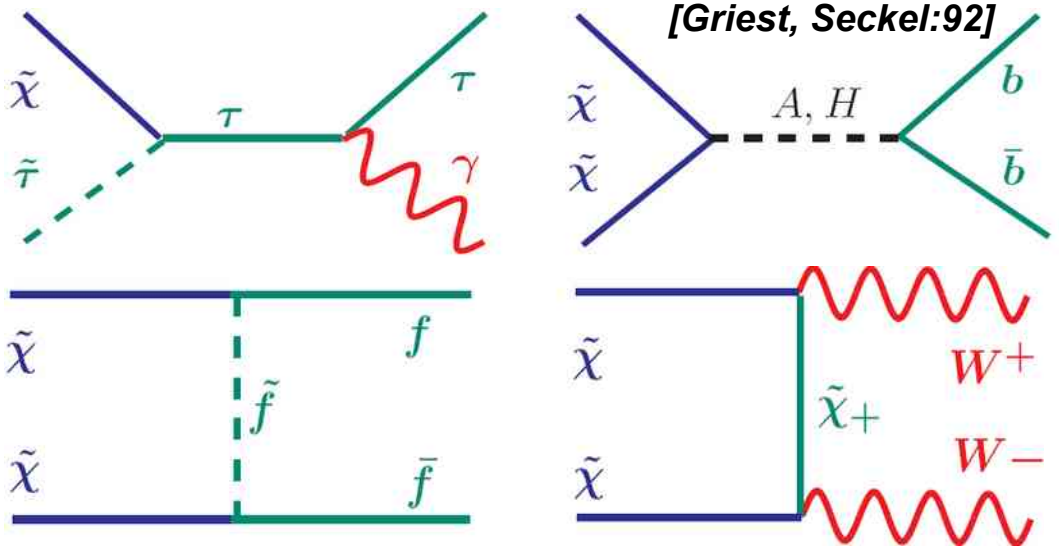

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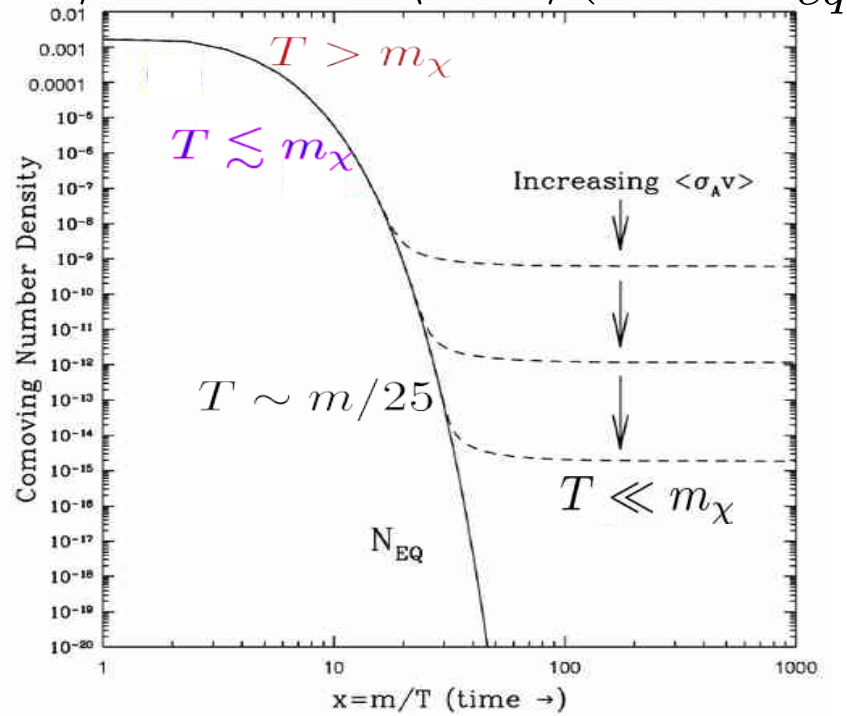

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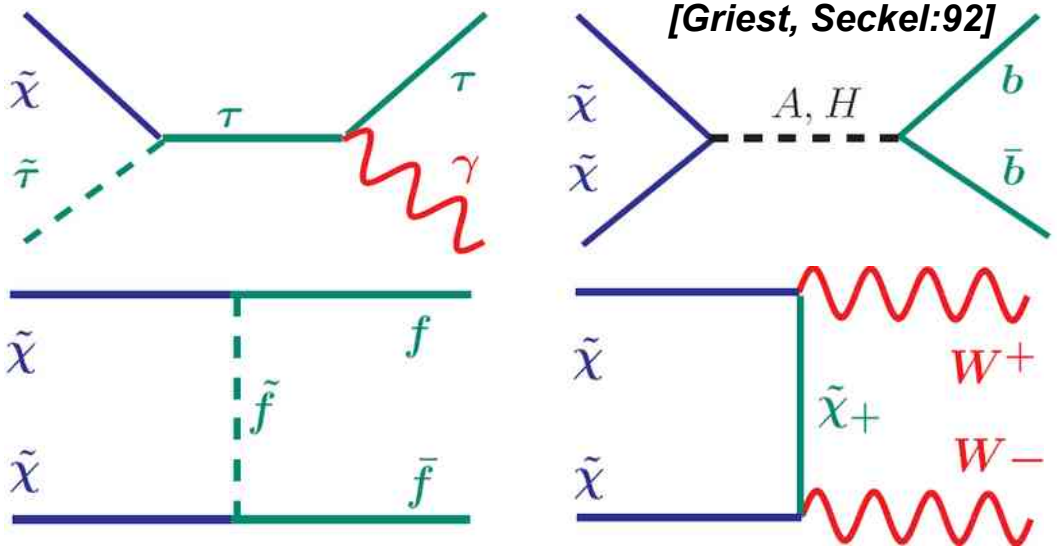

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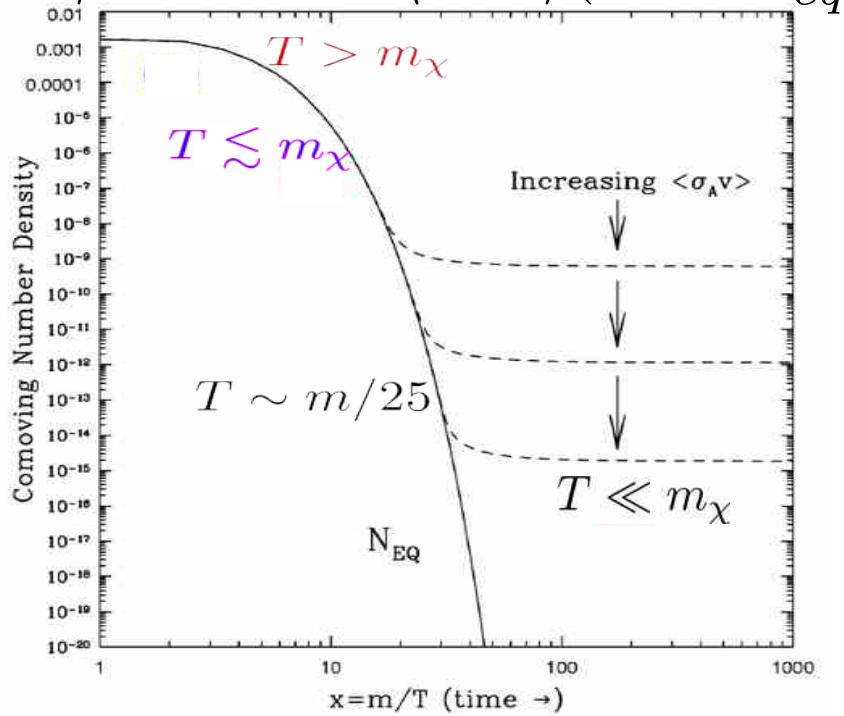

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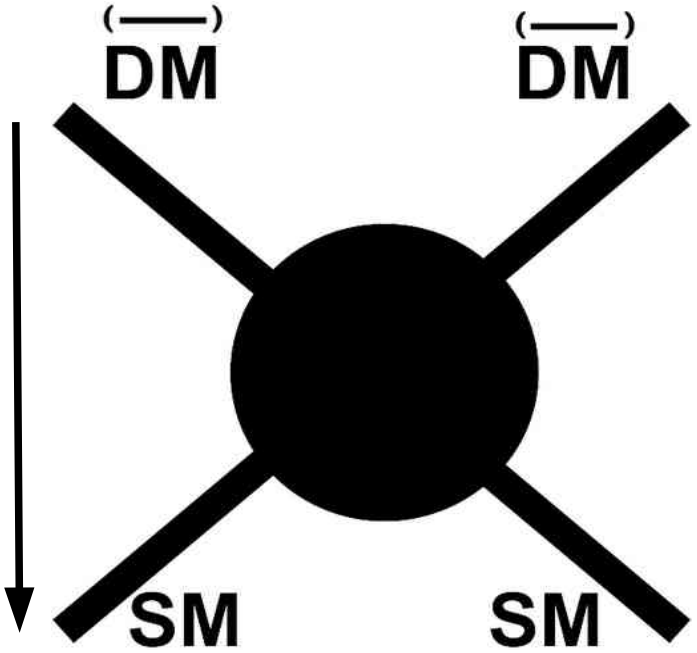
$$m = 100\mathrm{GeV}$$

mass of the mediator

Packages:
MicrOMEGAs (Pukhov et al), DarkSusy, ISARED

DM Observables: the power of WIMP

Correct Relic density: efficient (co) annihilation
WMAP, Planck ; annihilation to photons can affect CMB



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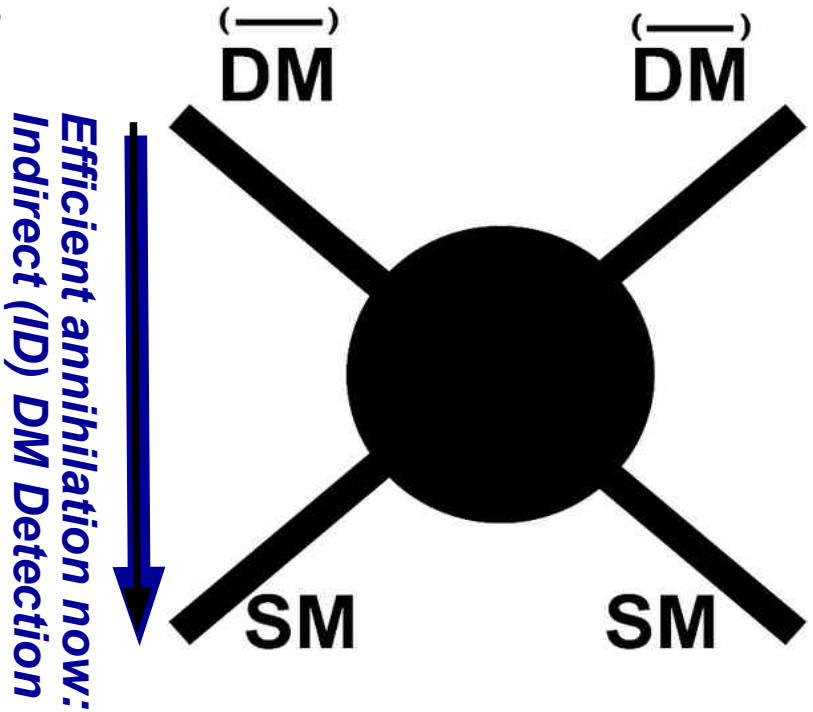
Signatures from neutralino annihilation in halo, core of the Earth and Sun

- **photons,**
- **Anti-protons**
- **positrons,**
- **Neutrinos**

Neutrino telescopes:

- **Amanda**
- **Icecube**
- **Antares**



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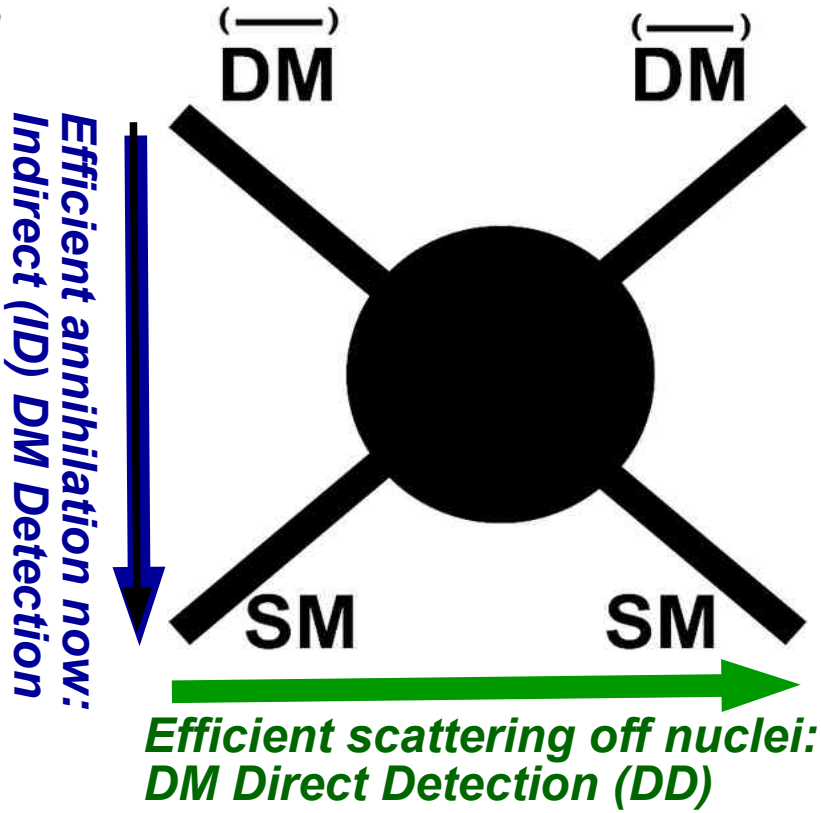

Signature from energy deposition from nuclei recoil: LUX, XENON, WARP,

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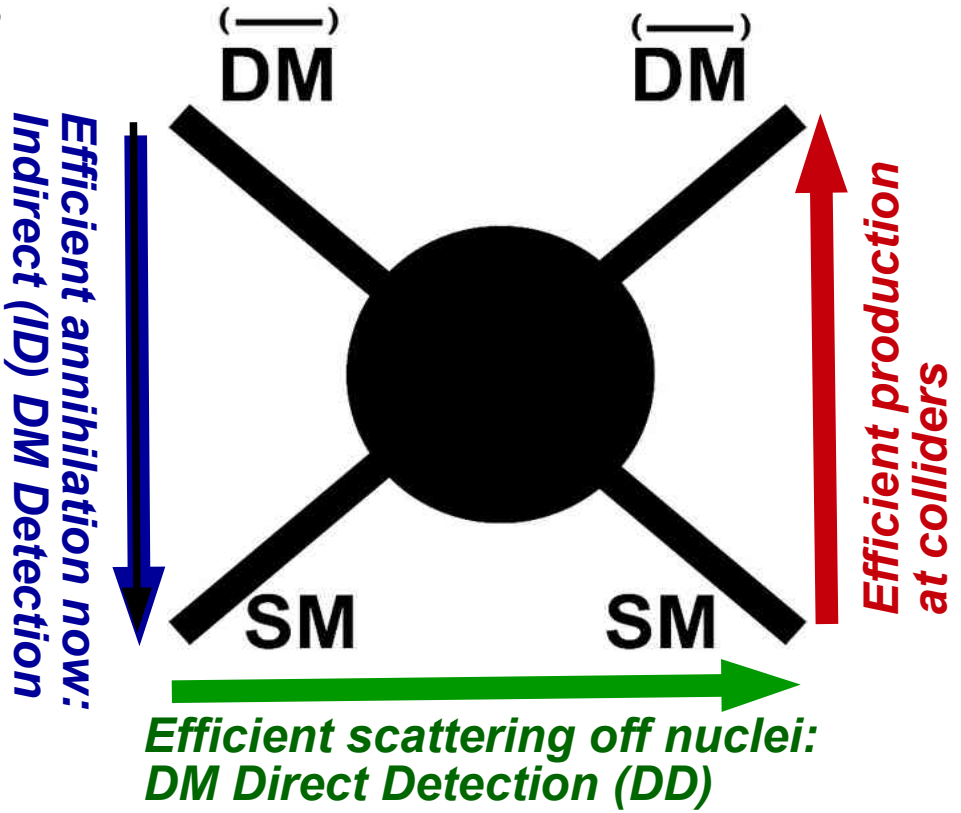

LHC signatures

- **mono-jet**
- **mono-photon**
- **mono-Z**
- **mono Higgs**
- **VBF+MET**
- **soft leptons+MET**
- **….**

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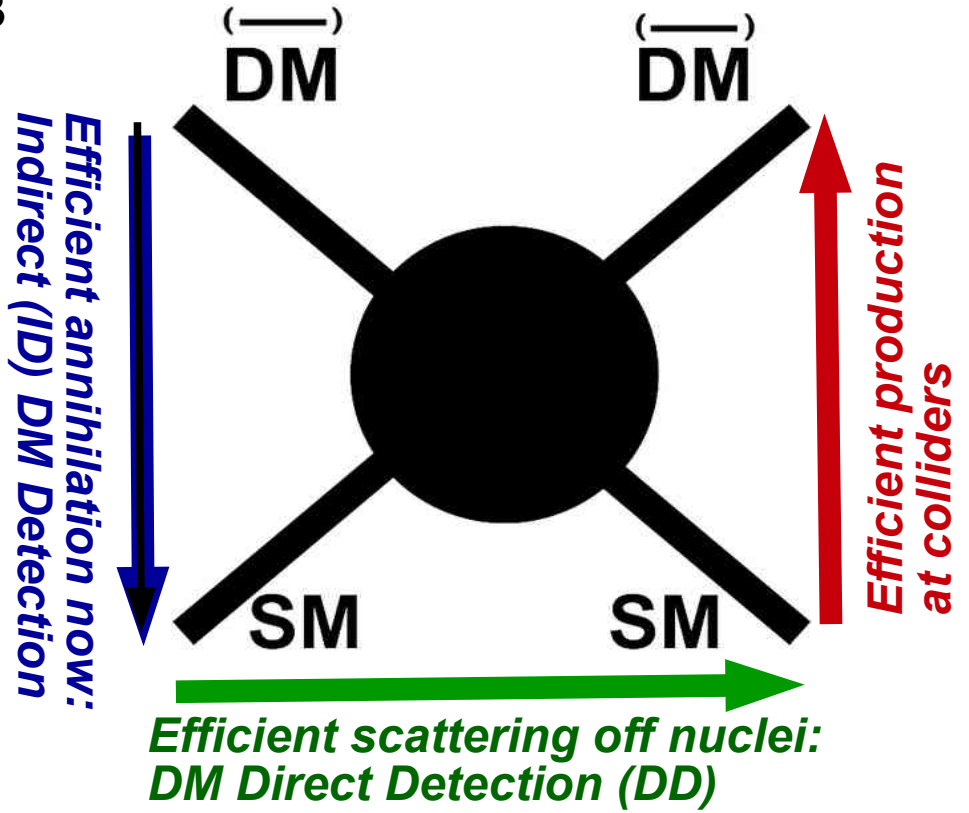

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- **….**

Signature from energy deposition from nuclei recoil: LUX, XENON, WARP,

Note: there is no 100%correlation between signatures above. For example, the high rate of annihilation does not always guarantee high rate for DD!

Actually there is a great complementarity in this:

- **In case of NO DM Signal – we can efficiently exclude DM models**
- **In case of DM signal – we can efficiently determine the nature of DM**

Dark Matter in models of particle interaction.

Discrete symmetry.

To describe DM in field theory we need a symmetry which is responsible for stability of DM. For instance it could be
a Z_2 symmetry which divides all particles on two classes, odd and even.
Then the lightest odd particle is stable and can be treated as DM.

In many models such symmetry appears quite natural. For instance, it is R-parity for SUSY modes where SM particles are even ones, but their superpartners belong to odd sector.

In realistic models with one extra dimension the extra dimension is presented by interval with special boundary condition. $x_5 \to -x_5$ symmetry leads to stability of the lightest Kaluza-Klein mode.

As a rule model contains several odd particles and it becomes important when we calculate DM relic density and Direct Detection and collider signals.

Installation of micrOMEGAs package

micrOMEGAS site http://lapth.in2p3.fr/micromegas

Click Download and Install (left -top part of the screen)
And then DOWNLOAD (right-top part of the screen)
The name of received file should be

micromegas_x.y.z.tgz

Unpack it by tar -xvzf micromegas_x.y.z.tgz

It should create directory micromegas_x.y.z/ which occupies about 40 Mb of disk space. You will need more disk space after compilation of specific models and generation of matrix elements .

In case of problems and questions

email: micro.omegas@lapp.in2p3.fr

File structure of micrOMEGAs package.

Makefile
CalcHEP_src/ *generator of matrix elements*
sources/ *micrOMEGAs own codes*
man/ *manual_4.2.tex, manual_4.2.pdf*
description of micrOMEGAs routines

Packages/
SuSpect_2.41 NMSSMTools_4.7.1 CpsuperH2.3,
LoopTools-2.1 – external packages

model directories:

MSSM/	
NMSSM/	Next-to-Minimal SuSy Model
CPVMSSM/	MSSM with complex parameters
UMSSM/	MSSM + U(1) gauge field
IDM/	Inert dublet model
LHM/	Little Higgs Model
RHNM/	Right-handed Neutrino model

To compile micrOMEGAS use 'gmake' or 'make'
To clean use [g]make clean

Structure of MODEL directory

main.c main.F files with main program for given model
lib/ directory for routines specific routines model
Makefile

work/ CalcHEP working directory
models/ model specification (just one model should be there)
vars1.mdl func1.mdl prtcls1.mdl lgrng1.mdl extlib1.mdl
so_generated/ directory to store generated matrix elements

Makefile supports compilation of C,Fortran and C++ user codes

[g]make main=XXX.c => executable XXX
[g]make main=YYY.F => executable YYY
[g]make main=ZZZ.cpp => executable ZZZ
[g]make is equivalent to **[g]make main=main.c**

ex#9: Install micrOMEGAs

Module structure of main programs

main.c, main.F files presented in micrOMEGAs model directories consist from several blocks enclosed into

```
#ifdef XXXXX
   .....................
#endif
```

User can switch on/off any of this block via corresponding *#define* instruction in the top of file

```
#define MASSES_INFO                /* Display information about mass spectrum  */
#define CONSTRAINTS                /* Display B->s,gamma, Bs->mu,mu, ...*/
#define OMEGA                      /* Calculate relic density  */
#define INDIRECT_DETECTION         /* Signals of DM annihilation in galaxy hallo */
//#define RESET_FORMFACTORS        /* Redefinition of  Form Factors and other parameters */
#define CDM_NUCLEON                /* Calculate amplitudes and cross-sections for  CDM-
                                      nucleon  collisions */
//#define CDM_NUCLEUS              /* Calculate number of events for 1kg*day and recoil
                                      energy distribution  for various nuclei */
```

Simple example. Inert Doublet Model

Inert Doublet model contains two SU(2) doublets

$$H_1 = \begin{pmatrix} 0 \\ < v > +h/\sqrt{2} \end{pmatrix} \quad , \quad H_2 = \begin{pmatrix} \tilde{H^+} \\ (\tilde{X} + i \cdot \tilde{H3})/\sqrt{2} \end{pmatrix}$$

The Lagrangian contains only *even* powers of H_2 doublet

$$L = (SM\ terms) + D^\mu H_2^* D_\mu H_2$$

$$-\mu^2 H_2^2 - \lambda_2 H_2^4 - \lambda_3 H_1^2 H_2^2 - \lambda_4 |H_1^* H_2|^2 - \lambda_5 Re[(H_1^* H_2)^2]$$

Because of symmetry $H_2 \rightarrow -H_2$ the lightest of $\tilde{H^+}, \tilde{X}, \tilde{H3}$ is stable

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

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

Free parameters of the model.

Free model parameters are presented in
*MODEL/**work/models/vars1.mdl***
For example:

```
Inert Doublet Model
 Variables
 Name  |  Value      |>  Comment                                  <|
EE     |0.31333      |Electromagnetic coupling constant
SW     |0.474        |sin of the Weinberg angle
MZ     |91.187       |Mass of Z
MHX    |111          |Mass of Inert Doublet Higgs
MH3    |222          |Mass of CP-odd Higgs
MHC    |333          |Mass of charged Higgs
LaL    |0.01         |Coupling in Inert Sector
.....................................
```

findValW(char * name) - returns numerical value of parameter
assignValW(char *name, double value) - *assigns new value to parameter.*
If 'name' does not correspond to any parameter, you'll get a warning .

In order to download set of parameters micrOMEGAs has the function

readVar(fileName)

which returns zero in case of successful reading. Structure of file records has to be

name value [# comment]

For instance, in case of IDM (data1.par file)

```
laL      0.001    # coupling
MHX      600      # inert sector Higgs
la2      0.01     # coupling
MHC      604      # mass of charged Higgs
MH3      601      # mass of CP odd Higgs
```

Usually micrOMEGAs main.c[F] files requires to present input file with model parameters in a command line.

./main data1.par

Example of micrOMEGAs session
IDM ./main data1.par

Dark matter candidate is '~X' with spin=0/2

=== MASSES OF HIGGS AND ODD PARTICLES: ===
Higgs masses and widths
h 125.00 4.12E-03

Masses of odd sector Particles:
~X : MHX = 600.0 || ~H3 : MH3 = 601.0 || ~H+ : MHC = 604.0

==== Calculation of relic density =====
Xf=2.66e+01 Omega=1.1402e-01
# Channels which contribute to 1/(omega) more than 1%.
# Relative contributions in % are displayed
21% ~X ~X ->W+ W-
14% ~X ~X ->Z Z
11% ~H3 ~H3 ->W+ W-
9% ~H+ ~H- ->W+ W-
7% ~H3 ~H3 ->Z Z
6% ~H+ ~X ->A W+
5% ~H3 ~H+ ->A W+
4% ~H+ ~H- ->A A
4% ~H3 ~H+ ->Z W+
3% ~H+ ~X ->Z W+
3% ~H+ ~H- ->A Z

Example of micrOMEGAs session
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6% ~H+ ~X ->A W+
5% ~H3 ~H+ ->A W+
4% ~H+ ~H- ->A A
4% ~H3 ~H+ ->Z W+
3% ~H+ ~X ->Z W+
3% ~H+ ~H- ->A Z

```
==== Indirect detection =======
   Channel          vcs[cm^3/s]
=================================
 annihilation cross section 6.10E-26 cm^3/s
 contribution of processes
  ~X,~X -> W+ W-        6.02E-01
  ~X,~X -> Z Z          3.98E-01

Photon flux  for angle of sight f=0.10[rad]
and spherical region described by cone with angle 0.10[rad]
Photon flux = 9.25E-16[cm^2 s GeV]^{-1} for E=300.0[GeV]
Positron flux  =    1.03E-13[cm^2 sr s GeV]^{-1} for E=300.0[GeV]
Antiproton flux  =  5.83E-13[cm^2 sr s GeV]^{-1} for E=300.0[GeV]


==== Calculation of CDM-nucleons amplitudes  =====
CDM[antiCDM]-nucleon micrOMEGAs amplitudes:
proton:  SI  1.497E-11 [1.497E-11]  SD  0.000E+00 [0.000E+00]
neutron: SI  1.512E-11 [1.512E-11]  SD  0.000E+00 [0.000E+00]
CDM[antiCDM]-nucleon cross sections[pb]:
 proton  SI 9.766E-14 [9.766E-14] SD 0.000E+00 [0.000E+00]
 neutron SI 9.961E-14 [9.961E-14] SD 0.000E+00 [0.000E+00]
```

ex#10: evaluate relic density for IDM vs MHX for LaL=0.001, la2=0.01, MHC=100 GeV, MH3=100 GeV and MHX running from 50 GeV to 95 GeV with the step = 5 GeV. You need to modify main.c respectively to implement the loop over the MHX mass.

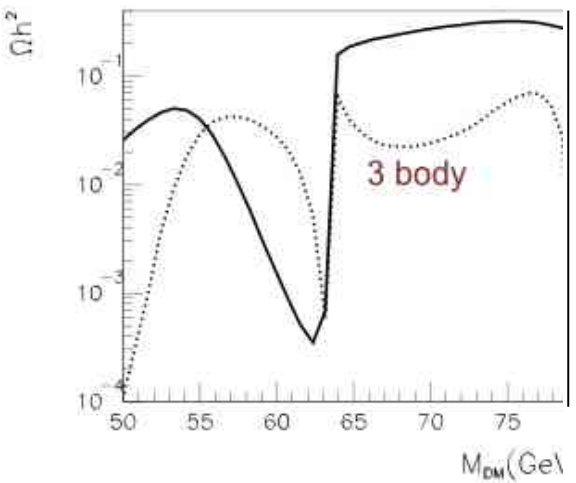
micrOMEGAs

http://lapth.in2p3.fr/micromegas
Belanger, Boudjema, Pukhov, Semenov

hep-ph/0112278, hep-ph/0405253, hep-ph/0607059, arXiv:0803.2360, arXiv:1305.0237, arXiv:1407.6129

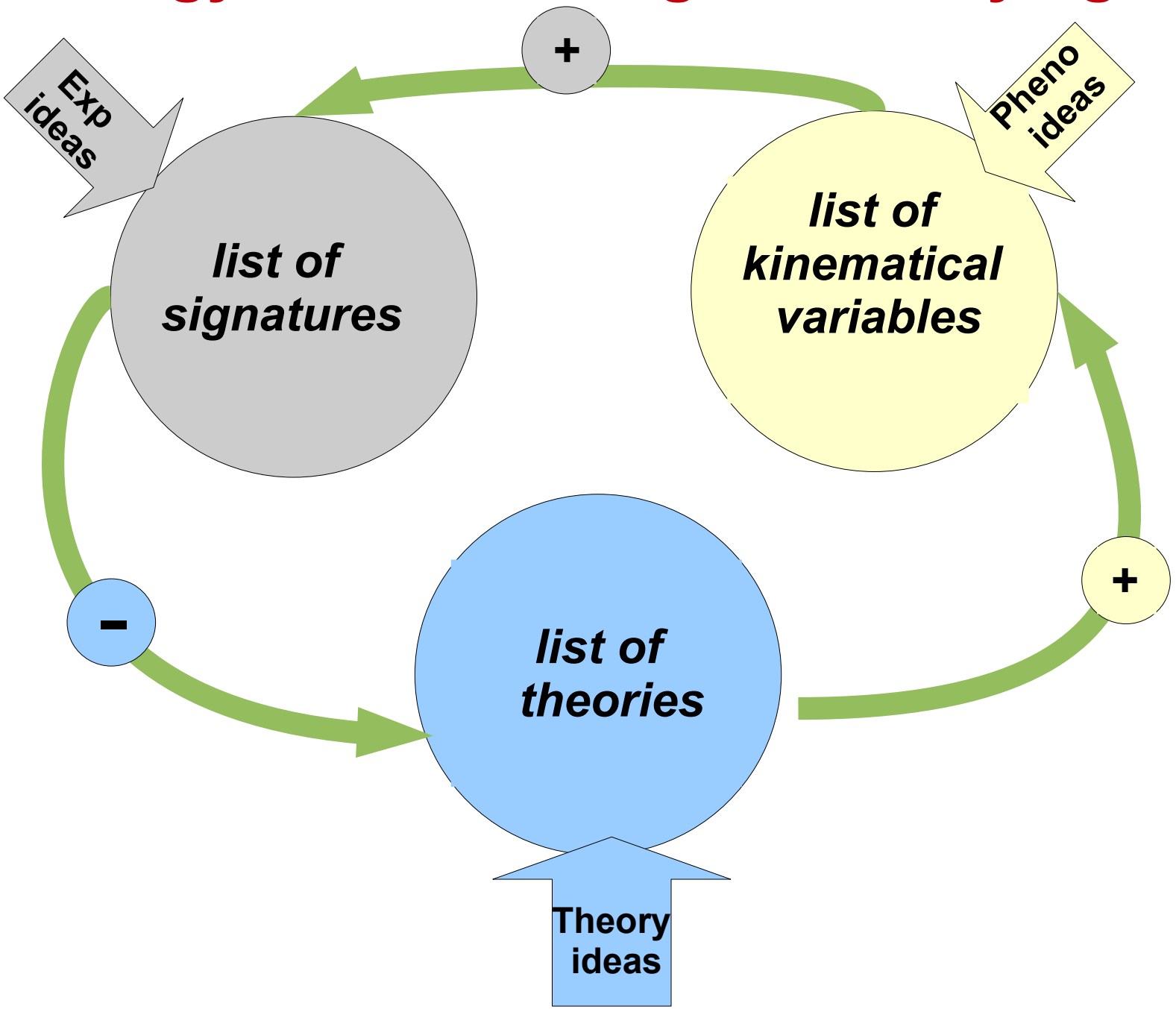
- Was born in 2001, the latest version 4.3
- Comprehensive tool for dark matter studies : precise calculation of relic density, direct detection, indirect detection, cross section at colliders and decays
- Comes with models: MSSM, NMSSM,CPV-MSSM, RH-neutrino, Littlest Higgs, Inert doublet+singlet Z3,Z4; many more models are available at ***hepmdb.soton.ac.uk***
- **Additional features**

  - **Neutrino signal** from DM capture (for SuperKamiokande, IceCube), both neutrino flux and muon flux are computed
  - **Higgs 3-body decays** and loop-induced decays are included – a good agreement with HDECAY (Djouadi et al) for SM-like Higgs
  - Links to **external packages**: HiggsSignals/HiggsBounds (Bechtle et al), Smodels (Kraml et al)
  - Includes **3/4-body processes** with one/two virtual W/Z
  - Z2,Z3,Z4,Z5 symmetries and **two DM candidates**
  - **Asymmetric DM:** option to define $\Delta Y = Y^{+} - Y$
  - Collider limits for Z' on-shell mediator (Barducci et al)



HEPMDB

The strategy for delineating of underlying theory



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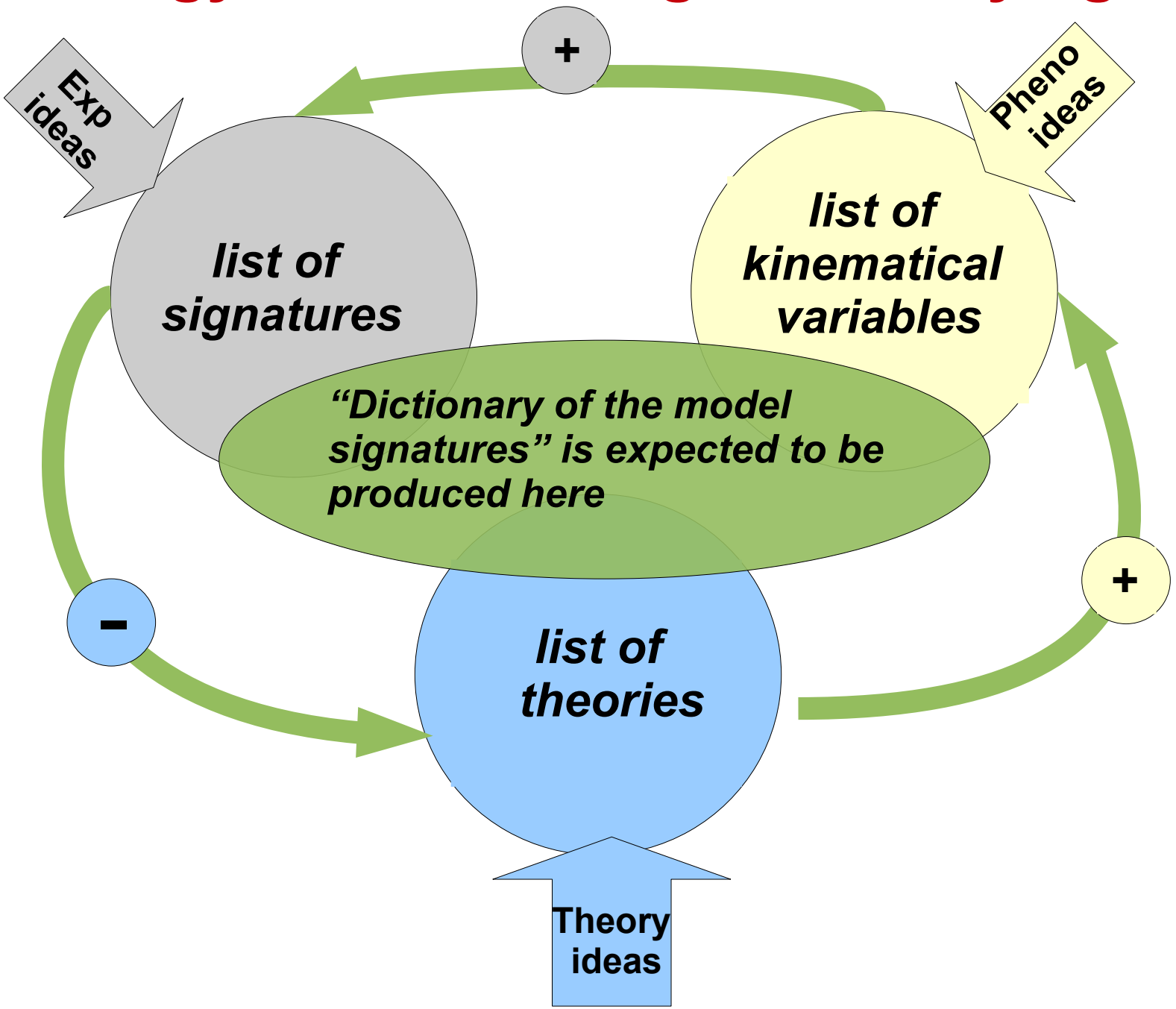

First Steps towards "Dictionary"

AB, Asesh Datta, A. De Roeck 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	$tt + \not{E}_T$	to be studied	to be studied	to be studied
	$\tau\tau + \not{E}_T$	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]

It was realised that
“Dictionary of the LHC Signatures”
in the form of various tables are far
from realistic accommodation
of promising models
and their signatures

It was realised that
"Dictionary of the LHC Signatures"
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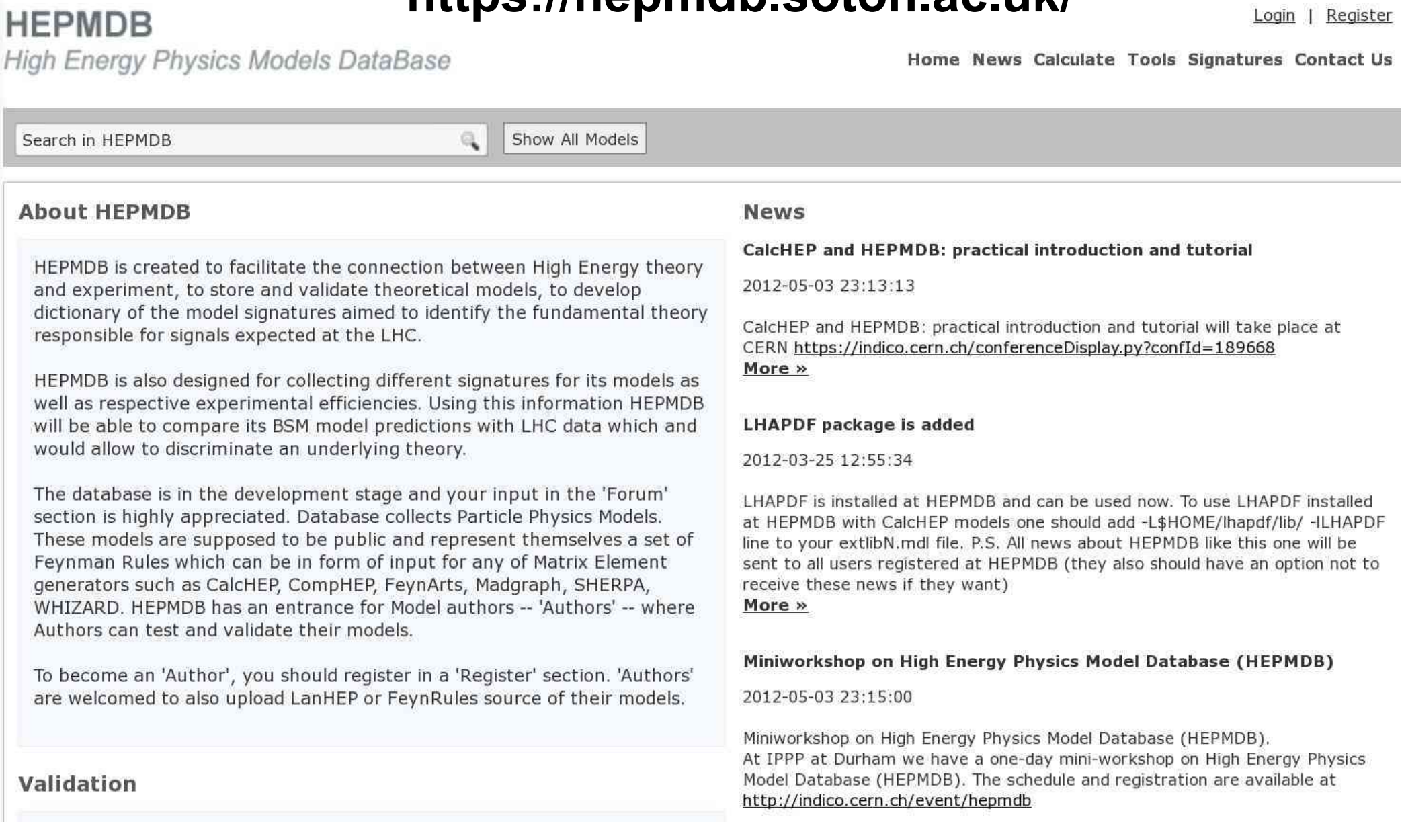
of promising models
and their signatures

We need dictionary in the form of
the Model Database and their Signatures

High Energy Physics Model Database
[HEPMDB]

High Energy Physics Model Database

https://hepmdb.soton.ac.uk/



High Energy Physics Model Database

- **Developed at Southampton with support from IPPP, Durham**
  as a result of ideas discussed in the context of the "Dictionary of LHC signatures", at the FeynRules workshop (April, 2010) and at the Mini-Workshop on Dynamical Symmetry Breaking models and tools (July 2010)
- **Further developed at the Les Houches Workshop, June 2011**

High Energy Physics Model Database – HEPMDB. Towards decoding of the underlying theory at the LHC.

arXiv:1203.1488 (the last section of the Les Houches 2011 proceedings)

Maksym Bondarenko[1], Alexander Belyaev[1,2], Lorenzo Basso[1,2,3], Edward Boos[4], Vyacheslav Bunichev[4], R. Sekhar Chivukula[5], Neil D. Christensen[6], Simon Cox[7], Albert De Roeck[8], Stefano Moretti[1,2], Alexander Pukhov[4], Sezen Sekmen[8], Andrei Semenov[9], Elizabeth H. Simmons[5], Claire Shepherd-Themistocleous[2], Christian Speckner[3]

Abstract

We present here the first stage of development of the High Energy Physics Model Data-Base (HEPMDB) which is already a convenient centralized storage environment for HEP models, and can accommodate, via web interface to the HPC cluster, the validation of models, evaluation of LHC predictions and event generation-simulation chain. The ultimate goal of HEPMDB is perform an effective LHC data interpretation isolating the most successful theory for explaining the LHC observations.

Aims of the HEPMDB (1)

- *to collect HEP models for various multipurpose Matrix Element (ME) generators like CalcHEP, CompHEP, FeynArts, MadGraph/MadEvent, AMEGIC ++/COMIX within SHERPA and WHIZARD.*

  Under "HEP models" we denote the set of particles, Feynman rules and parameters written in the format specific for a given package
- *to collect models' sources which can be used in the HEPMDB to generate HEP models for various ME generators using FeynRules or LanHEP which automate the process of generating Feynman Rules, particle spectra, etc..*

  For the moment, FeynRules supports formats for CompHEP, CalcHEP, FeynArts, GoSam, MadGraph/MadEvent, SHERPA and WHIZARD Currently LanHEP works with CalcHEP, CompHEP, FeynArts and GoSam. Also, the latest LanHEP version 3.15 has an option under testing of outputting the model in UFO format which provides a way to interface it with MadGraph/MadEvent
- to allows users upload their models and perform evaluation of HEP processes and event generation for their own models using the full power of the High Performance Computing (HPC) cluster behind the HEPMDB.

  This is one of the very powerful features of the HEPMDB: it provides a web interface to various ME generators which can then also be run directly on the HPC cluster. This way, users can preform calculations for any model from HEPMDB avoiding problems related to installing the actual software, which can sometimes be quite cumbersome

Aims of HEPMDB (2)

- to plot and document various kinematical distributions from generated events in the LHE format
- to allow to compare predictions from models generated from LanHEP and FeynRules
- to collect predictions and specific features of various models in the form of database of signatures and perform comparison of various model predictions with experimental data (to be developed)

  There are a lot of different aspects related to this problem. This task includes a comprehensive development of a database of signatures as well as development of the format of presentation of these signatures. This format will be consistent with the format which will be used by the experimentalists for the presentation of the LHC data, discussed in the context of the "Les Houches Recommendations for the Presentation of LHC Results" activity.
- to trace the history of the model modifications, and makes available all the versions of the model

  Through this application, we stress the importance of reproducibility of the results coming from HEPMDB or from a particular model downloaded from HEPMDB.

Sounding similar but qualitatively different related projects

- "Database of Numerical HEP scattering cross sections"
  http://durpdg.dur.ac.uk/HEPDATA/REAC
  collects various particle scattering process which are connected to experimental searches of different reactions

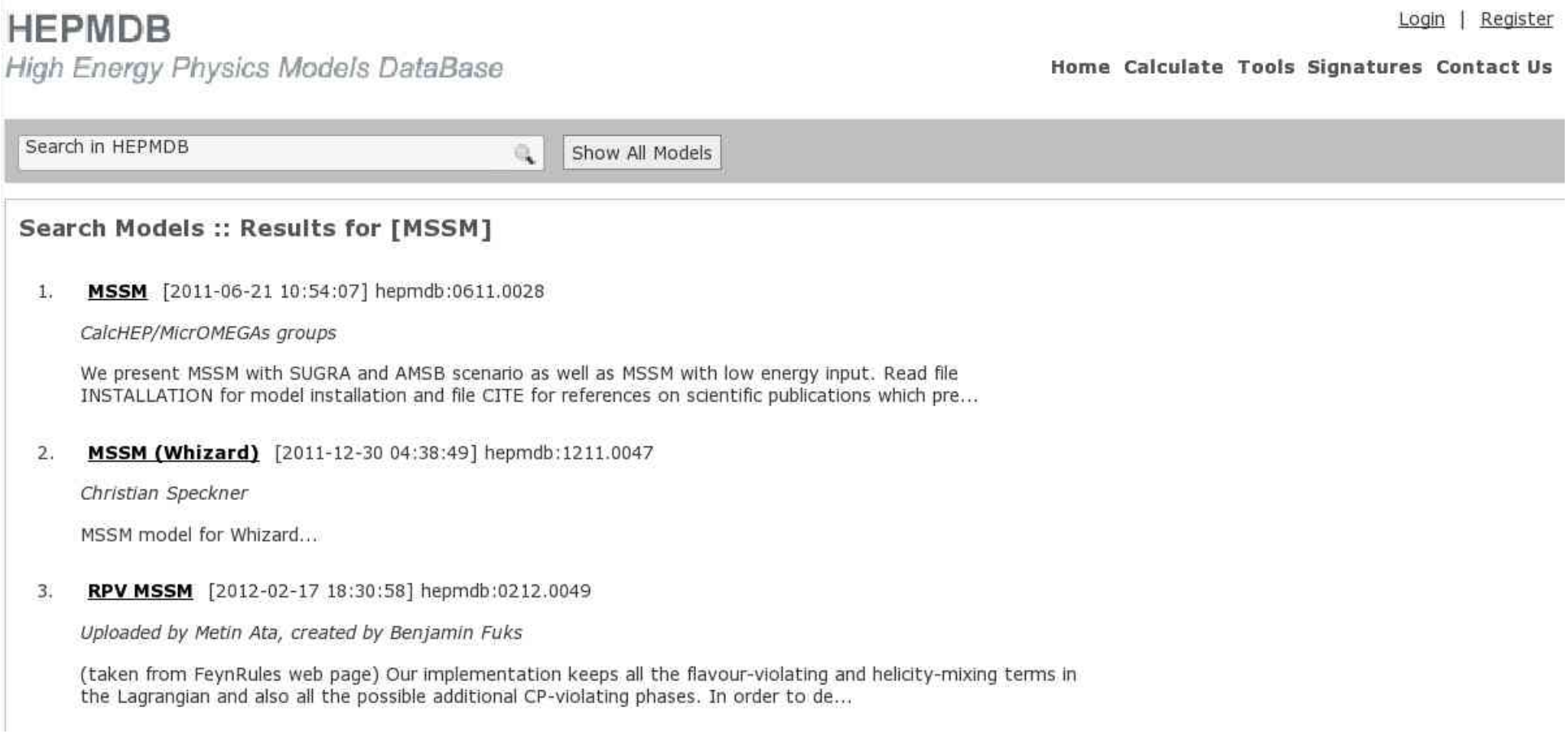
- "Signatures of New Physics at the LHC" web-site
  http://www.lhcnewphysics.org/
  collects various BSM signatures, their classification and related papers

- FeynRules and models database
  http://feynrules.irmp.ucl.ac.be
  collects various models implemented into FeynRules and have an effective way to validate them

- **HEPMDB can effectively collaborate with all projects above!**

The current status of HEPMDB (1)

- Allows to search and download an existing HEP model. The search engine checks patterns in the fields:
  Model, Authors, References, Abstract, Signatures and Information



The current status of HEPMDB (2)

- one can upload a new model (upon user registration). The model can be uploaded in the format of any ME generator. Also, a user can upload the model source in FeynRules or LanHEP formats, allows to keep model privately!

Model : MSSM

http://hepmdb.soton.ac.uk/hepmdb:0611.0028

Authors

CalcHEP/MicrOMEGAs groups

Added By

Alexander Belyaev

References

G.~Belanger, F.~Boudjema, A.~Pukhov and A.~Semenov, Comput. Phys. Commun. 174, 577 (2006)[arXiv:hep-ph/0405253]
A.~Djouadi, J.~L.~Kneur and G.~Moultaka, arXiv:hep-ph/0211331

Abstract

Updated MSSM model for CalcHEP is uploaded (bug for SC constant in the file with dependences is corrected)

Information

We present MSSM with SUGRA and AMSB scenario as well as MSSM with low energy input. Read file INSTALLATION for model installation and file CITE for references on scientific publications which present realization of the model.

Tools

CalcHEP [model]

Model History

2011-12-02 15:01:19
2011-10-14 13:40:10

Download Model File | Validate Model on HPCx | Edit Model

Reviews

The current status of HEPMDB (3)

- allows to the evaluate cross sections for user-defined processes for the chosen model and produce a respective LHE file with generated parton-level events. This file is becomes available for download once the process is finished (user will receive an e-mail notification on this)
  Currently, the HEPMDB allows the user to perform these calculations (using the HPC) for CalcHEP, WHIZARD and MadGRAPH 5
- produces ntuple files and allows to plot various kinematical distributions
- allows to update/add features and respective signatures specific to each model.
  These features and signatures can be used in the future to distinguish the model from others and connect it to the LHC signatures.
- keeps track of the model changes, providing reproducibility for the results obtained with previous versions of the models uploaded to HEPMDB
- allows to collect feedback/remarks on particular model from users in Review section

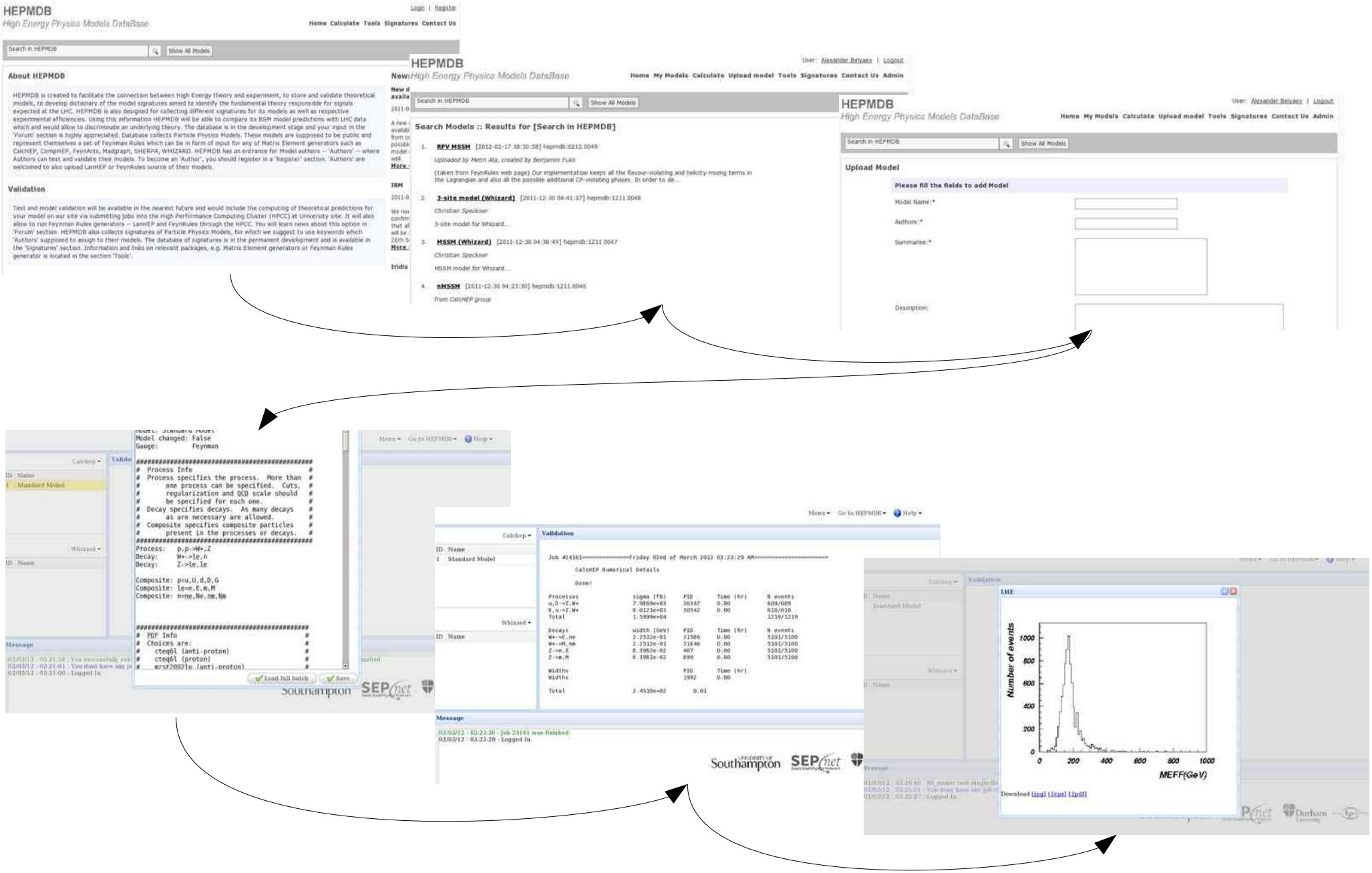
Future prospects for HEPMDB (months scale)

- The LanHEP and FeynRules packages will be added to provide model generation from model sources
- CompHEP package will be added.
- A systematic model validation process will be started and the respective pages will be added.
- The possibility to study events beyond the parton level will be carefully considered, up to detector simulation.
  One concrete possibility would be the chain
  LHE events -> HEPMC events -> FASTSIM events (ROOT format)
  For the FASTSIM package, Delphes seems a promising candidate.
- The structure of the database of signatures will be extended to deal with correlated signatures (i.e., whereby multiple signatures, or lacks thereof, must be accounted for simultaneously)

Future prospects for HEPMDB

- we plan to install the MicrOMEGAs package for evaluation of the dark matter relic density as well as to provide a possibility for scans of various model parameter spaces.
- Author of other packages/models are welcome to install/upload them
- the format for model predictions consistent with the format for presentation of the LHC data by experimentalists is planned.

Tutorial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High Energy Physics Models DataBase
Home Calculate Tools Signatures Contact Us
About HEPMDB
Validation
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Home My Models Calculate Upload model Tools Signatures Contact Us Admin
Search Models :: Results for [Search in HEPMDB]
RPV MSSM
3-site model (Whizard)
MSSM (Whizard)
nMSSM
HEPMDB
High Energy Physics Models DataBase
Home My Models Calculate Upload model Tools Signatures Contact Us Admin
Upload Model
Please fill the fields to add Model
Model Name:*
Authors:*
Summarise:*
Description:
Model changed: False
Gauge: Feynman
Process: p,p->W+,Z
Decay: W+->le,n
Decay: Z->le,le
Composite: p=u,U,d,D,G
Composite: le=e,E,m,M
Composite: n=ne,Ne,nm,Nm
Load full batch
Save
Validation
Job #24161==========Friday 02nd of March 2012 03:23:29 AM==========
CalcHEP Numerical Details
Done!
Message
02/03/12 : 03:23:30 : Job 24161 was finished
02/03/12 : 03:23:28 : Logged in
LHE
Number of events
MEFF(GeV)
Download [png] [eps] [pdf]
Southampton
SEPnet

Tutorial

HEPMDB

High Energy Physics Models DataBase

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Search in HEPMDB | Show All Models

About HEPMDB

HEPMDB is created to facilitate the connection between High Energy theory and experiment, to store and validate theoretical models, to develop dictionary of the model signatures aimed to identify the fundamental theory responsible for signals expected at the LHC.

HEPMDB is also designed for collecting different signatures for its models as well as respective experimental efficiencies. Using this information HEPMDB will be able to compare its BSM model predictions with LHC data which and would allow to discriminate an underlying theory.

The database is in the development stage and your input in the 'Forum' section is highly appreciated. Database collects Particle Physics Models. These models are supposed to be public and represent themselves a set of Feynman Rules which can be in form of input for any of Matrix Element generators such as CalcHEP, CompHEP, FeynArts, Madgraph, SHERPA, WHIZARD. HEPMDB has an entrance for Model authors -- 'Authors' -- where Authors can test and validate their models.

News

We suffered a failure of the Iridis cooling system earlier this morning

2012-07-10 18:52:13

We suffered a failure of the Iridis cooling system earlier this morning, which led to temperatures in the data centre rising very rapidly. We do not expect to be able o resume a batch service until after lunch.
More »

CalcHEP and HEPMDB: practical introduction and tutorial

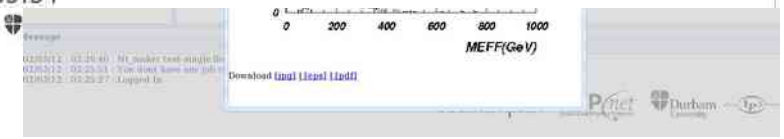
2012-05-03 23:13:13

CalcHEP and HEPMDB: practical introduction and tutorial will take place at CERN https://indico.cern.ch/conferenceDisplay.py?confId=189668
More »

LHAPDF package is added

2012-03-25 12:55:34

Southampton SEPnet



Tutorial

HEPMDB
High Energy Physics Models DataBase

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Search in HEPMDB

Show All Models

Search Models :: Results for [MSSM]

1. **MSSM** [2011-06-21 10:54:07] hepmdb:0611.0028

   CalcHEP/MicrOMEGAs groups

   We present MSSM with SUGRA and AMSB scenario as well as MSSM with low energy input. Read file INSTALLATION for model installation and file CITE for references on scientific publications which pre...

2. **MSSM with bilinear R-Parity violation** [2011-11-17 20:00:51] hepmdb:1111.0036

   Florian Staub

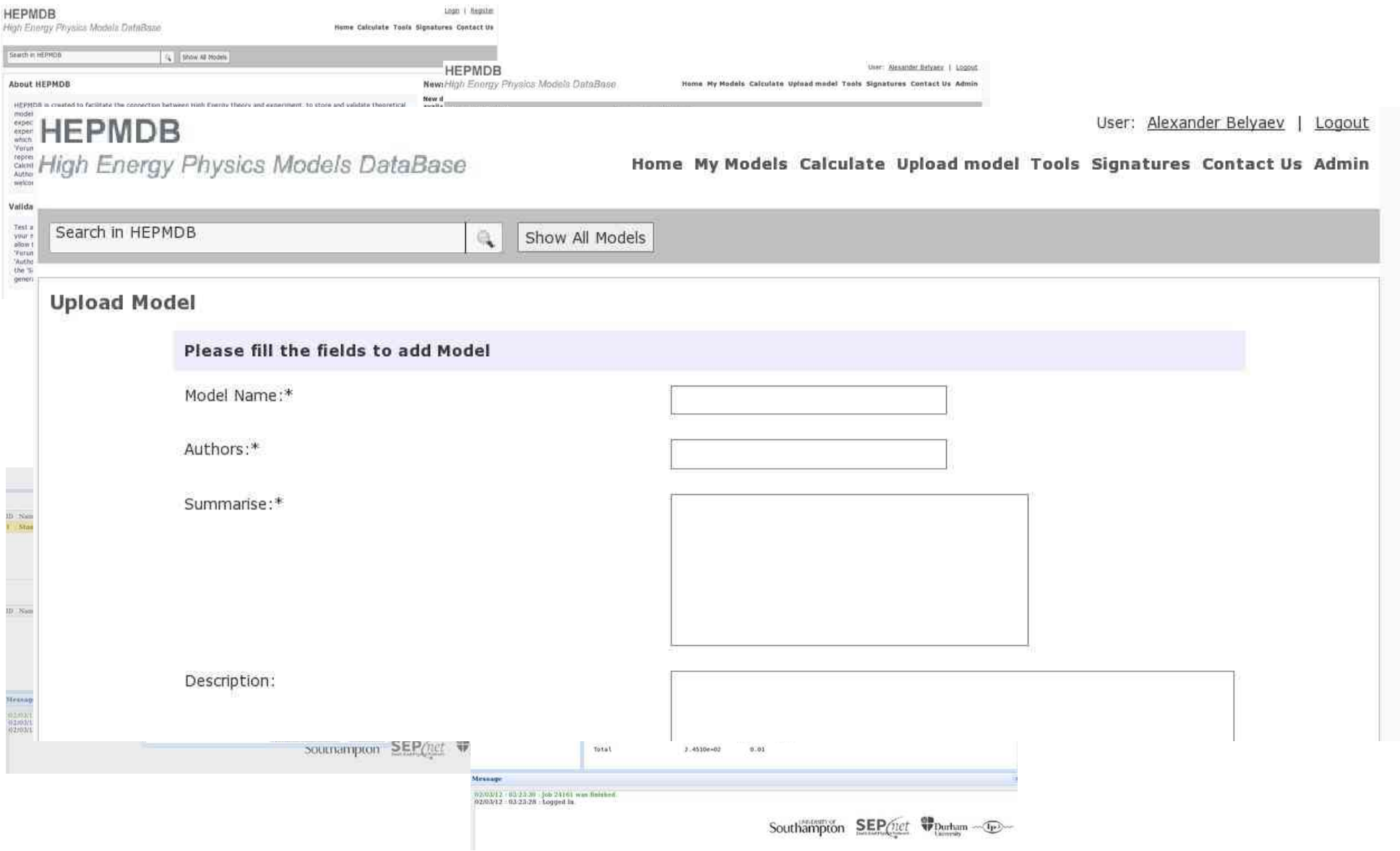
   The MSSM with bilinear R-Parity violating terms in the superpotential and for the soft-breaking terms. Model files created by SARAH 3.1.0 Support of SLHA+ functionality to read spectrum files...

3. **TMSSM** [2011-11-17 20:06:23] hepmdb:1111.0037

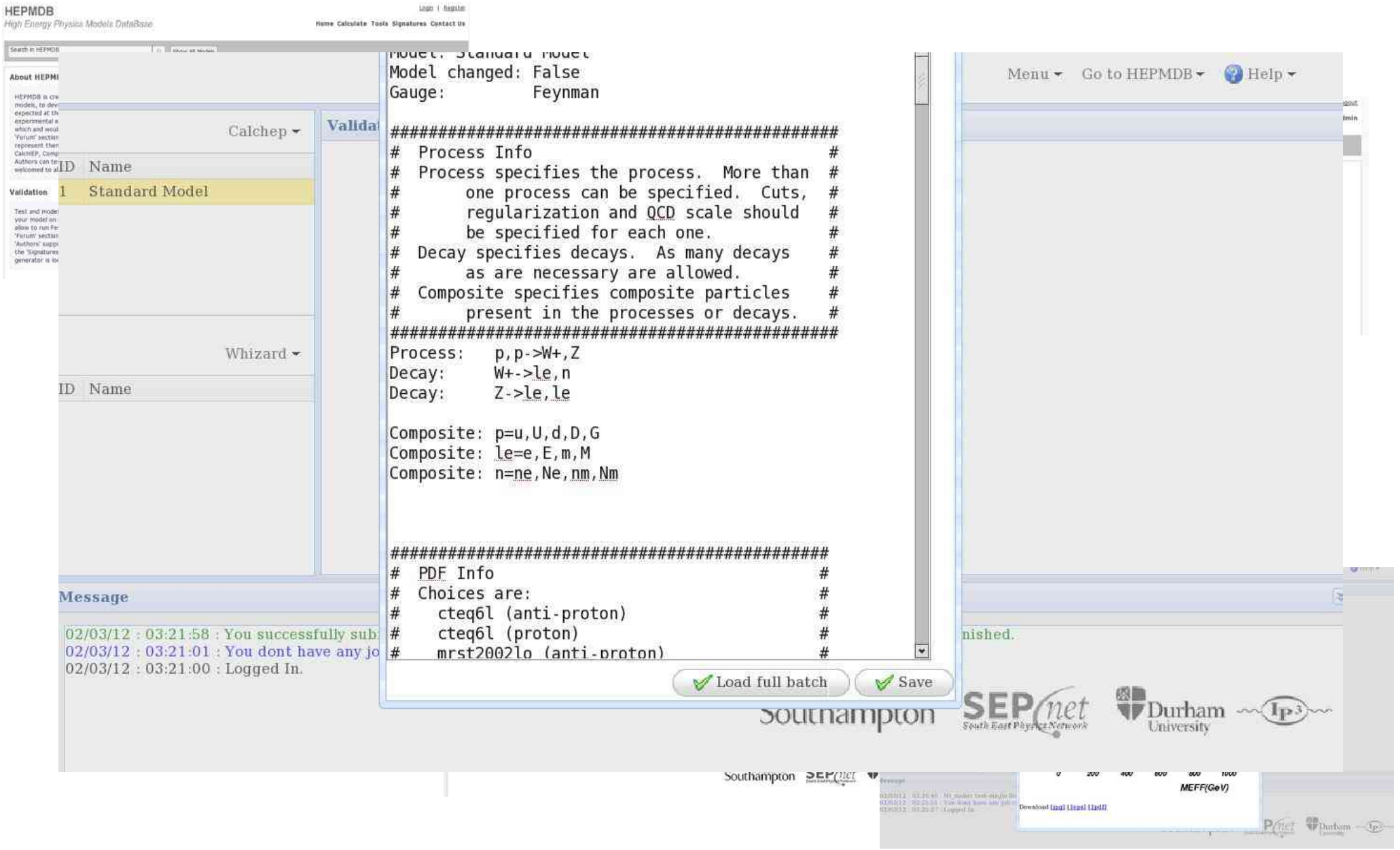
   Florian Staub

   Triplet extended MSSM (including possibility of flavor violation) Model files created by SARAH 3.1.0 Support of

Tutorial


HEPMDB
High Energy Physics Models DataBase
User: Alexander Belyaev | Logout
Home My Models Calculate Upload model Tools Signatures Contact Us Admin
Search in HEPMDB
Show All Models
Upload Model
Please fill the fields to add Model
Model Name:*
Authors:*
Summarise:*
Description:
Southampton
SEPnet
Durham

Tutorial


HEPMDB
High Energy Physics Models DataBase
Model changed: False
Gauge: Feynman
Process: p,p->W+,Z
Decay: W+->le,n
Decay: Z->le,le
Composite: p=u,U,d,D,G
Composite: le=e,E,m,M
Composite: n=ne,Ne,nm,Nm
PDF Info
Choices are:
cteq6l (anti-proton)
cteq6l (proton)
Load full batch
Save
Menu
Go to HEPMDB
Help
Calchep
Whizard
Standard Model
Message
02/03/12 : 03:21:58 : You successfully sub
02/03/12 : 03:21:01 : You dont have any jo
02/03/12 : 03:21:00 : Logged In.
Southampton
SEPnet
Durham University
MEFF(GeV)

Batch file in details(1)

```
################################################
#  batch_file for CalcHEP                      #
#  It has to be launched via                   #
#          ./calchep_batch batch_file          #
#  Lines beginning with # are ignored.         #
################################################

################################################
#  Model Info                                  #
#  Model is the exact model name.              #
#  Model changed specifies whether a change    #
#       was made to the model files.  Changes  #
#       to the numerical values of external    #
#       parameters is ok.  Other changes       #
#       require that the process library be    #
#       recreated.  Values are True or False.  #
#  Gauge specifies gauge.  Choices are         #
#       Feynman or unitary.                    #
################################################
Model:         Standard Model(CKM=1)
Model changed: False
Gauge:         Feynman

################################################
#  Process Info                                #
#  Process specifies the process.  More than   #
#       one process can be specified.  Cuts,   #
#       regularization and QCD scale should    #
#       be specified for each one.             #
#  Decay specifies decays.  As many decays     #
#       as are necessary are allowed.          #
#  Composite specifies composite particles     #
#       present in the processes or decays.    #
################################################
Process:   p,p->W,b,B
Decay:     W->le,n
```

```
Composite: p=u,U,d,D,s,S,c,C,b,B,G
Composite: W=W+,W-
Composite: le=e,E,m,M
Composite: n=ne,Ne,nm,Nm
Composite: jet=u,U,d,D,s,S,c,C,b,B,G



################################################
#  PDF Info                                    #
#  Choices are:                                #
#    cteq6l (anti-proton)                      #
#    cteq6l (proton)                           #
#    mrst2002lo (anti-proton)                  #
#    mrst2002lo (proton)                       #
#    cteq6m (anti-proton)                      #
#    cteq6m (proton)                           #
#    cteq5m (anti-proton)                      #
#    cteq5m (proton)                           #
#    mrst2002nlo (anti-proton)                 #
#    mrst2002nlo (proton)                      #
#    ISR                                       #
#    ISR & Beamstrahlung                       #
#    Equiv. Photon                             #
#    Laser photons                             #
#    Proton Photon                             #
#    OFF                                      #
#                                               #
#  ISR and Beamstrahlung are only available     #
#    for electrons and positrons. while the     #
#    others are available for protons and       #
#    antiprotons.                               #
#    Default pdf: OFF                          #
#  Bunch x+y sizes (nm)                         #
#    Ignored unless ISR & Beam chosen.          #
#    Default: 560                               #
#  Bunch length (mm)                            #
#    Ignored unless ISR & Beam chosen.          #
```

Batch file in details(2)

```
#    Default: 0.4                                #
#  Number of particles                           #
#    Ignored unless ISR & Beam chosen.           #
#    Default: 2E+10                              #
#  Default Beamstrahlung parameters              #
#    correspond roughly with ILC.                #
#                                                #
#  Equiv. Photon, Laser photons and              #
#    Proton Photon are available for             #
#    photons.                                    #
#    Default pdf: OFF                           #
#  Photon particle                               #
#    Ignored unless Equiv. Photon chosen.        #
#    Choices are: mu^-,e^-,e^+,mu^+              #
#    Default: e^+                                #
#  |Q|max                                        #
#    Ignored unless Equiv. Photon chosen.        #
#    Default: 100                                #
#  Incoming particle mass                        #
#    Ignored unless Proton Photon chosen.        #
#    Default: 0.938                              #
#  Incoming particle charge                      #
#    Ignored unless Proton Photon chosen.        #
#    Choices are: 1,-1                           #
#    Default: 1                                  #
#  |Q^2|max                                      #
#    Ignored unless Proton Photon chosen.        #
#    Default: 2                                  #
#  Pt cut of outgoing proton                     #
#    Ignored unless Proton Photon chosen.        #
#    Default: 0.1                                #
################################################
pdf1:      cteq6l (proton)
pdf2:      cteq6l (proton)
```

```
#Bunch x+y sizes (nm)       : 202500
#Bunch length (mm)          : 10
#Number of particles        : 5E+11

#Photon particle            : e^-
#|Q|max                     : 250
#Incoming particle mass     : 0.938
#Incoming particle charge   : -1
#|Q^2|max                   : 2.0
#Pt cut of outgoing proton  : 0.15

################################################
#  Momentum Info                               #
#    in GeV                                    #
################################################
p1:        4000
p2:        4000

################################################
#  Parameter Info                              #
#  Masses and Energies are in GeV              #
################################################
#Parameter: EE=0.31

################################################
#  Run Info                                    #
#  Masses and Energies are in GeV              #
#  More than one run can be specified at       #
#     the same time.                           #
################################################
Run parameter: Mh
Run begin:     120
Run step size: 5
Run n steps:   3
```

Batch file in details(3)

```
##################################################
#  QCD Running Info                              #
#  As in the gui:                                #
#  parton dist. alpha                            #
#     default: ON                                #
#  alpha(MZ)                                     #
#     default: 0.1172                            #
#  alpha nf                                      #
#     default: 5                                 #
#  alpha order                                   #
#     choices: LO, NLO, NNLO                     #
#     default: NLO                               #
#  mb(mb)                                        #
#     default: 4.2                               #
#  Mtop(pole)                                    #
#     default: 175                               #
#  alpha Q                                       #
#     Must be in terms of the final state        #
#     particles.                                 #
#     default: M12                               #
#     :n: specifies which process.               #
#     : means to apply to all processes.         #
##################################################
#parton dist. alpha: ON
#alpha(MZ):          0.118
#alpha nf:           5
#alpha order:        NLO
#mb(mb):             4
#Mtop(pole):         174

#alpha Q :1:         M34
#alpha Q :2:         M45
alpha Q :           M45
```

```
##################################################
#  Cut Info                                      #
#  Must be in terms of the (production mode)     #
#     final state particles.                     #
#     :n: specifies which process.               #
#     : means to apply to all processes.         #
##################################################

Cut parameter:    M(b,B)
Cut invert:       False
Cut min:          100
Cut max:

Cut parameter:    J(jet,jet)
Cut invert:       False
Cut min:          0.5
Cut max:

Cut parameter:    T(jet)
Cut invert:       False
Cut min:          20
Cut max:

Cut parameter:    N(jet)
Cut invert:       False
Cut min:         -2.5
Cut max:          2.5



##################################################
#  Kinematics Info                               #
#  Must be exactly as in CH.                     #
#     Comment out to use the CH defaults.        #
#     :n: specifies which process.               #
#     : means to apply to all processes.         #
##################################################
```

Batch file in details(4)

```
#Kinematics :1:    12 -> 34 , 56
#Kinematics :1:    34 -> 3 , 4
#Kinematics :1:    56 -> 5 , 6

Kinematics :      12 -> 3, 45
Kinematics :      45 -> 4 , 5



#################################################
#  Regularization Info                          #
#  Must be in terms of the final state          #
#     particles.                                #
#     :n: specifies which process.              #
#     : means to apply to all processes.        #
#################################################
Regularization momentum:1: 45
Regularization mass:1:     Mh
Regularization width:1:    wh
Regularization power:1:    2


#################################################
#  Distribution Info                            #
#  Only 1 dimensional distributions are         #
#     currently supported.                      #
#  Dist n bins should be one of:                #
#     300, 150, 100, 75, 60, 50, 30, 25,        #
#     20, 15, 12, 10, 6, 5, 4, 3, 2             #
#  Dist title and Dist x-title should be        #
#     plain text.                               #
#################################################
Dist parameter:    M(b,B)
Dist min:          100
Dist max:          200
Dist n bins:       100
Dist title:        p,p->W,b,B
Dist x-title:      M(b,B) (GeV)
```

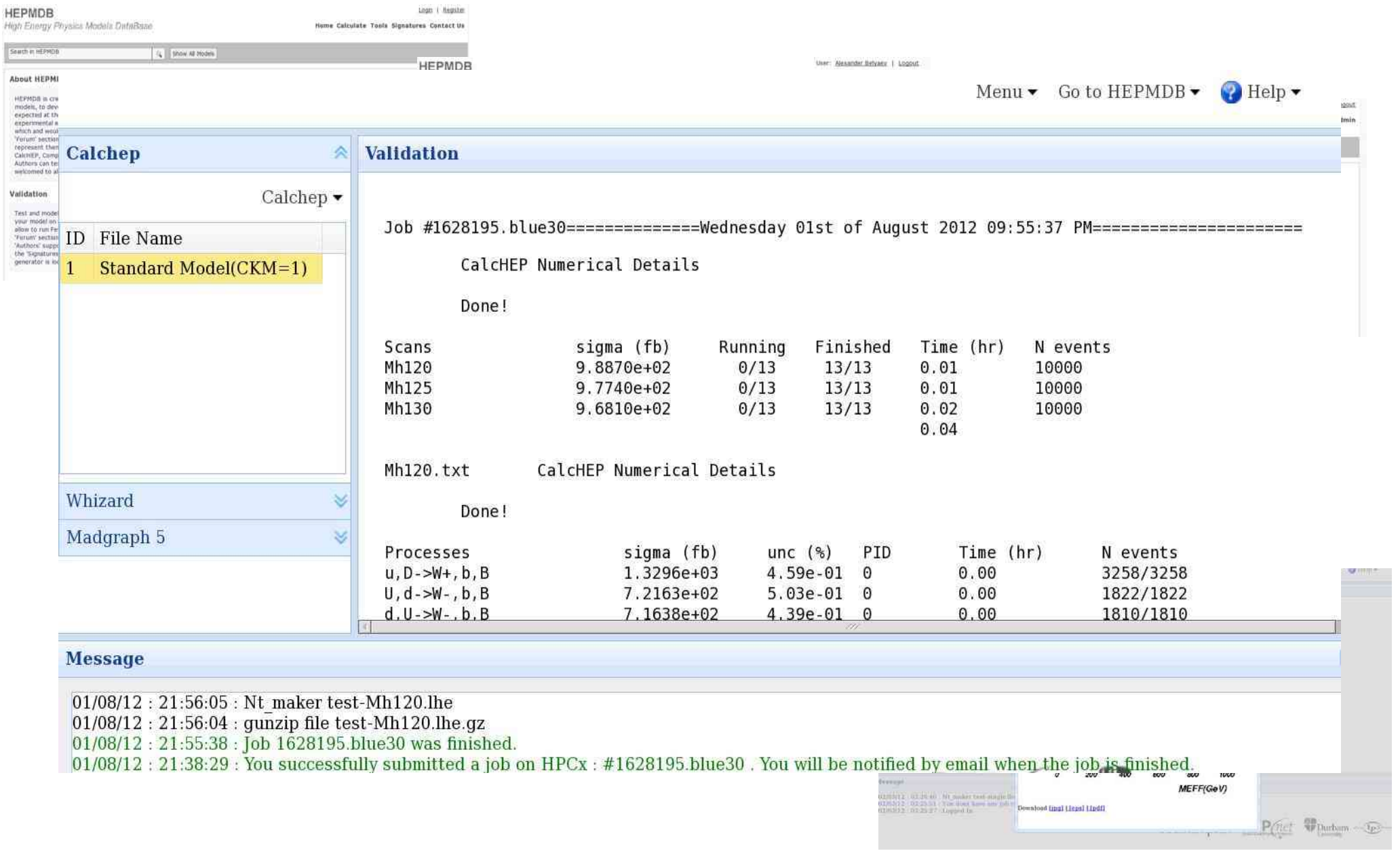
```
Dist parameter:    M(W,jet)
Dist min:          100
Dist max:          200
Dist n bins:       100
Dist title:        p,p->W,b,B
Dist x-title:      M(W,jet) (GeV)

#################################################
#  Events Generation                            #
#  Number of events determines how many         #
#       events to produce for each run.         #
#  Filename is the name used for the event      #
#       files.  If no parameter is run over     #
#       then, -Single.lhe is appended.  If      #
#       a parameter is run over then its        #
#       value will be appended as in            #
#       pp-WW-MW400.lhe.                        #
#  NTuple determines whether PAW ntuples        #
#       are created.  This only works if        #
#       nt_maker is properly compiled and       #
#       in the bin directory.                   #
#       Choices are True or False.              #
#  Cleanup determines whether the               #
#       individual event files are removed      #
#       after they are combined.                #
#       Default: True                           #
#################################################
Number of events (per run step): 1000
Filename:                        test
NTuple:                          False
Cleanup:                         False
```

Batch file in details(5)

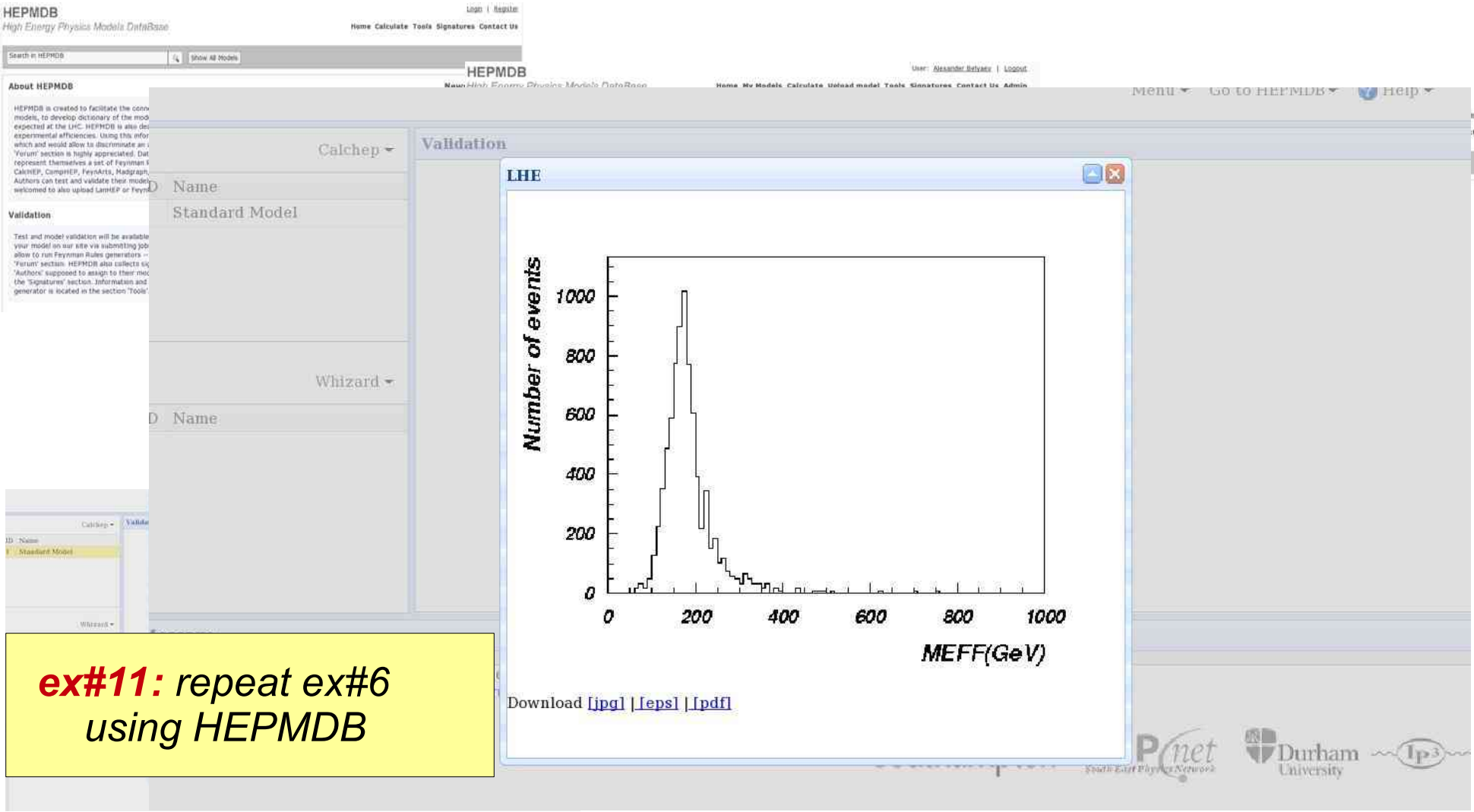
```
################################################
#  Parallelization Info                        #
#  Parallelization method choices:             #
#      local                                   #
#      pbs                                     #
#  Que can be left blank if not required       #
#      on your pbs cluster.                    #
#  Walltime should be the number               #
#      of hours necessary for each job.        #
#      Leave blank if your pbs cluster does    #
#      not require this and will let a         #
#      job run until it is finished.           #
#  Memory is the amount of memory required     #
#      for each job in gb.  Leave blank        #
#      if not required on your cluster.        #
#  email is only used on the pbs cluster       #
#      if you want it to inform you of         #
#      problems. email is currently ignored.   #
#  sleep time determines how often the         #
#      script updates (in seconds)             #
#      while waiting for processes to finish.  #
#  nice level is used for the CH jobs in       #
#      local mode and combining events in      #
#      all modes.                              #
#      default: 19                             #
################################################
Parallelization method:      local
#Que:                         brody_main
#Walltime:                    0.15
#Memory:                      1
#email:                       name@address
Max number of cpus:          2
sleep time:                  3
nice level :                 19
```

```
################################################
#  Vegas                                       #
#  The variables are the same as in the gui.   #
#  If commented out, the default values        #
#      are used.                               #
#                                              #
#  nSess_1 : number of the 1st sessions        #
#     default: 5                               #
#  nCalls_1 : number of calls per 1st sessions#
#     default: 10000                           #
#  nSess_2 : number of the 2nd sessions        #
#     default: 0                               #
#  nCalls_2 : number of calls per 2nd sessions#
#     default: 10000                           #
################################################
nSess_1:   5
nCalls_1:  100000
nSess_2:   5
nCalls_2:  100000


################################################
#  Event Generator                             #
#  The variables are the same as in the gui.   #
#  If commented out, the default values        #
#      are used.                               #
#                                              #
#  sub-cubes:                                  #
#     default: 1000                            #
#  random search:                              #
#     default: 100                             #
#  simplex search:                             #
#     default: 50                              #
#                                              #
#  MAX*N: integer to multiply max by           #
#     default: 2                               #
#  find new MAX:                               #
#     default: 100                             #
################################################
#sub-cubes:      100000
#random search:  100
#simplex search: 50

#MAX*N:          2
#find new MAX:   100
```

Tutorial


HEPMDB
High Energy Physics Models DataBase
Menu
Go to HEPMDB
Help
Calchep
Validation
Calchep
ID File Name
1 Standard Model(CKM=1)
Whizard
Madgraph 5
Job #1628195.blue30==========Wednesday 01st of August 2012 09:55:37 PM==========
CalcHEP Numerical Details
Done!
Scans sigma (fb) Running Finished Time (hr) N events
Mh120 9.8870e+02 0/13 13/13 0.01 10000
Mh125 9.7740e+02 0/13 13/13 0.01 10000
Mh130 9.6810e+02 0/13 13/13 0.02 10000
0.04
Mh120.txt CalcHEP Numerical Details
Done!
Processes sigma (fb) unc (%) PID Time (hr) N events
u,D->W+,b,B 1.3296e+03 4.59e-01 0 0.00 3258/3258
U,d->W-,b,B 7.2163e+02 5.03e-01 0 0.00 1822/1822
d,U->W-,b,B 7.1638e+02 4.39e-01 0 0.00 1810/1810
Message
01/08/12 : 21:56:05 : Nt_maker test-Mh120.lhe
01/08/12 : 21:56:04 : gunzip file test-Mh120.lhe.gz
01/08/12 : 21:55:38 : Job 1628195.blue30 was finished.
01/08/12 : 21:38:29 : You successfully submitted a job on HPCx : #1628195.blue30 . You will be notified by email when the job is finished.
MEFF(GeV)

Tutorial



ex#11: *repeat ex#6 using HEPMDB*

Example of models created for CalcHEP

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

Models at FeynRules web-site

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM (10)	Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars.
Supersymmetric Models (4)	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-dimensional Models (4)	Extensions of the SM including KK excitations of the SM particles.
Strongly coupled and effective field theories (4)	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators.
Miscellaneous (0)	

Remarks on collecting models at HEPMDB

- *there are numerous model implementations exist (FeynRules team, LanHEP/CalcHEP/CompHEP teams, private implementations)*
- *they are highly complementary and useful*
- *HEPMDB is the natural place to accommodate all of them (also allows to keep model privately, controlled by Public/Private option On/Off!)*

Summary on HEPMDB

- HEPMDB is already a convenient centralized storage environment for HEP models. Via web interface to the HPC cluster (12 cores per user) it allows to evaluate the LHC predictions and event generation-simulation chain

- Your relevant packages can be installed at HEPMDB!

- we hope that starting from the present stage, HEPMDB development will be boosted further via involvement of the HEP community
  (via direct involvement into HEPMDB, via various projects involving HEPMDB, via numerous comments/requests for HEPMDB features)

- we hope also that in the near future the HEPMDB will become a powerful tool for isolation of the most successful theory for explaining the LHC data

PhenoData

- spin-off the **PhenoData**
  hepmdb.soton.ac.uk/phenodata

- stores data (digitized curves from figures, tables etc) from those HEP papers which did not provide data in arXiv or HEPData, and to avoid duplication of work of HEP researchers on digitizing plots.

- has an easy search interface and paper identification via arXiv, DOI or preprint numbers. PhenoData is not intended to be a replication of any existing archive

- Has batch upload mode