# Theory-Experiment interplay in Probing BSM physics at the LHC

**Alexander Belyaev**

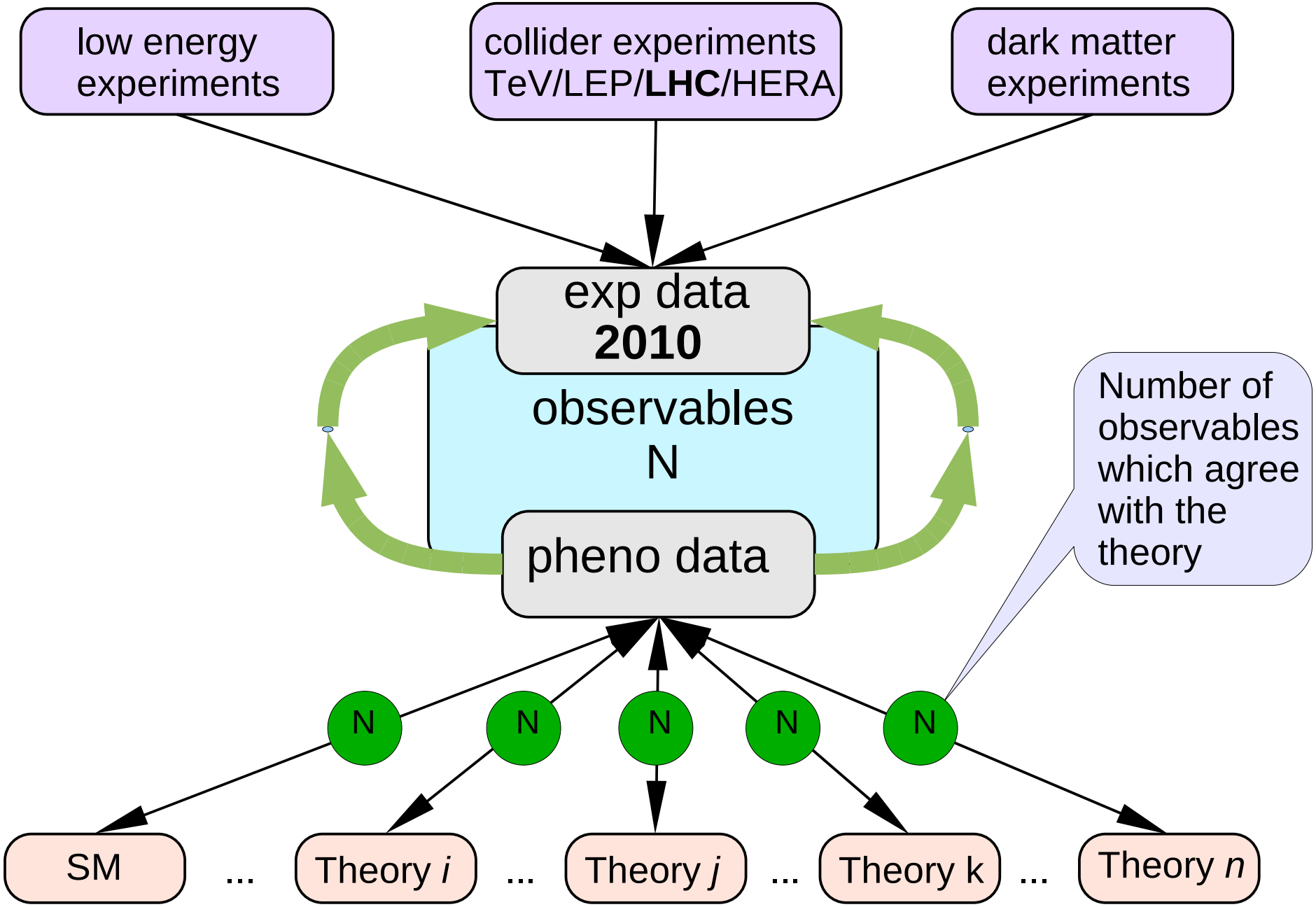
**Southampton University & Rutherford Appleton LAB**

**April 08, 2010**

**RHUL workshop on**

**"Theory-Experiment Interplay at the LHC"**

# Possible scenario in the near future



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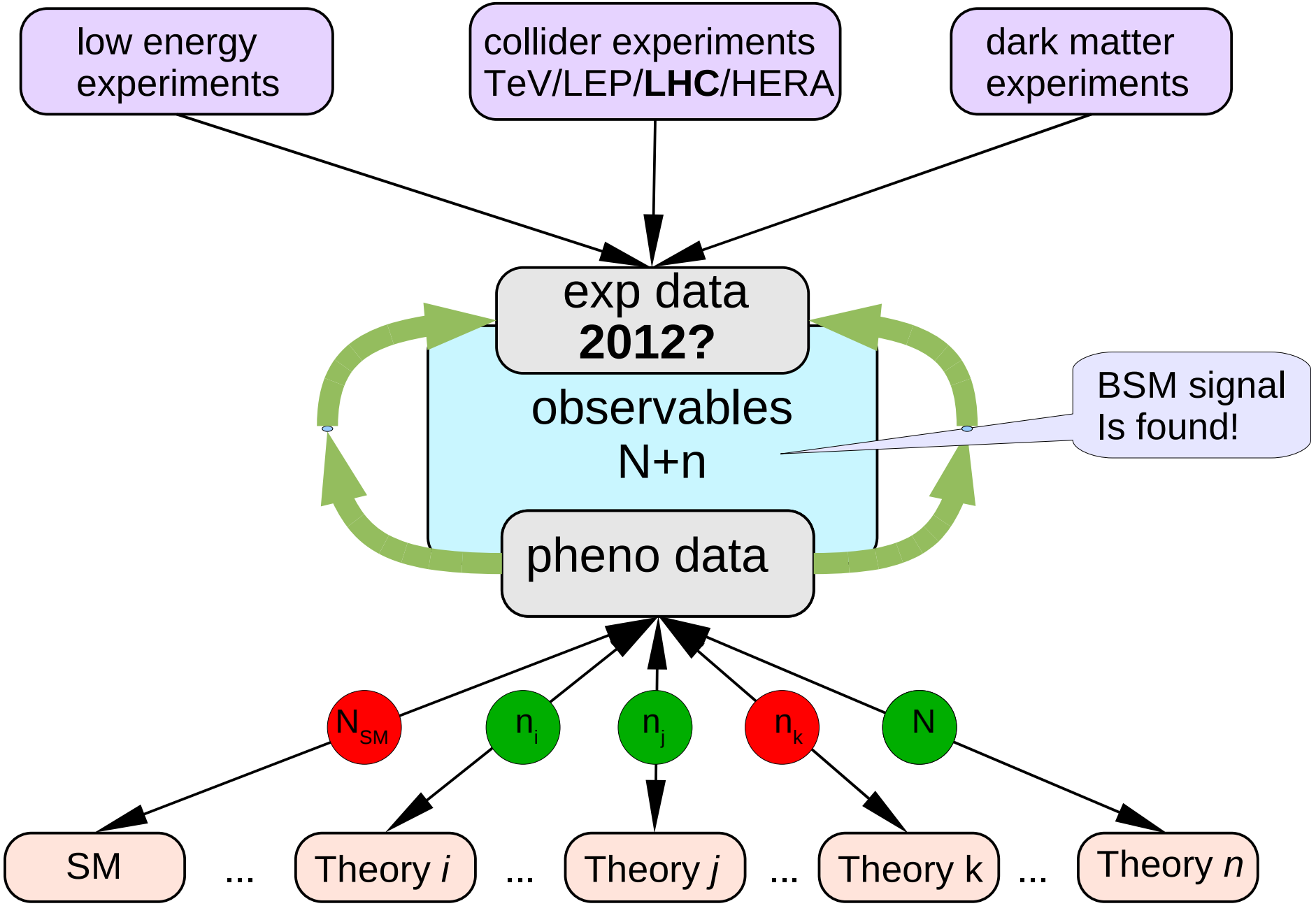

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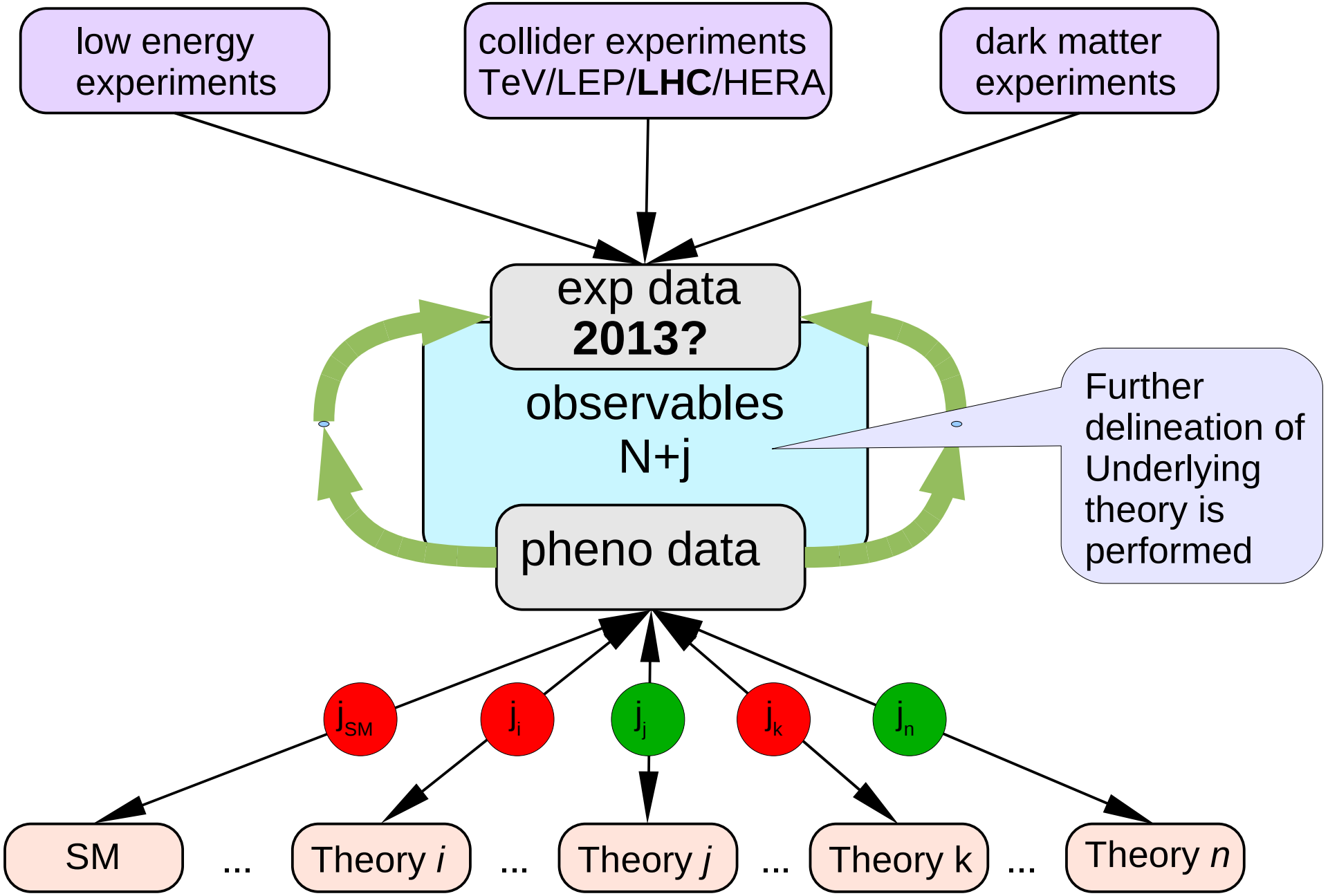

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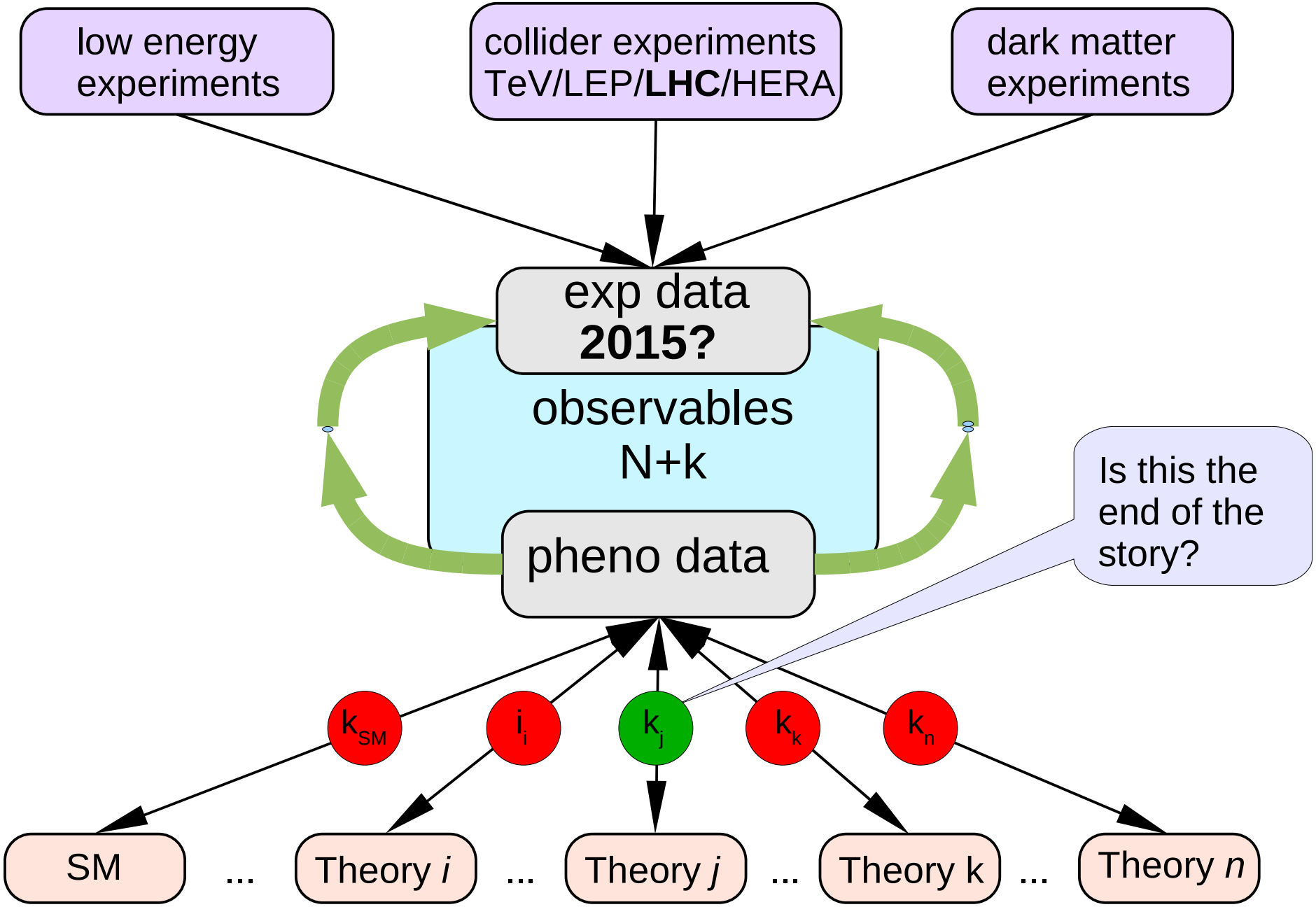

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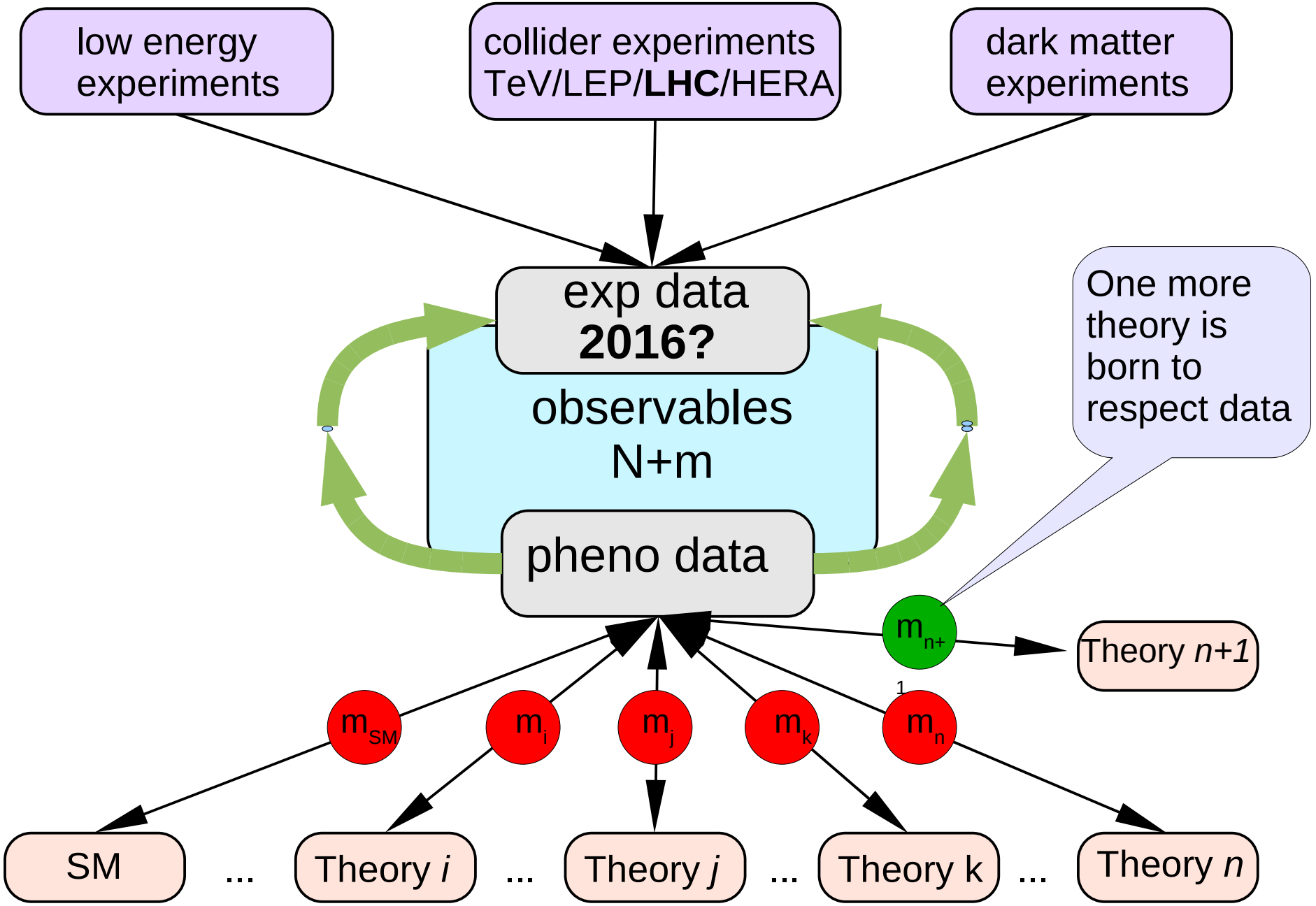
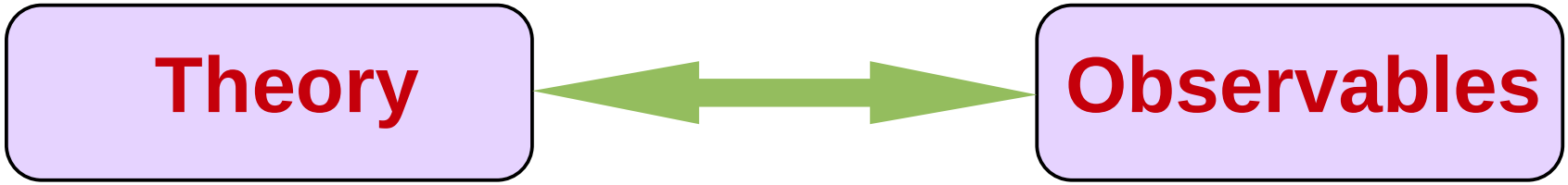
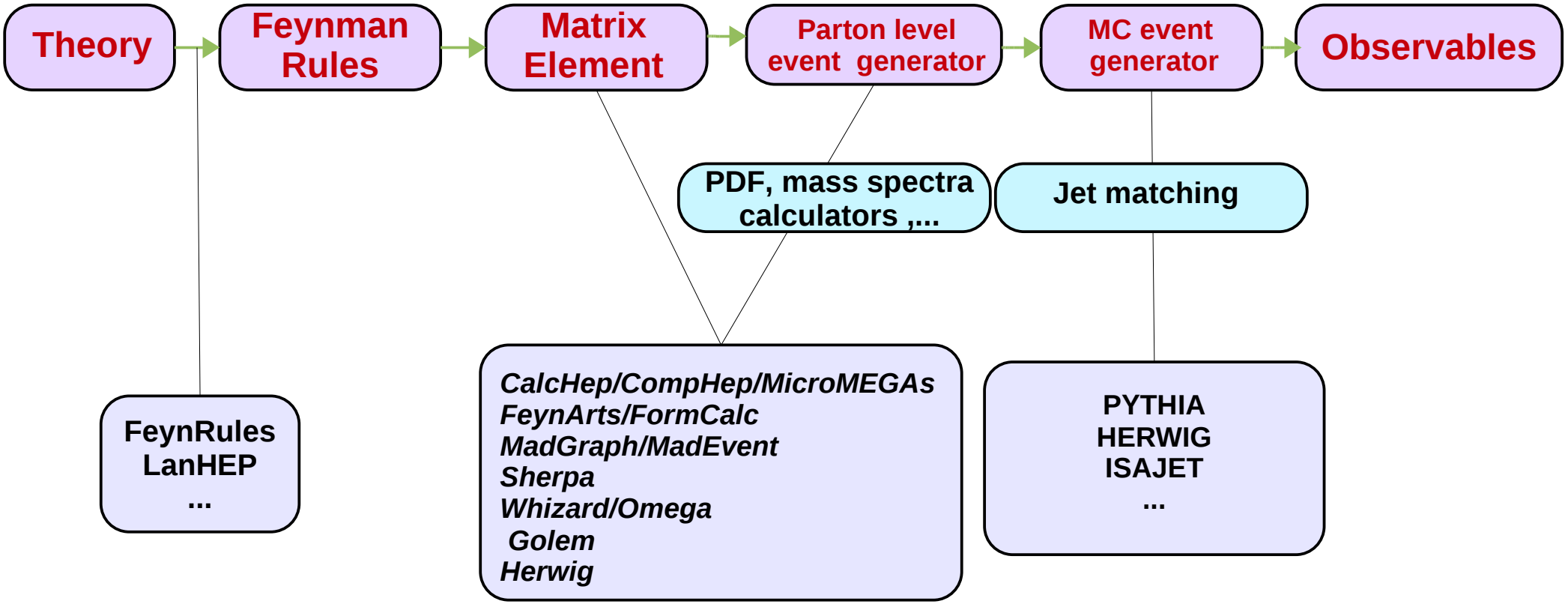


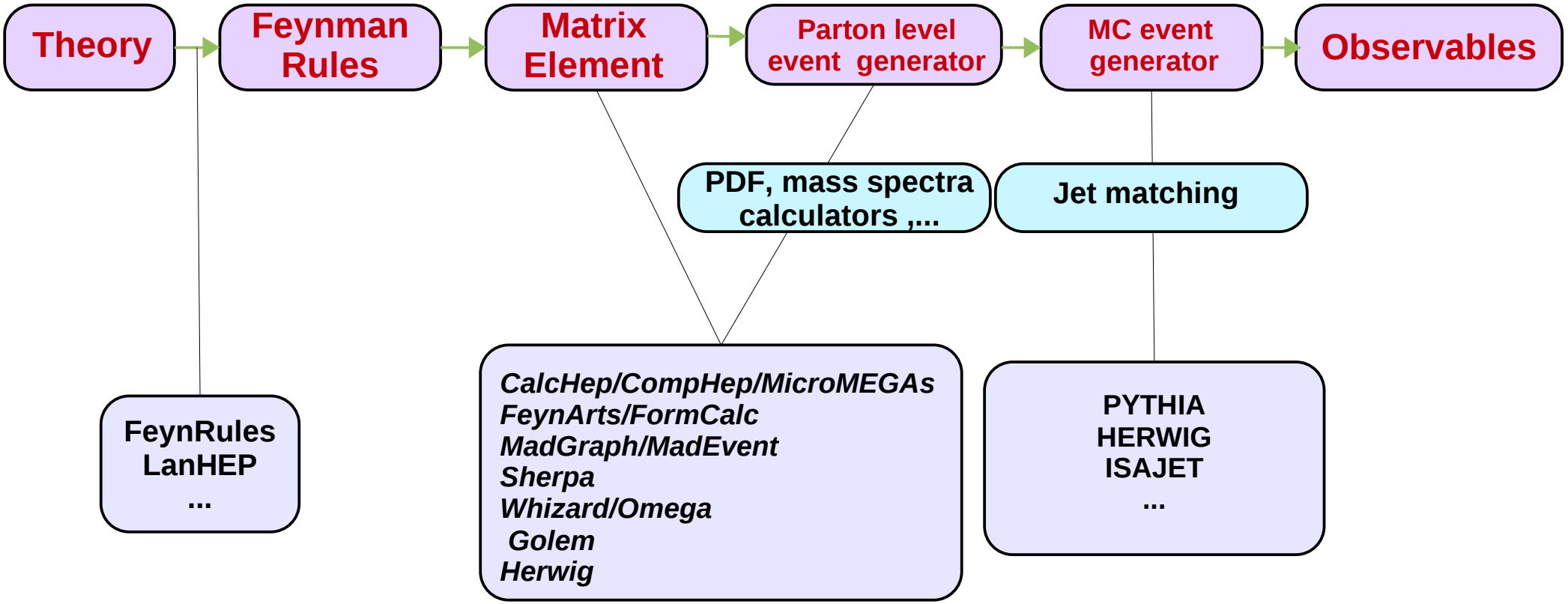



**is the crucial link**

**What does this link actually mean?**




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

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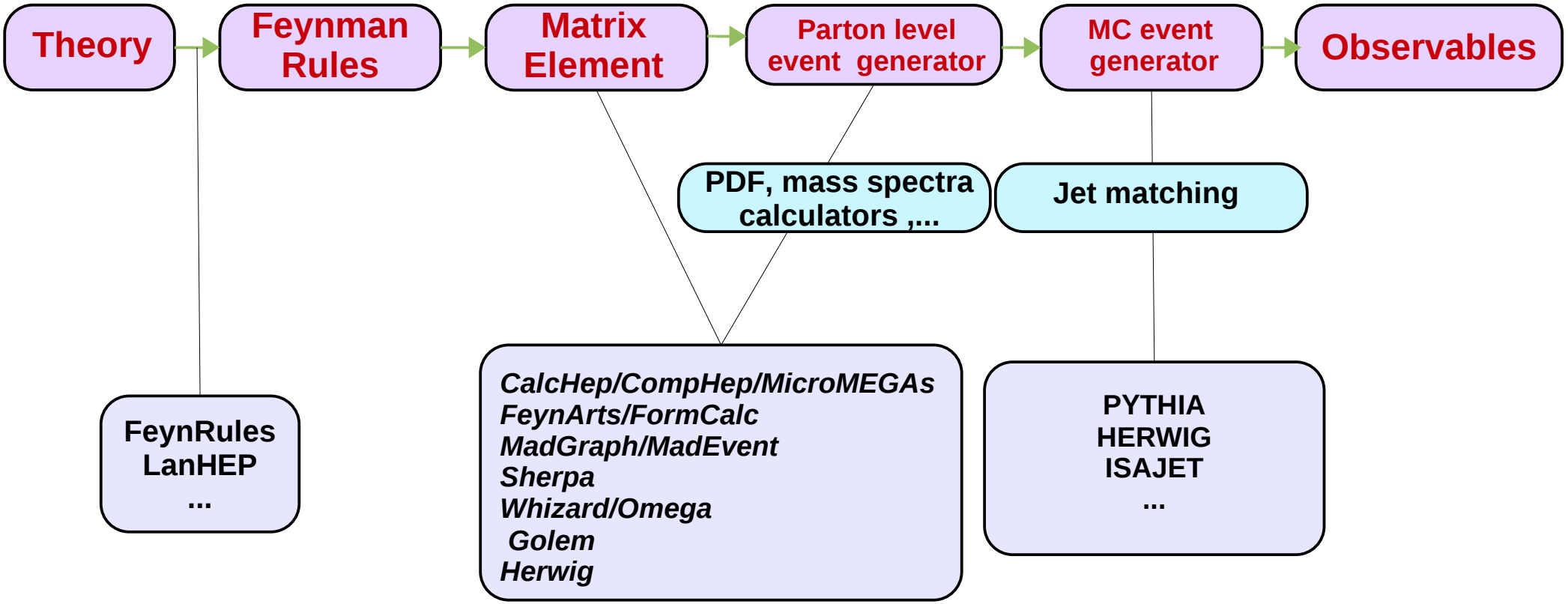
## Why [Theory <-> Feynman rules] link is that crucial ?

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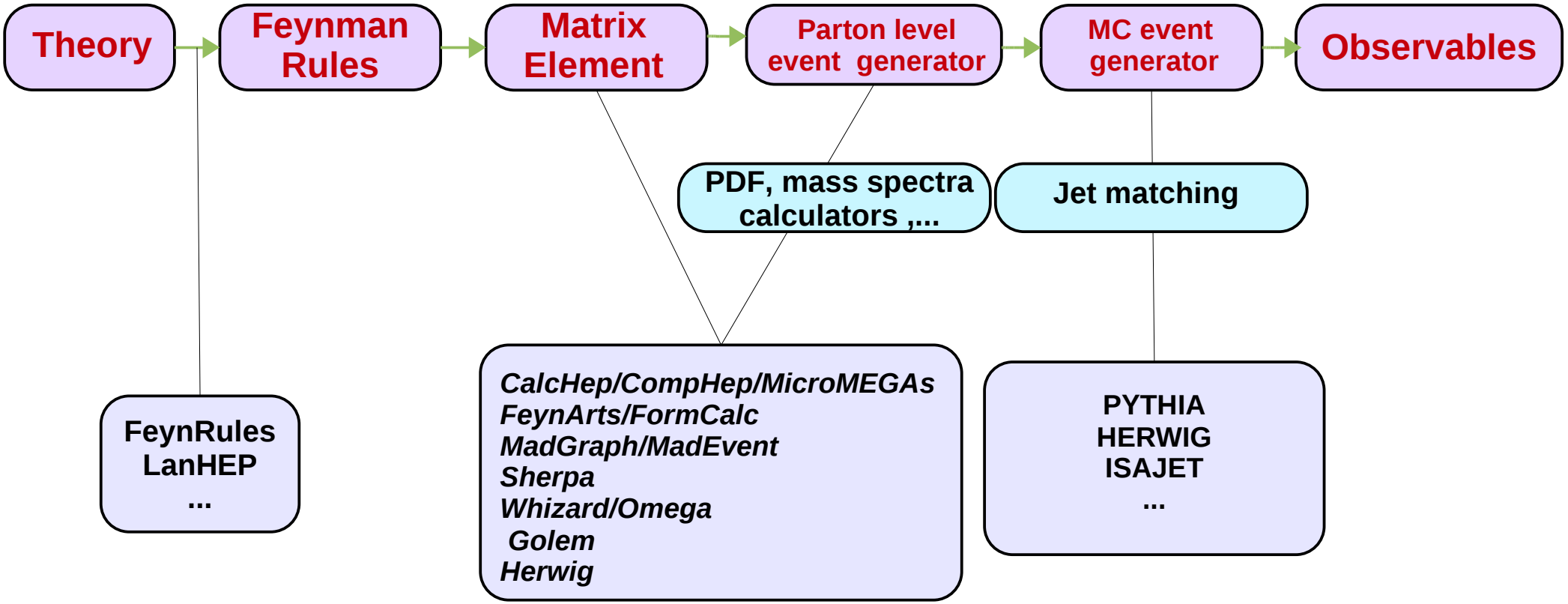
## Why [Theory <-> Feynman rules] link is that crucial ?

- **Experimentalist gets a tool to implement theory he is interested in and performs the rest of the chain**

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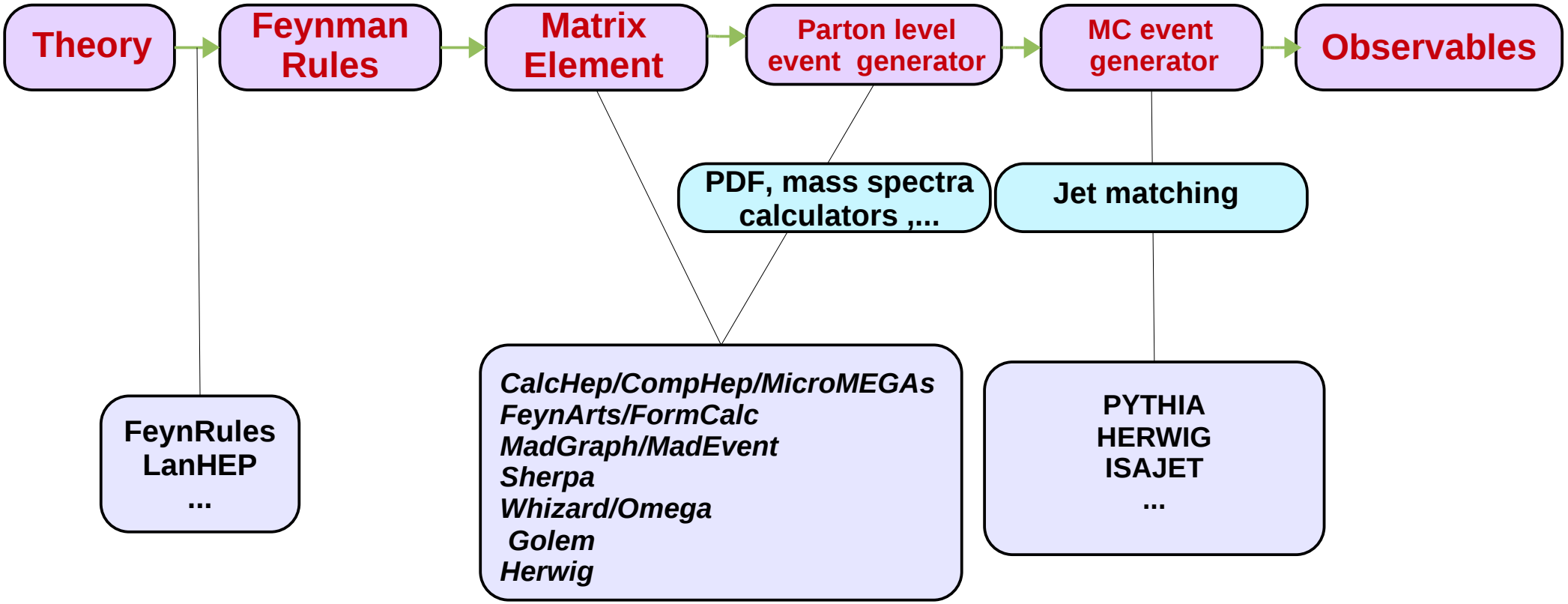


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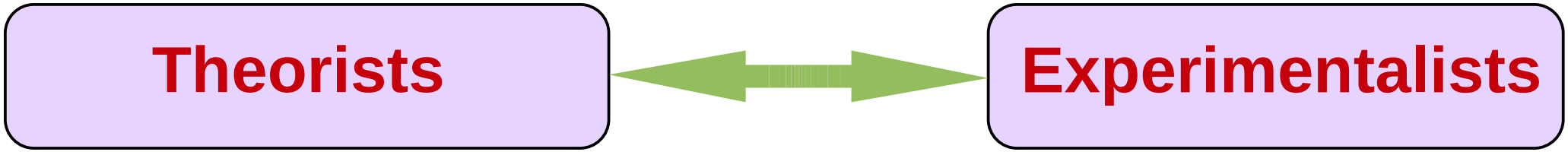
## Why [Theory <-> Feynman rules] link is that crucial ?

- **Experimentalist gets a tool to implement theory he is interested in and performs the rest of the chain**
- **Theorist has an access to observables for his favorite theory**
- **Not only phenomenology becomes easy(er) but also Experimentalists and Theorists become closer**

# Another crucial link




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

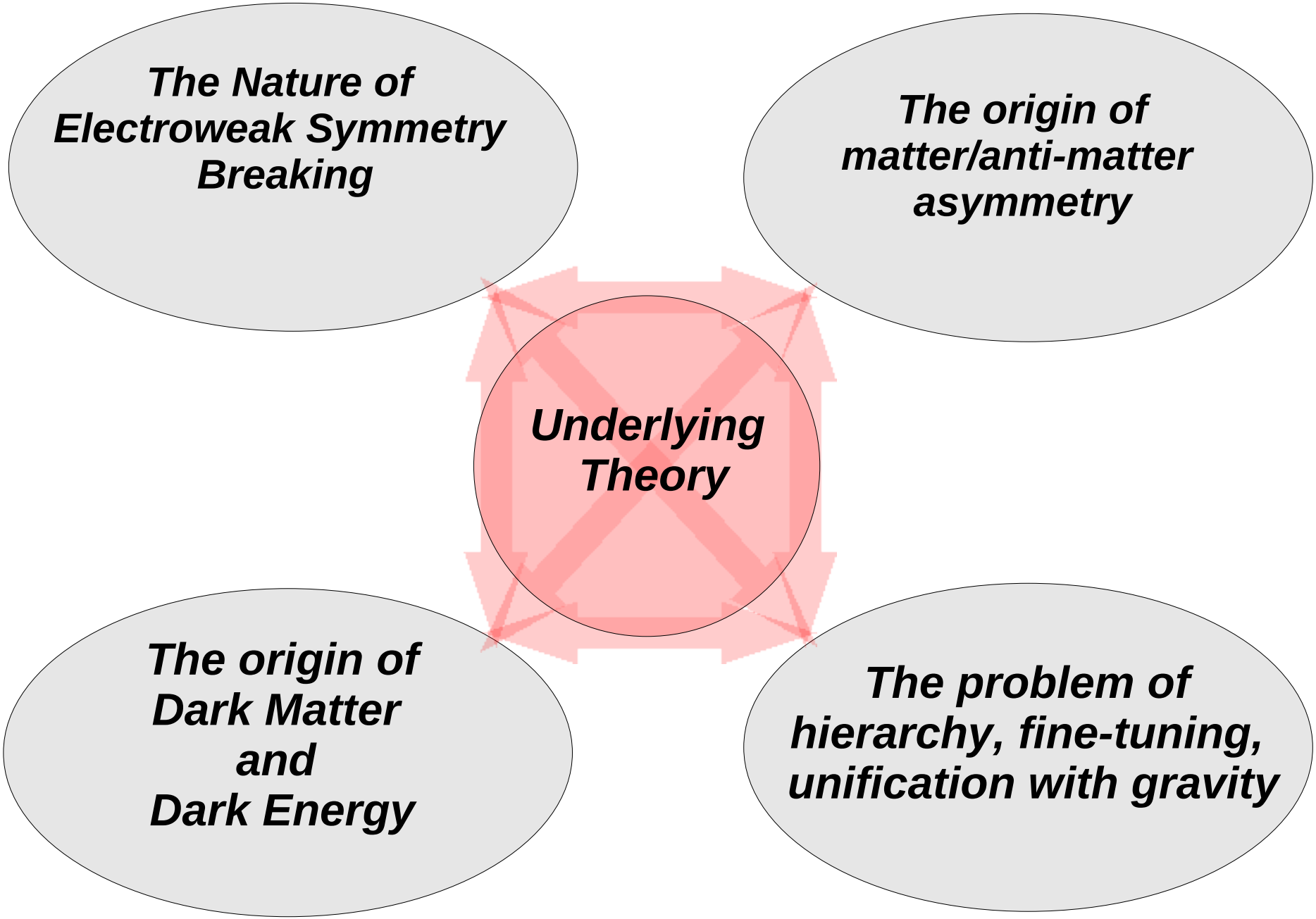
- But there are many different theories and many respective signatures preferred by different people ...
  and just one underlying theory preferred by Nature!

- Can we delineate THIS theory from LHC signatures?

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

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

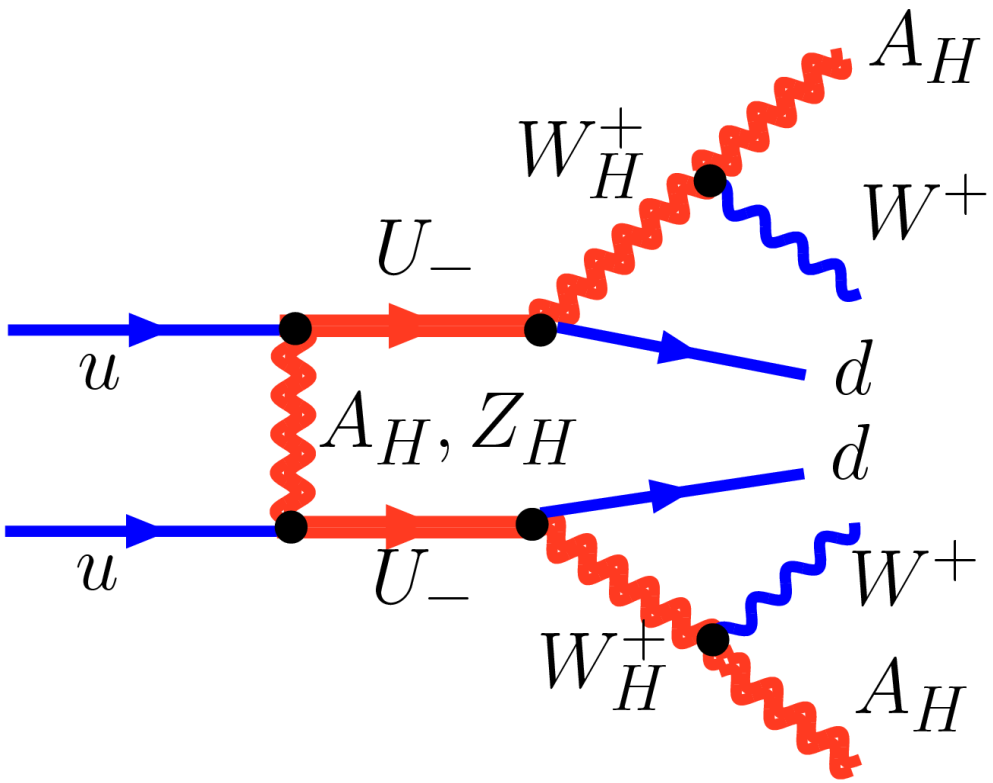
# What underlying theory should explain?

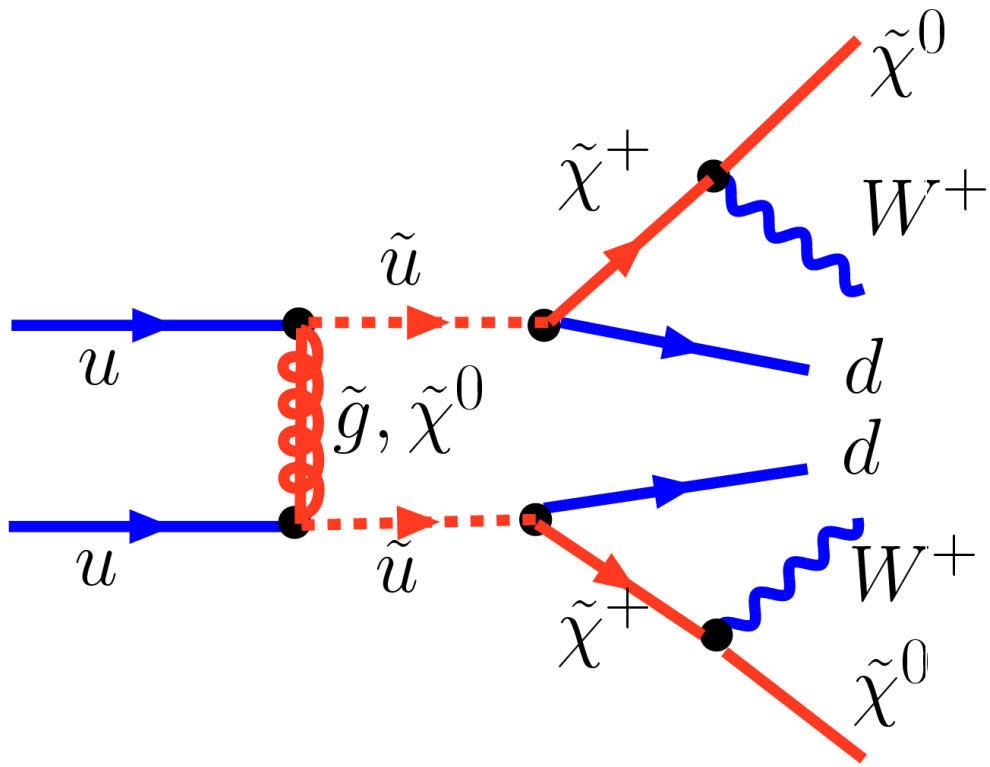


# Promising candidates for underlying theory ...

- **Supersymmetry:**
  - *cMSSM, MSSM, NMSSM, $E_6$SSM, ...*
- **Walking Technicolor**
- **Little Higgs models with T-parity**
- **Extradimensional Models:**
  - *Universal and Warp extra dimensions*

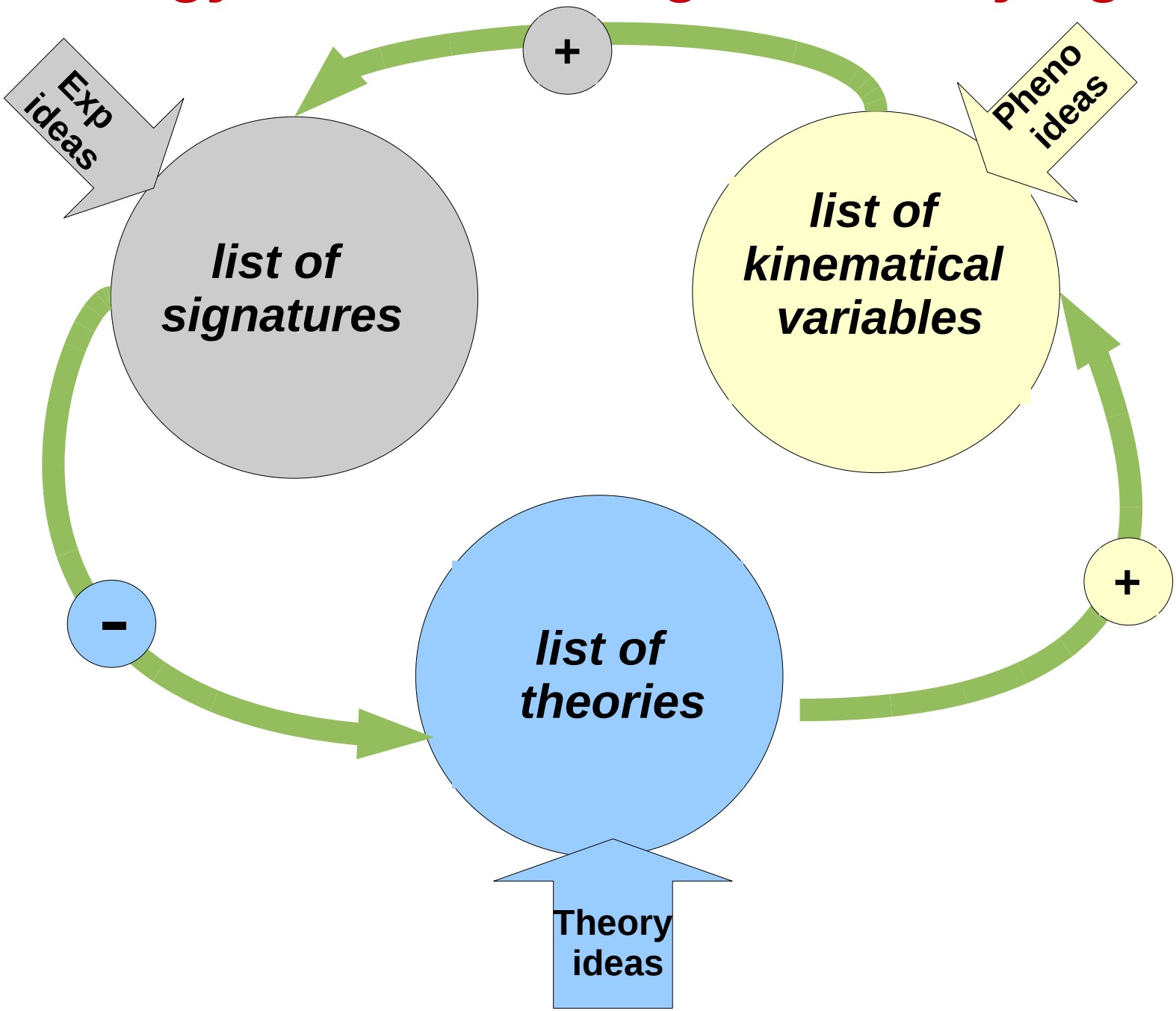
# Signatures could look alike




**LHT** **SUSY**

# The strategy for delineating of underlying theory



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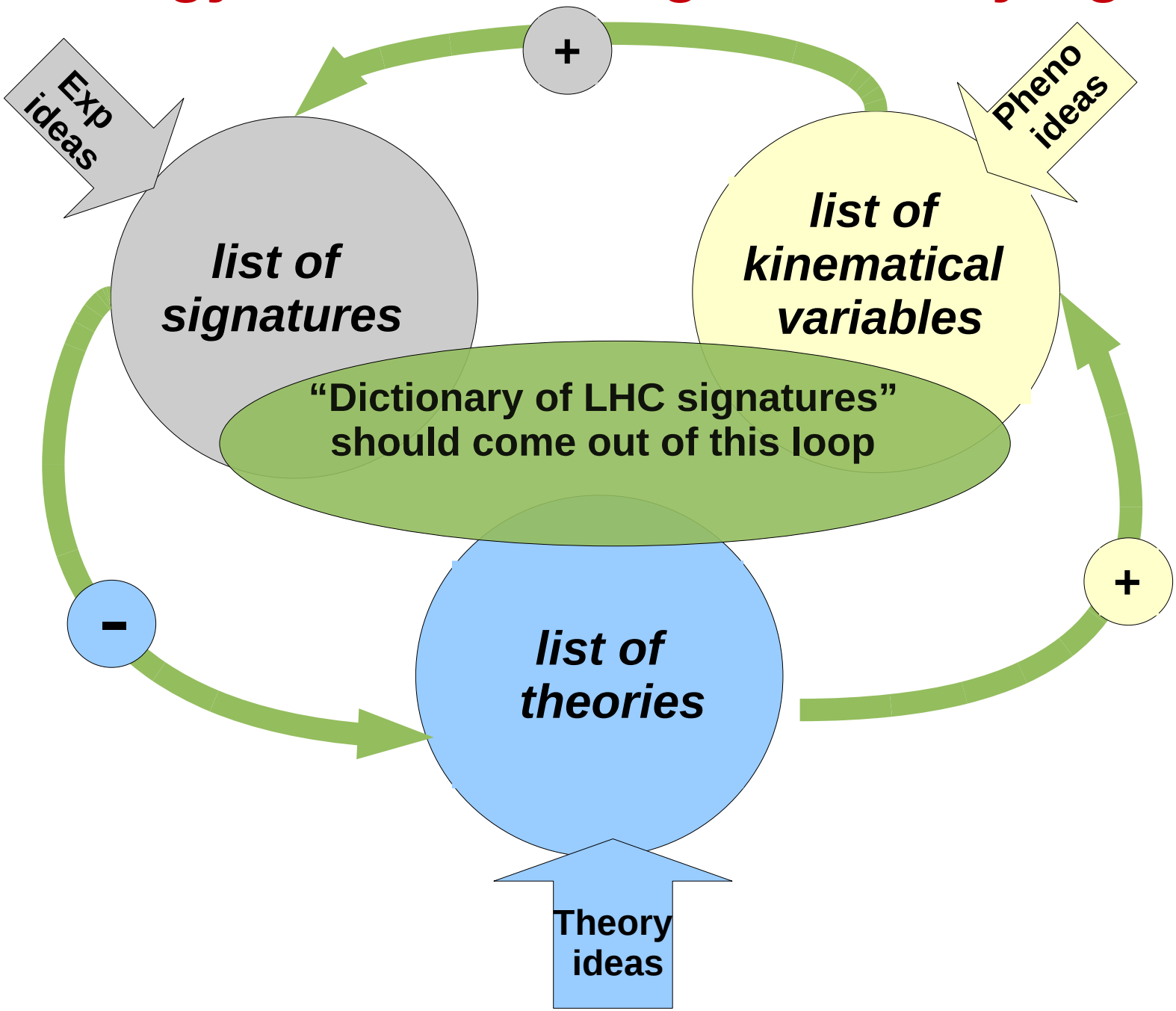
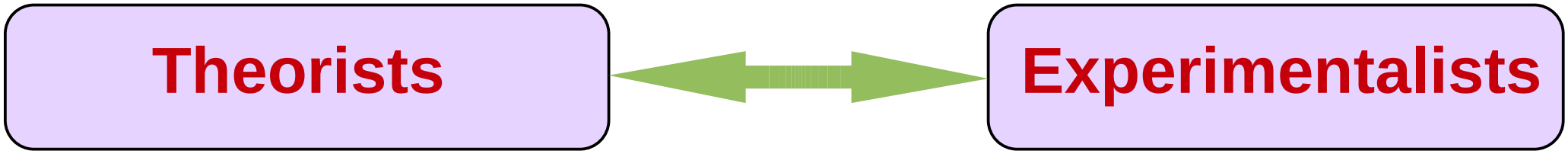


# First Steps towards "Dictionary"

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

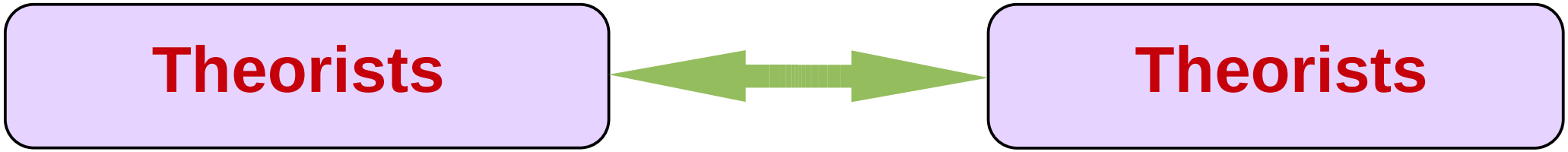
| Variables | | SUSY (MSSM) | LHT | UED |
|---|---|---|---|---|
| Spin | | heavy partners differ in spin by 1/2 | heavy partners have the same spin, no heavy gluon | heavy partners have the same spin |
| Higher level modes | | NO heavy partners | NO heavy partners | YES heavy partners |
| $N_{l^+l^+}/N_{l^-l^-}$ | | $R_{SUSY} < R_{LHT}$ | $R_{LHT}$ | $R_{UED} \simeq R_{LHT}$ |
| SS leptons rates | | from several channels: SS heavy fermions, Majorana fermions | only from SS heavy fermions | only from SS heavy fermions |
| $R = \frac{N(\not{E}_T + jets)}{N(l's + \not{E}_T + \text{jets})}$ | | $R_{\rm SUSY}$ | $R_{\rm LHT} < R_{\rm SUSY}$ | $R_{\rm UED}$ 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 $\gamma_1$(5D) DM [22] typically high for $\gamma_H$(6D) DM [22] |




# What we can do at this workshop?

- Create a list of the models to be implemented into ME generators
- Discuss the validation of such models (follow Les Hocuhes paper and FeynRules workshop @ Mont Sainte-Odile)
- Create the Wish List of features for MC generators/tools requested by experimentalists
- Discuss needs of theorists/phenomenologists from experimentalists
- Define the way of unambiguous reproduction of parton-level events (subject of discussion at recent FeynRules workshop)
  - *need a database of the models (under construction in Southampton) with unique model identifier*
  - *database will be the collection of models from FeynRules, Lanhep as well as manually created ones*
  - *we should make LHE events traceable – generate tag for tools chain*

# Another crucial link




**Let's talk to each other, this is what our workshop for!**

- Let's understand complementarity of our tools and join efforts
  - *validate models*
  - *discuss common projects*
- Talk openly about current problems and think about the way of their effective solution
- Once model is validated we could share our efforts on working on challenging physics problem using different packages

# Few words about CalcHEP

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

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

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

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

- **Idea**

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

- **Features/Limitations of the CalcHEP**
  - *Can evaluate any decay and scattering processes within any (user defined) model!*
  - *Tree-level processes*
  - *Squared Matrix Element calculation*

    *no spin information for outgoing particles – spin averaged amplitude*
  - *Limit on number of external legs (involved particles) and number of diagrams: official limit – 8 , unofficial – none,limit is set from the practical point of view:* 2 → 6 (1→7) set the essential time/memory limit number of diagrams ~ 500 set the disk space and the time limit

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

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

**Authors - Alexander Pukhov, Alexander Belyaev, Neil Christensen**

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

General information
• Main facilities , • Old Versions , • Acknowledgments • News&Bugs

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Manual
• calchep_man_2.3.5(ps.gz) (137 pages, 445KB, March 18, 2005)
• HEP computer tools (Lecture by Alexander Belyaev)
See also: Dan Green, High Pt physics at hadron colliders (Cambrige University Press)

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Codes download.
• Licence • Installation • References&Contributions
CalcHEP code for UNIX: • version 2.5.4 (July 10 , 2009) • version 2.5.5 ( version for testing)

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Models:
• MSSM(04.08.2006) • NMSSM • CPVMSSM(04.08.2006) • LeptoQuarks
Universal Extra Dimension Models: • 5DSM • 6DSM SUSY models for CompHEP • By A.Semenov

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Relative packages on Web:
Packages for model generation: • LanHEP • FeynRules
RGE and spectrum calculation: • SuSpect • Isajet • SoftSUSY • SPheno • CPsuperH • NMHDecay
Particle widths in MSSM: • SDECAY • HDECAY
Parton showers: • PYTHIA

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

# Quick start: practical notes on the installation

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

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

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

    **(see *getFlags* file)**

# Starting CalcHEP

- **cd ../calc_work**

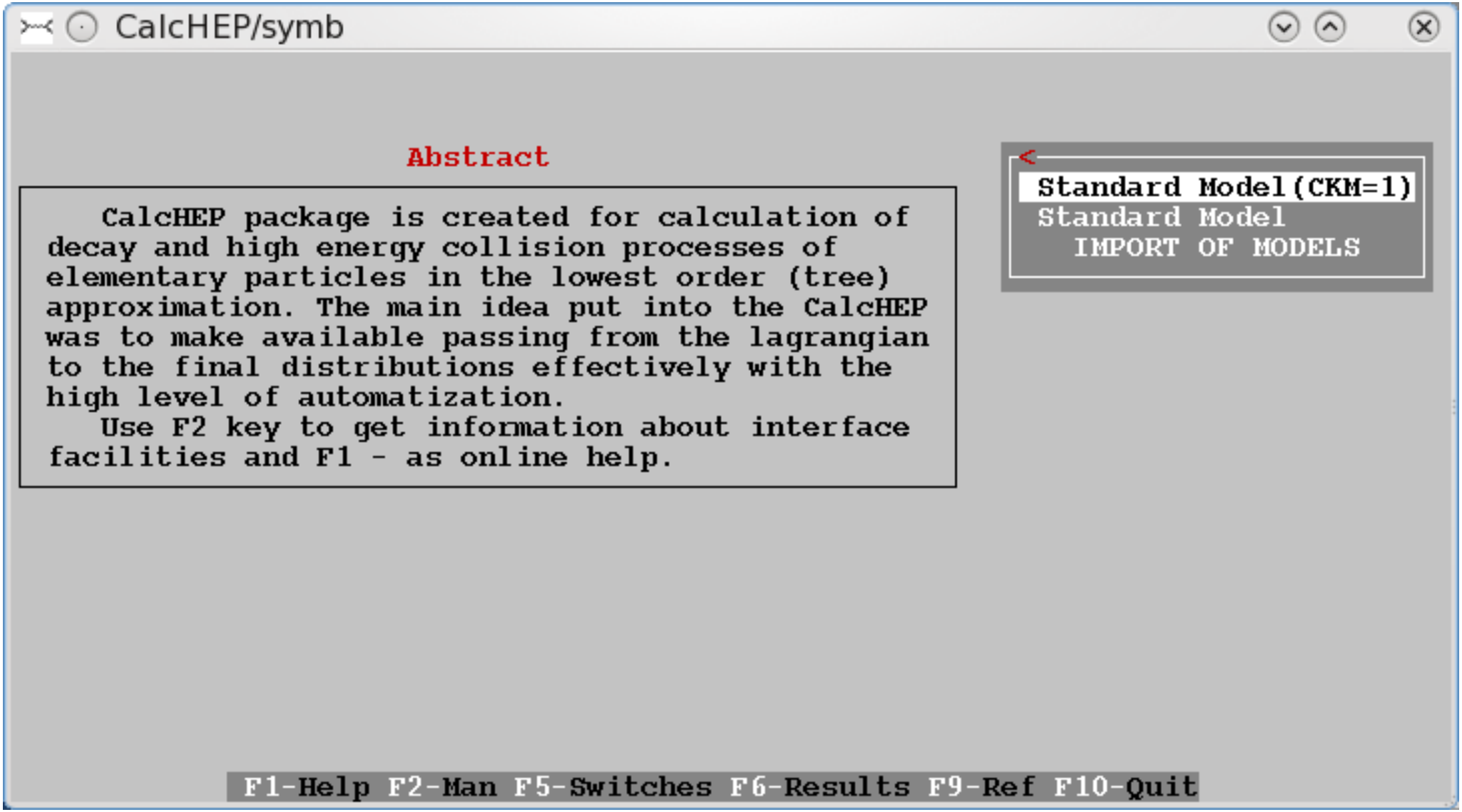
- **Files:**

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

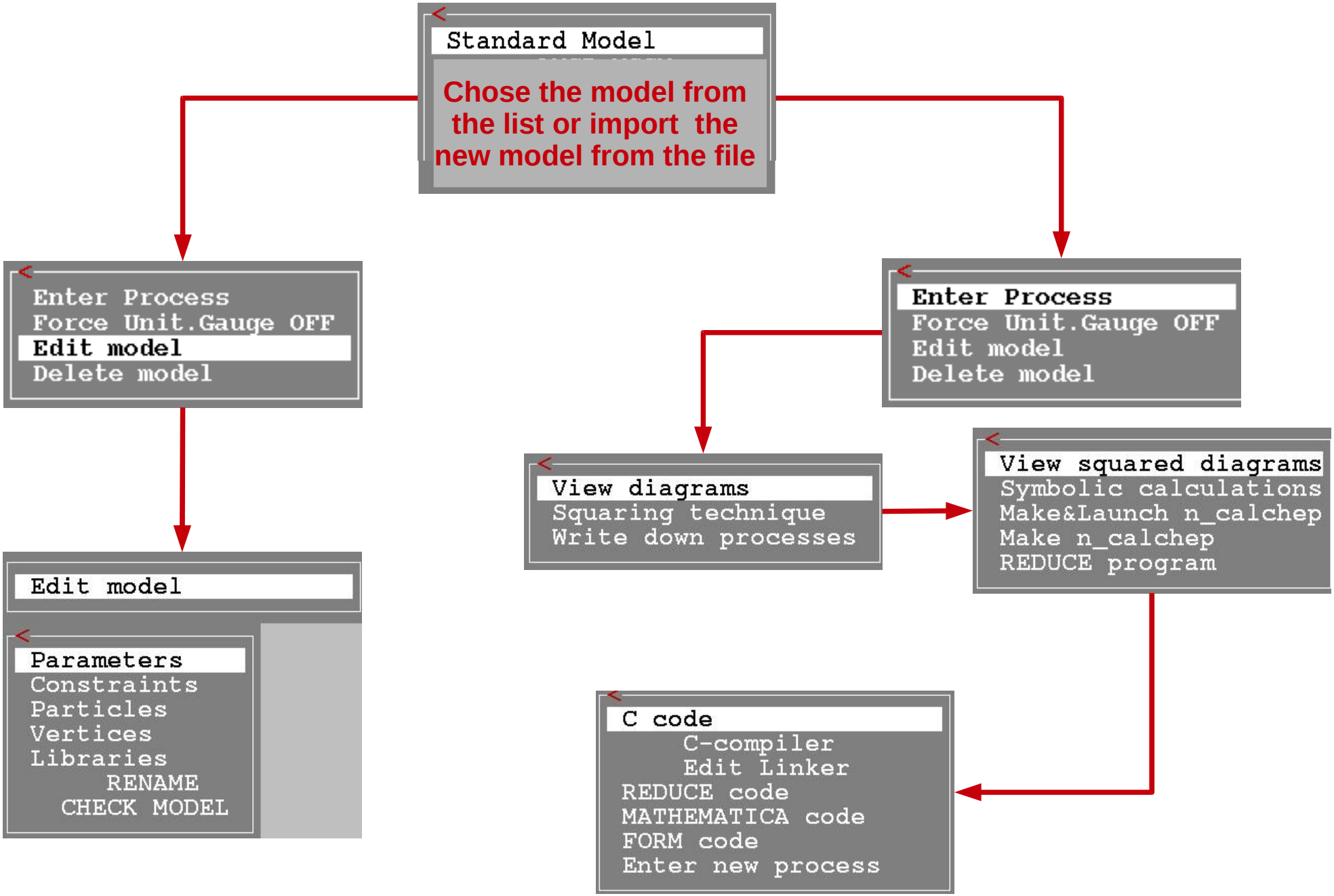
- **Start:**

**./calchep**

# Starting CalcHEP



# CalcHEP menu structure: symbolic part



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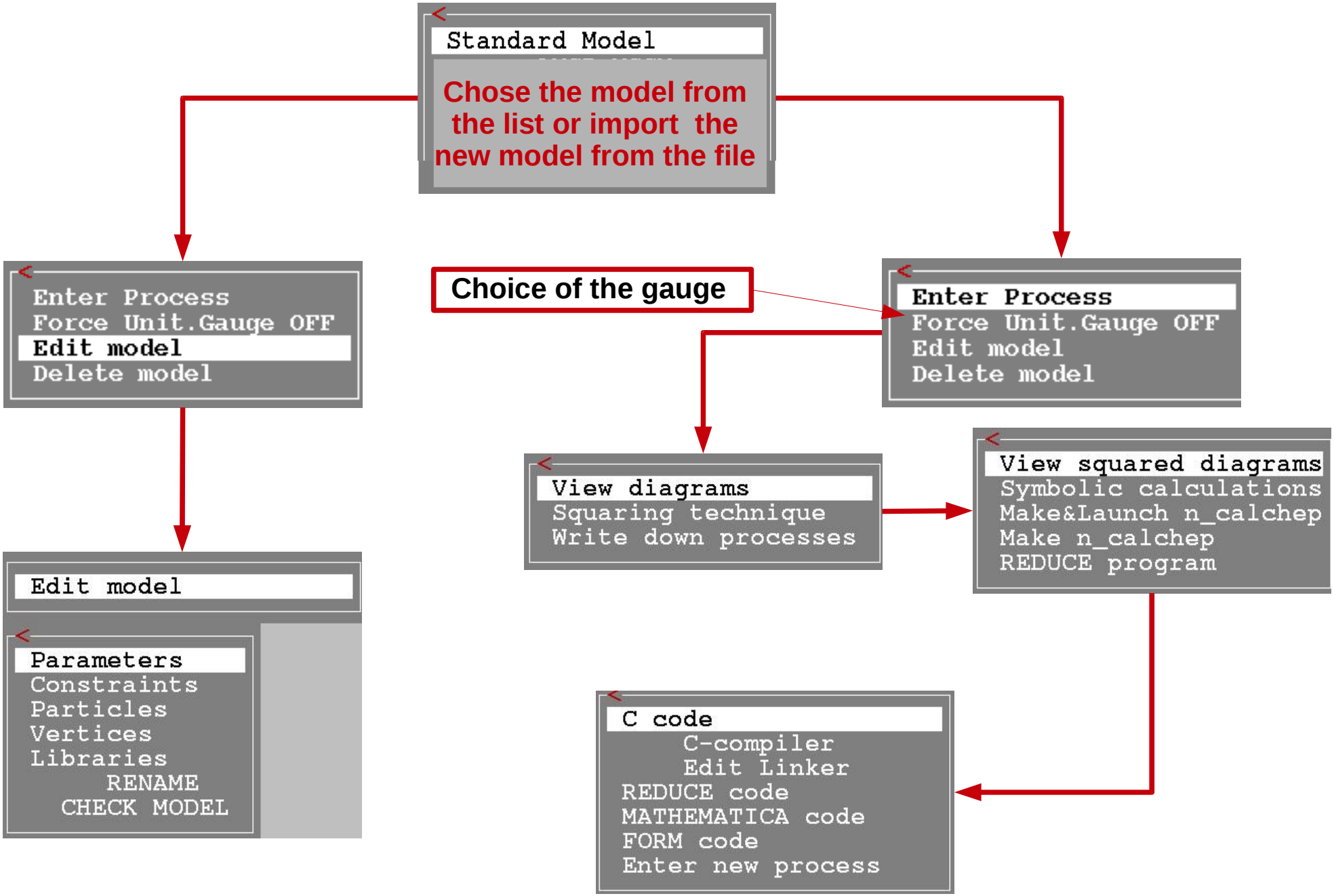
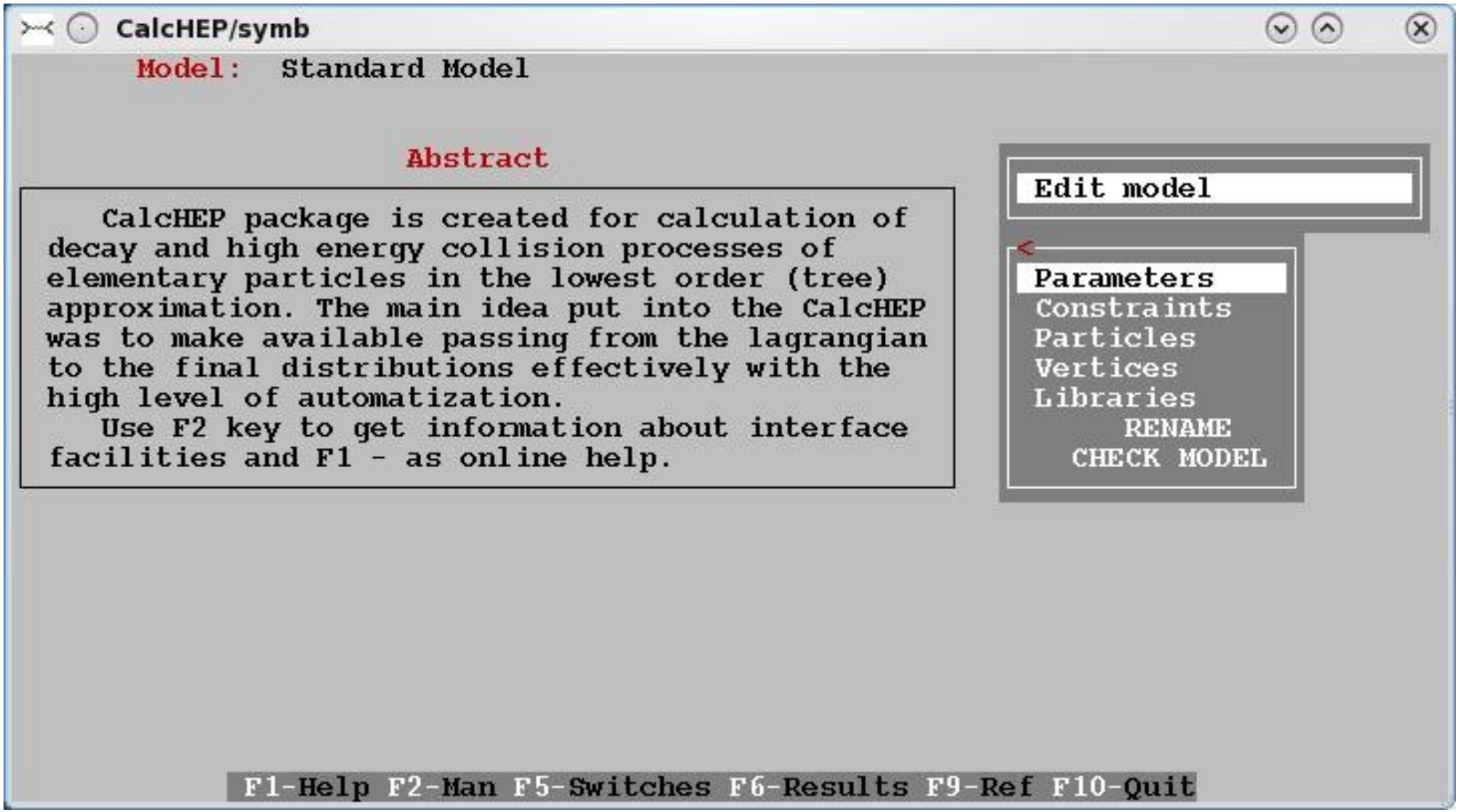


# Model Structure

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



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

CalcHEP/symb

Particles

Clr Del Size Read ErrMes

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

F1 F2 Xgoto Ygoto Find Write

# Particles: prtcl*xx*.mdl

CalcHEP/symb

Particles

Clr–Del–Size–Read–ErrMes

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

F1–F2–Xgoto–Ygoto–Find–Write

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

# Independent parameters: varsxx.mdl

CalcHEP/symb

Parameters 1

Clr Del Size Read ErrMes

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

F1 F2 Xgoto Ygoto Find Write

# Dependent parameters(constraints): funcxx.mdl

CalcHEP/symb

Constraints

Clr Del Size Read ErrMes

| Name | \|> Expression | |
|---|---|---|
| EE | \|sqrt(16*atan(1.)*alfEMZ) | % electromagnetic constant |
| CW | \|sqrt(1-SW^ 2) | % cos of the Weinberg angle |
| MW | \|MZ*CW | % W-boson mass |
| c12 | \|sqrt(1-s12^ 2) | % parameter of C-K-M matrix |
| c23 | \|sqrt(1-s23^ 2) | % parameter of C-K-M matrix |
| c13 | \|sqrt(1-s13^ 2) | % parameter of C-K-M matrix |
| Vud | \|c12*c13 | % C-K-M matrix element |
| Vus | \|s12*c13 | % C-K-M matrix element |
| Vub | \|s13 | % C-K-M matrix element |
| Vcd | \|-s12*c23-c12*s23*s13 | % C-K-M matrix element |
| Vcs | \|c12*c23-s12*s23*s13 | % C-K-M matrix element |
| Vcb | \|s23*c13 | % C-K-M matrix element |
| Vtd | \|s12*s23-c12*c23*s13 | % C-K-M matrix element |
| Vts | \|-c12*s23-s12*c23*s13 | % C-K-M matrix element |
| Vtb | \|c23*c13 | % C-K-M matrix element |
| qcdOk | \|initQCD(alfSMZ,McMc,MbMb,Mtp) | |
| Mb | \|MbEff(Q)*one(qcdOk) | |
| Mt | \|MtEff(Q)*one(qcdOk) | |
| Mc | \|McEff(Q)*one(qcdOk) | |

F1 F2 Xgoto Ygoto Find Write

# Dependent parameters(constraints): funcxx.mdl

- **MSSM case**

CalcHEP/symb

Constraints

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

# Feynman rules: lgrng*xx*.mdl

CalcHEP/symb

Vertices

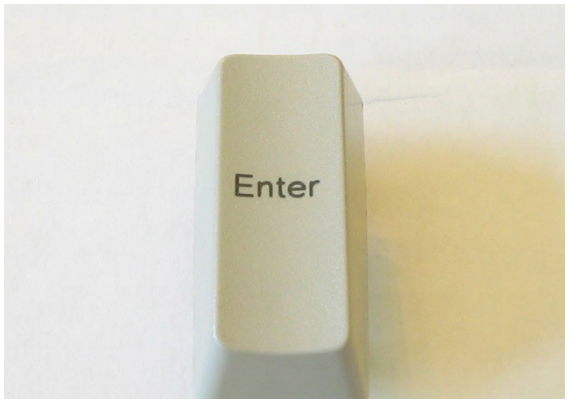
| A1 | A2 | A3 | A4 | Factor | Lorentz part |
|---|---|---|---|---|---|
| h | W+ | W- | | EE*MW/SW | m2.m3 |
| h | Z | Z | | EE/(SW*CW^ 2)*MW | m2.m3 |
| h | h | h | | -(3/2)*EE*Mh^ 2/(MW*SW) | 1 |
| h | h | h | h | (-3/4)*(EE*Mh/(MW*SW))^ 2 | 1 |
| h | h | Z | Z | (1/2)*(EE/(SW*CW))^ 2 | m3.m4 |
| h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

F1 F2 Xgoto Ygoto Find Write

# Models created/available for CalcHEP

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

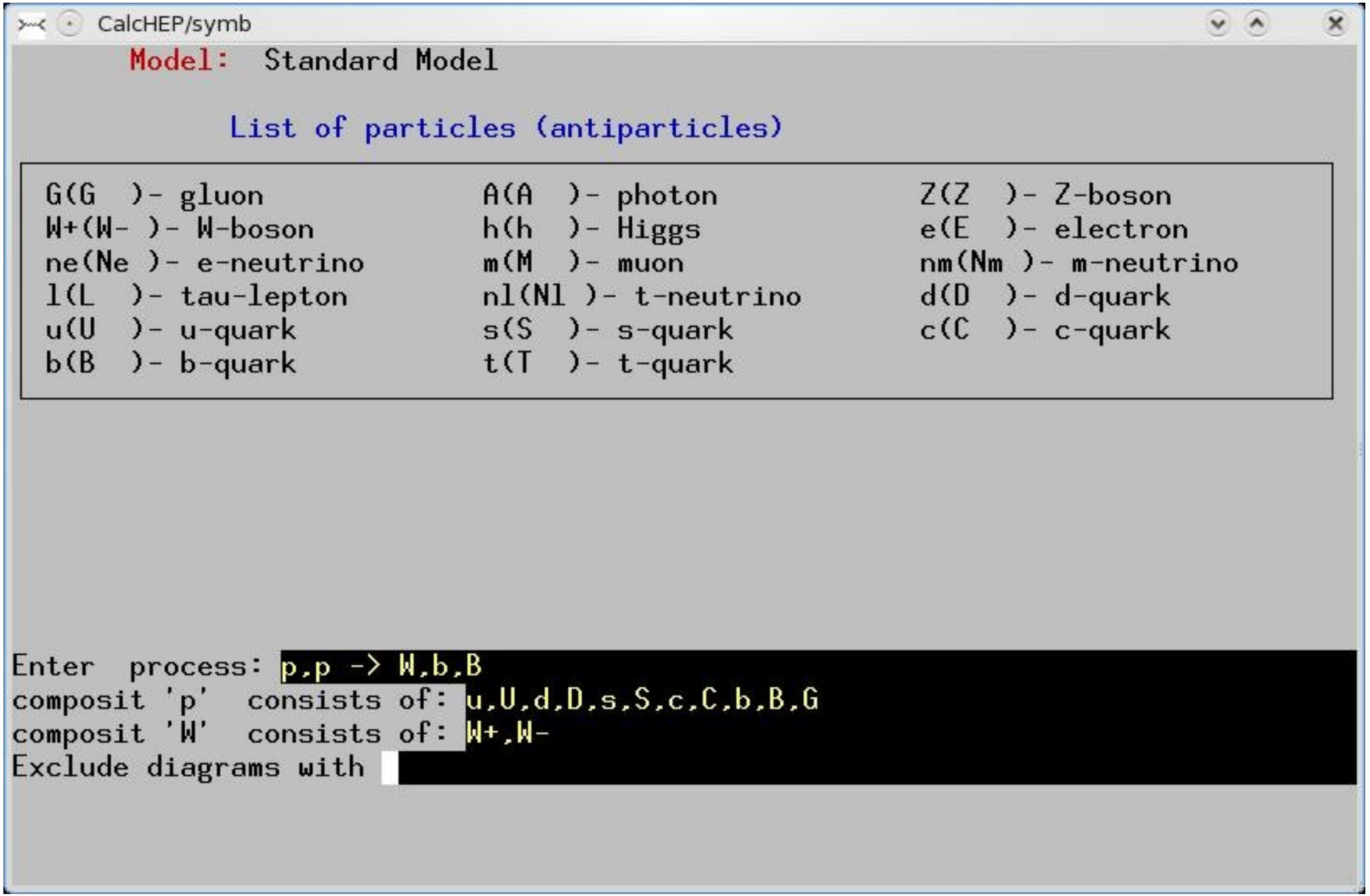
# Principle KEYS for CalcHEP's GUI

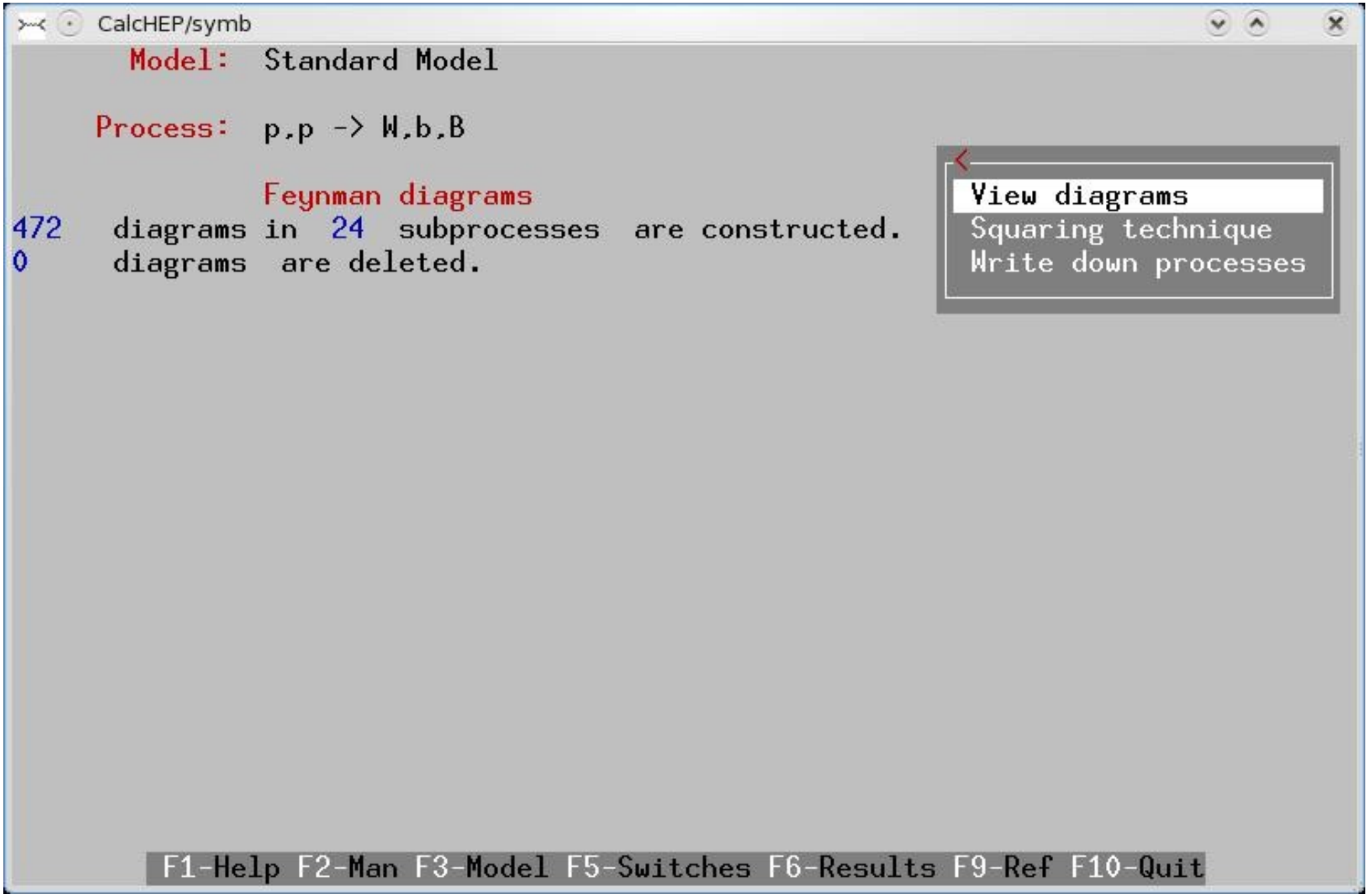


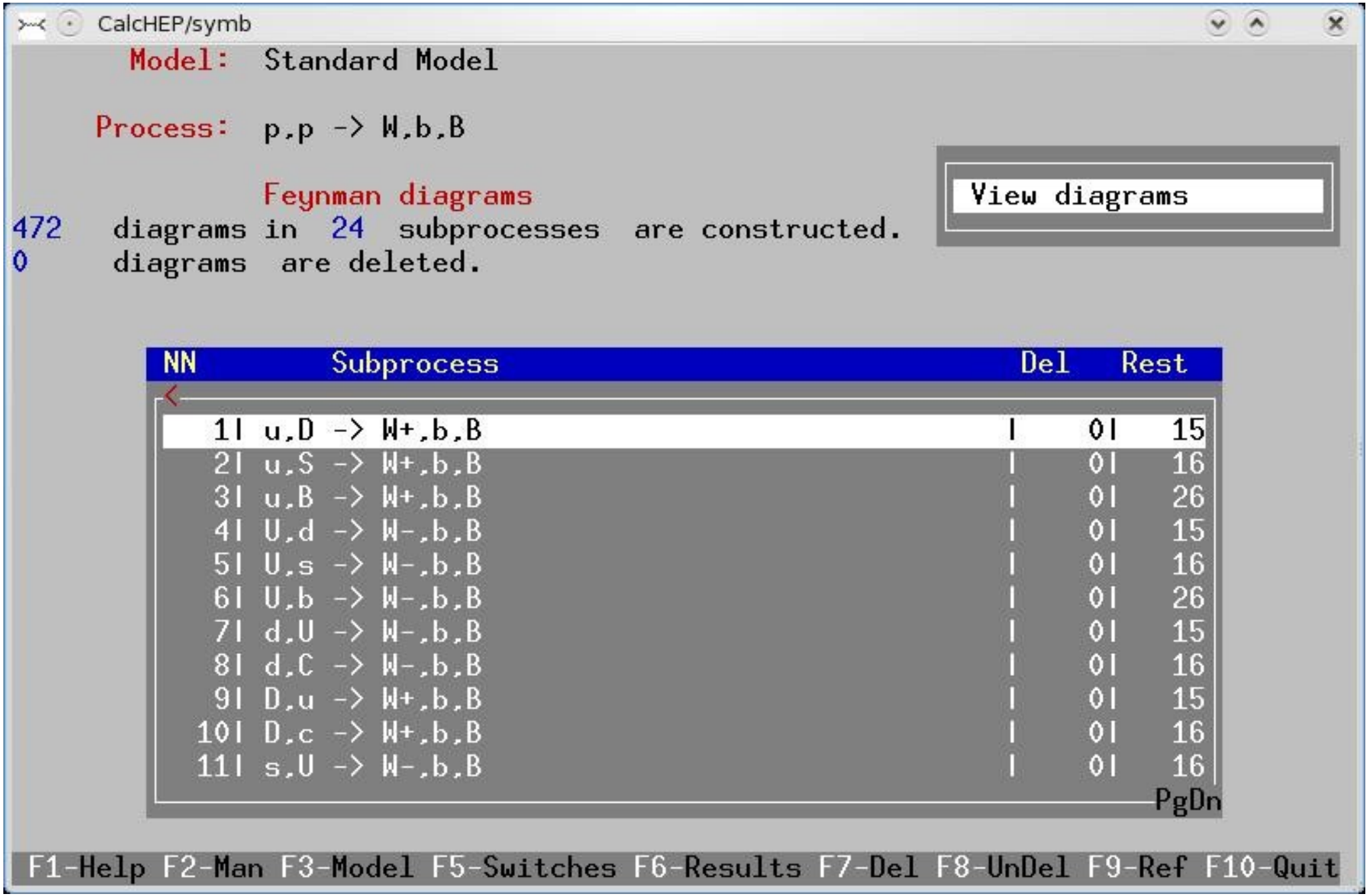

**Enter menu selection (forward)**

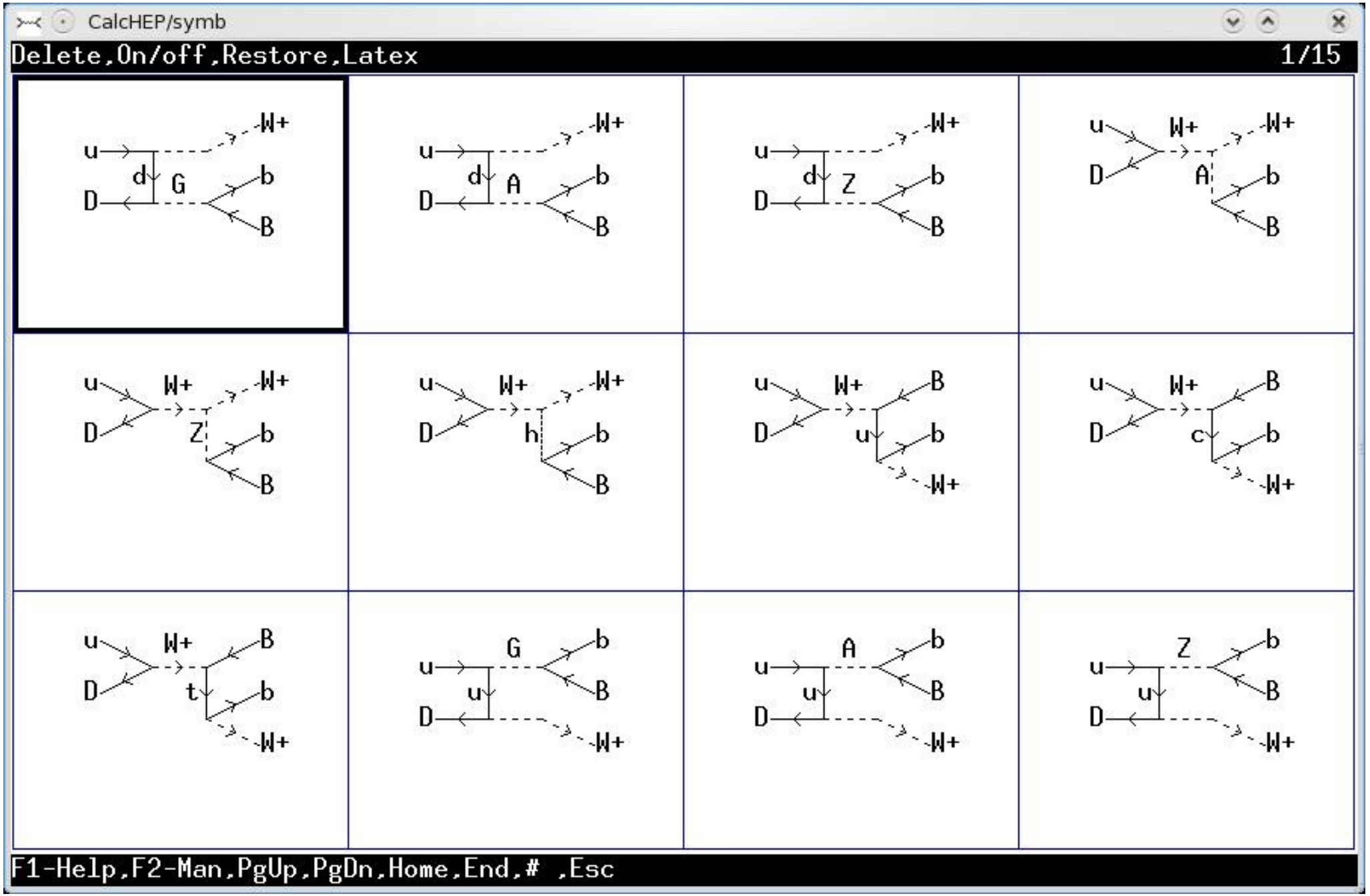

**Exit menu selection (back)**

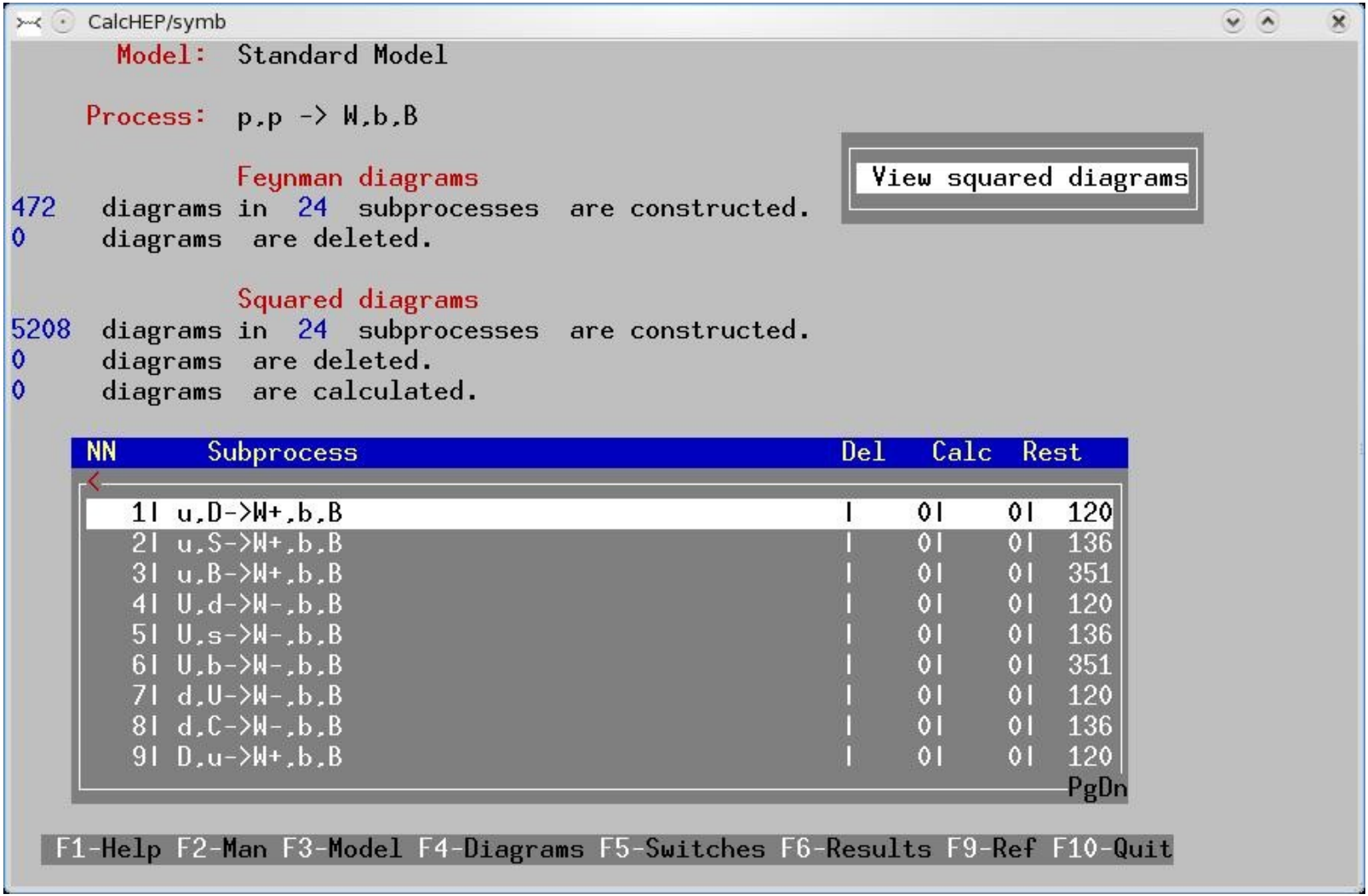

**Help! (details on the menu choice)**

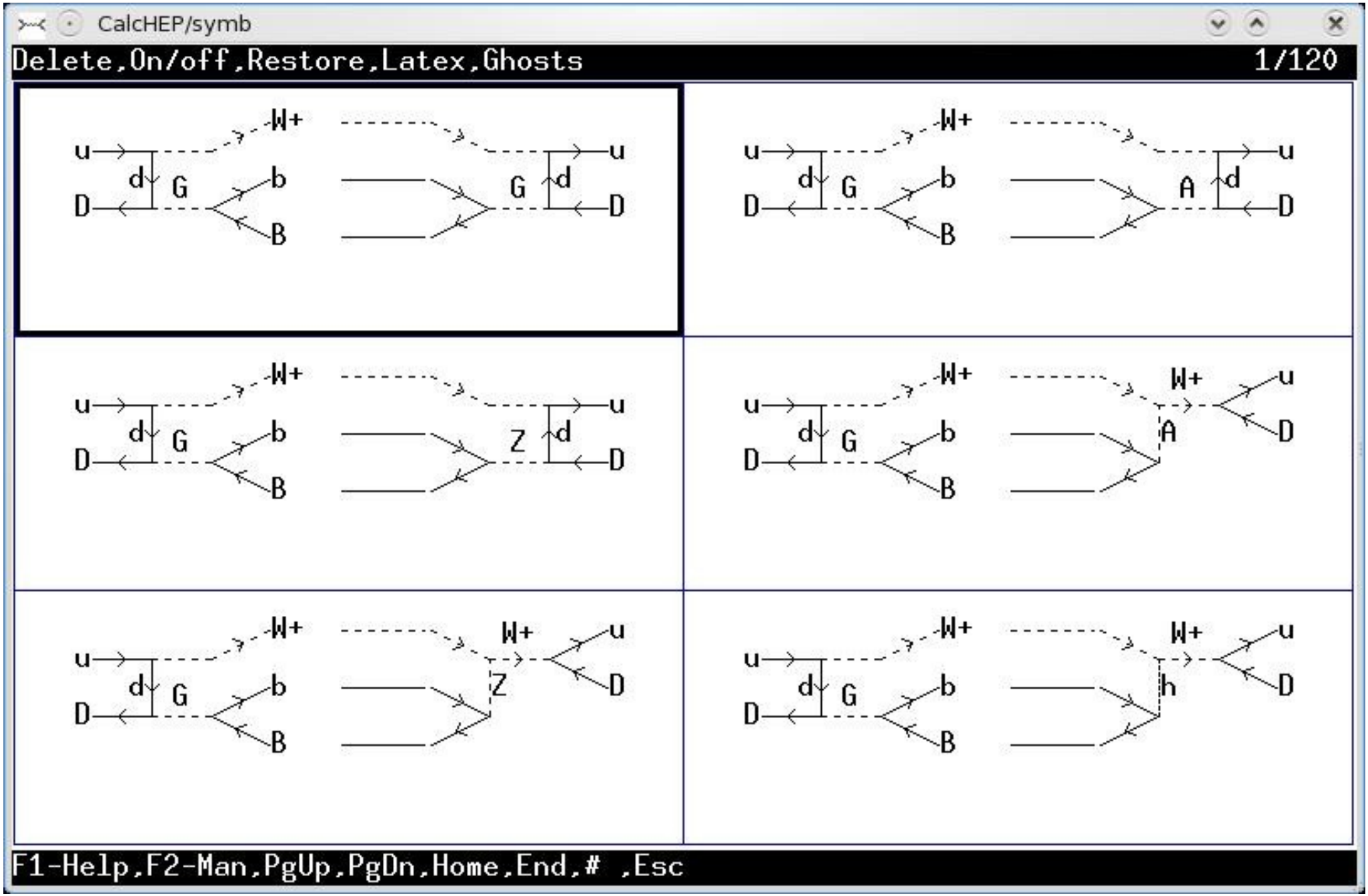

CalcHEP/symb
Model: Standard Model
List of particles (antiparticles)
G(G )- gluon
A(A )- photon
Z(Z )- Z-boson
W+(W- )- W-boson
h(h )- Higgs
e(E )- electron
ne(Ne )- e-neutrino
m(M )- muon
nm(Nm )- m-neutrino
l(L )- tau-lepton
nl(Nl )- t-neutrino
d(D )- d-quark
u(U )- u-quark
s(S )- s-quark
c(C )- c-quark
b(B )- b-quark
t(T )- t-quark
Enter process: p,p -> W,b,B
composit 'p' consists of: u,U,d,D,s,S,c,C,b,B,G
composit 'W' consists of: W+,W-
Exclude diagrams with

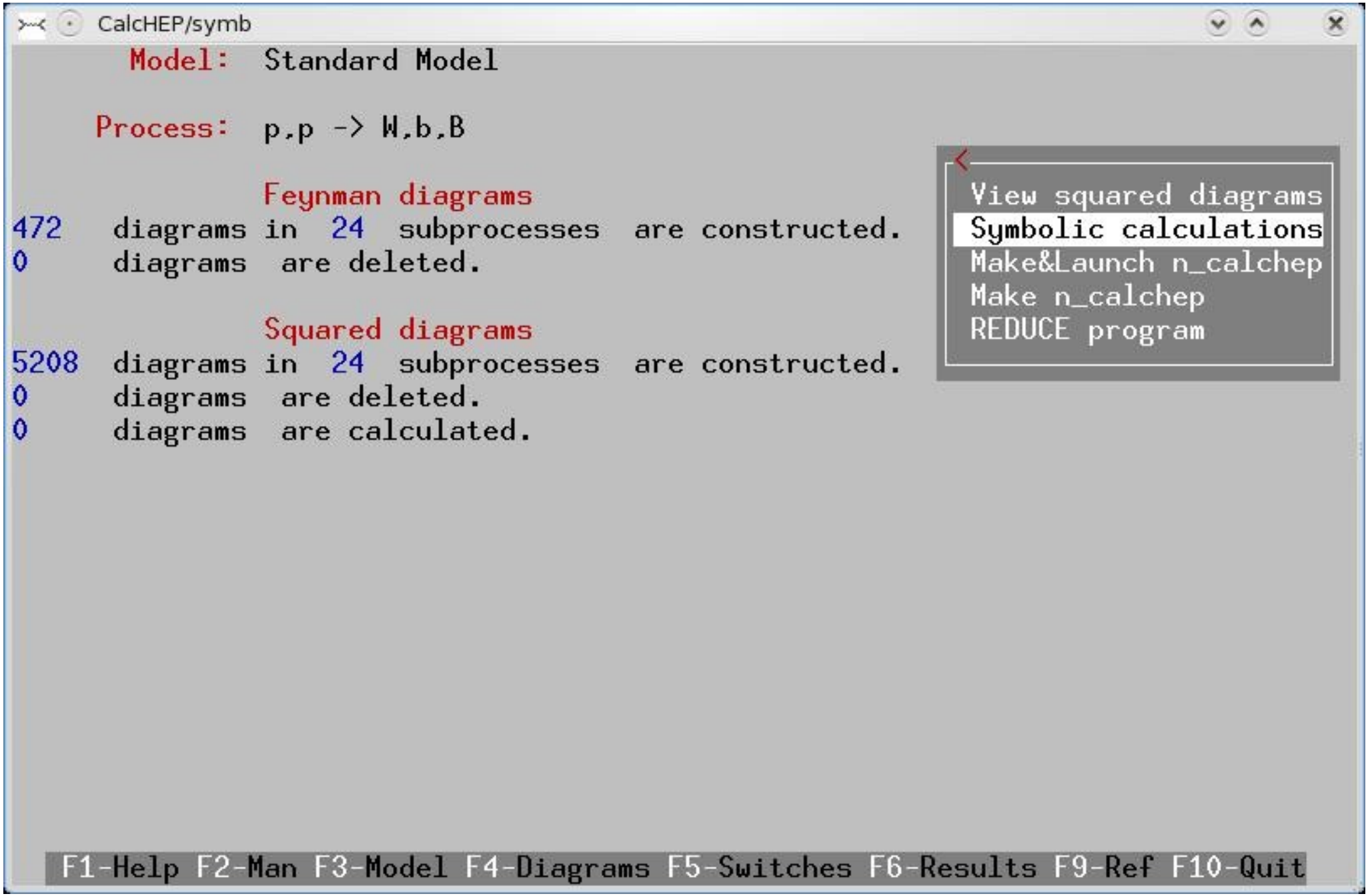

CalcHEP/symb
Model: Standard Model
Process: p,p -> W,b,B
Feynman diagrams
472 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.
View diagrams
Squaring technique
Write down processes
F1-Help F2-Man F3-Model F5-Switches F6-Results F9-Ref F10-Quit

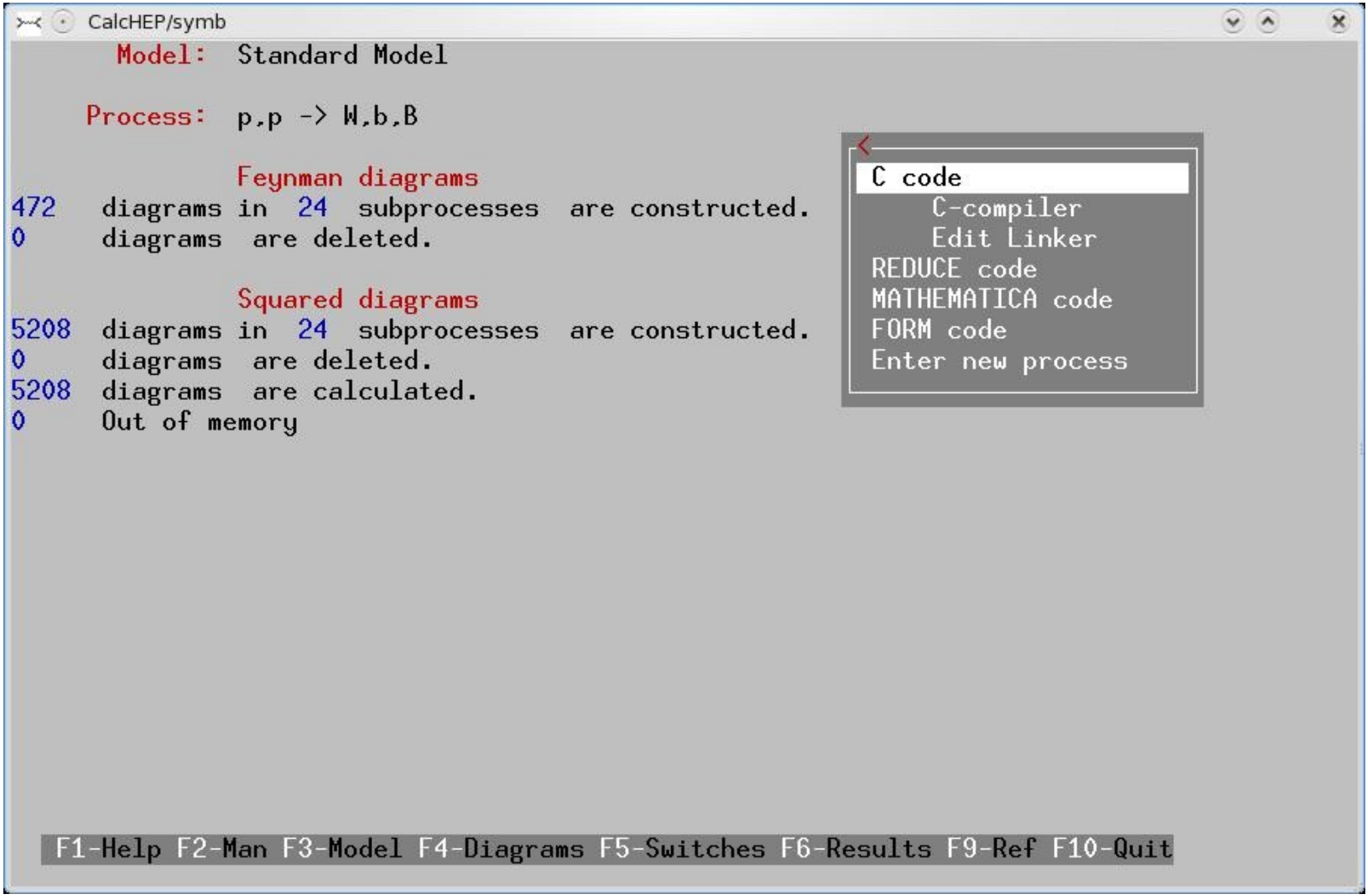

CalcHEP/symb
Model: Standard Model
Process: p,p -> W,b,B
Feynman diagrams
472 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.
View diagrams
NN Subprocess Del Rest
1| u,D -> W+,b,B | 0| 15
2| u,S -> W+,b,B | 0| 16
3| u,B -> W+,b,B | 0| 26
4| U,d -> W-,b,B | 0| 15
5| U,s -> W-,b,B | 0| 16
6| U,b -> W-,b,B | 0| 26
7| d,U -> W-,b,B | 0| 15
8| d,C -> W-,b,B | 0| 16
9| D,u -> W+,b,B | 0| 15
10| D,c -> W+,b,B | 0| 16
11| s,U -> W-,b,B | 0| 16
PgDn
F1-Help F2-Man F3-Model F5-Switches F6-Results F7-Del F8-UnDel F9-Ref F10-Quit

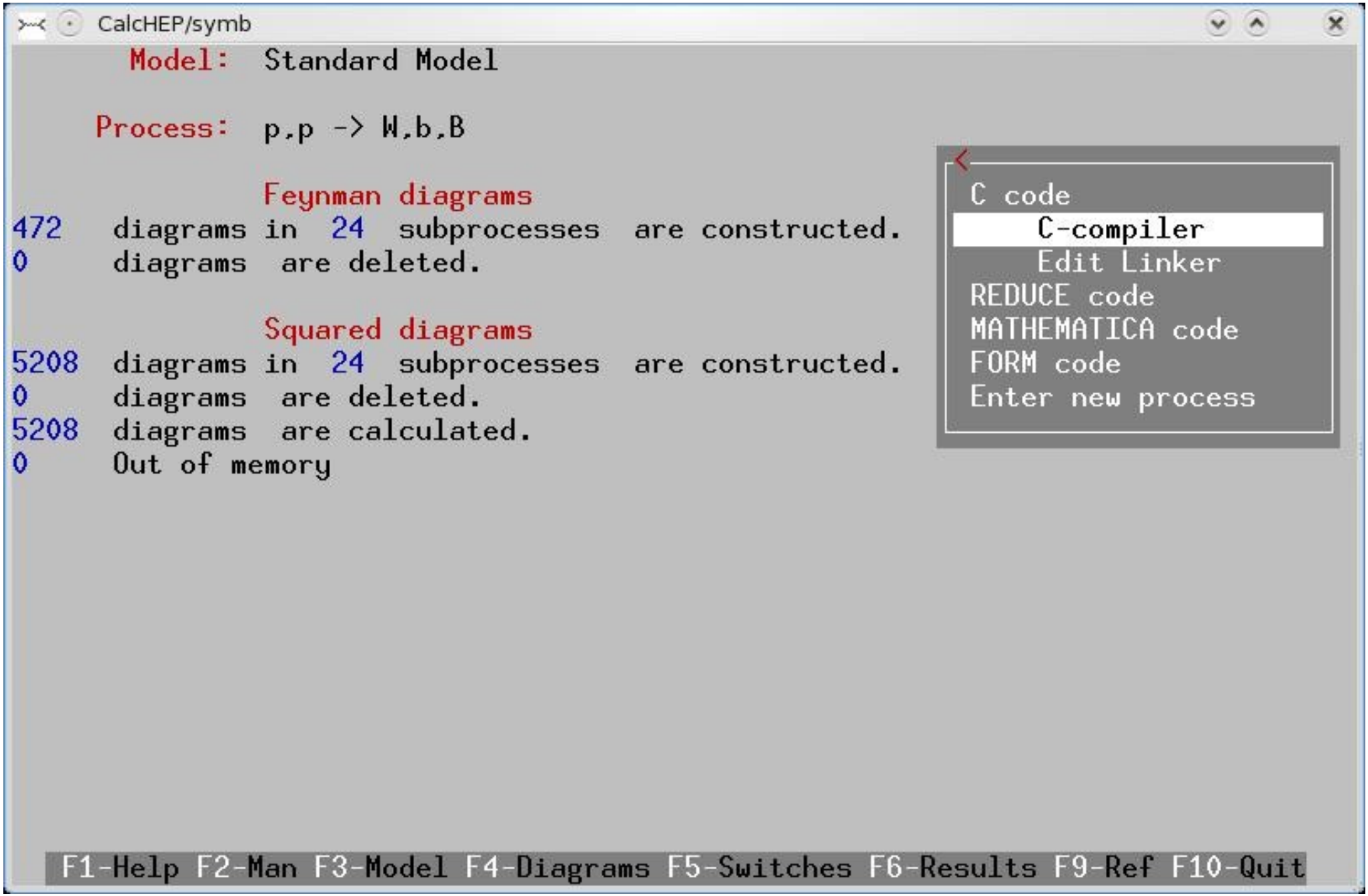

CalcHEP/symb
Delete,On/off,Restore,Latex
1/15
u
D
d
G
W+
b
B
u
D
d
A
W+
b
B
u
D
d
Z
W+
b
B
u
D
W+
A
W+
b
B
u
D
W+
Z
W+
b
B
u
D
W+
h
W+
b
B
u
D
W+
u
B
b
W+
u
D
W+
c
B
b
W+
u
D
W+
t
B
b
W+
u
D
G
u
b
B
W+
u
D
A
u
b
B
W+
u
D
Z
u
b
B
W+
F1-Help,F2-Man,PgUp,PgDn,Home,End,# ,Esc

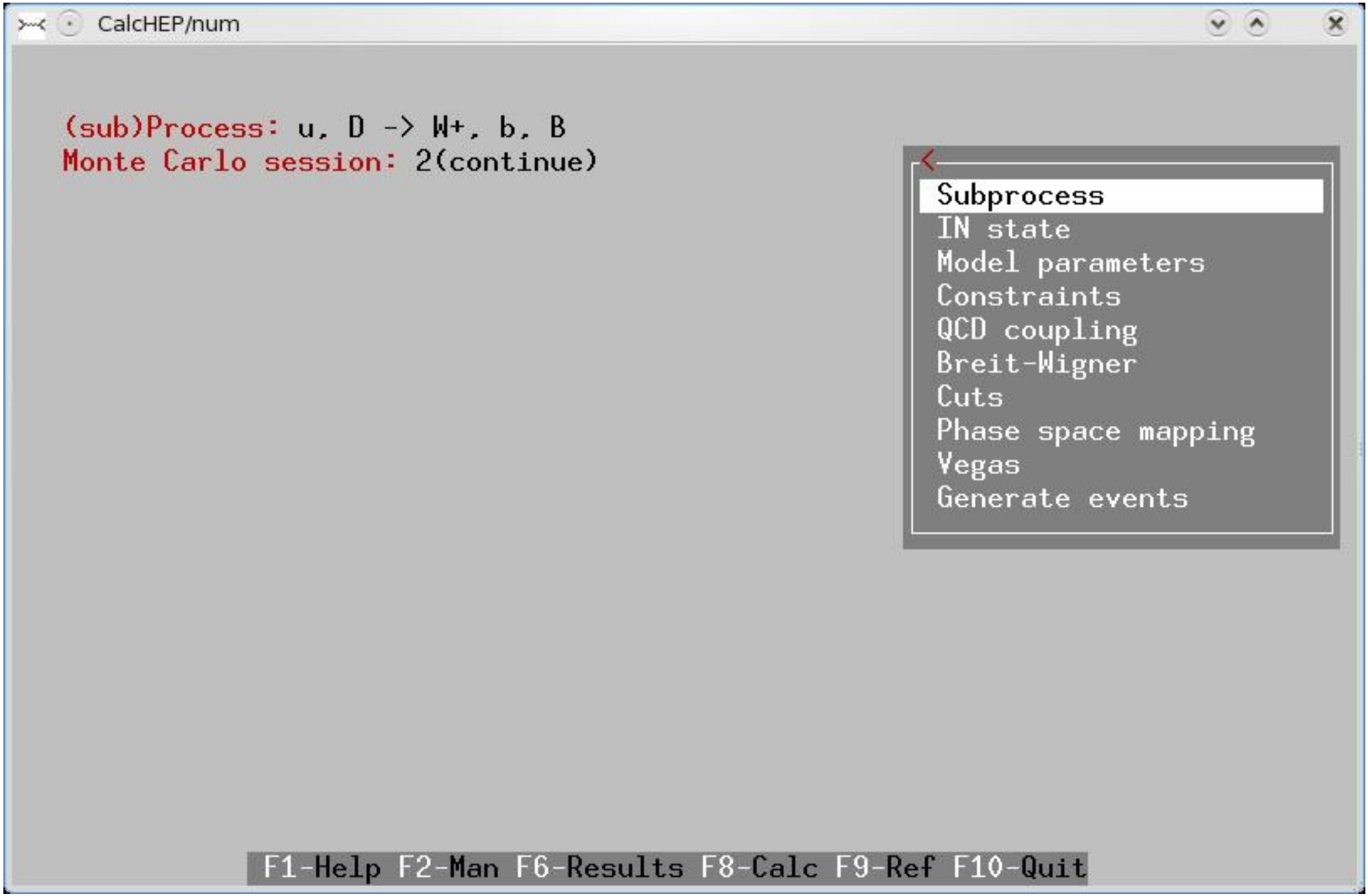

CalcHEP/symb
Model: Standard Model
Process: p,p -> W,b,B
Feynman diagrams
472 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.
View squared diagrams
Squared diagrams
5208 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.
0 diagrams are calculated.
NN Subprocess Del Calc Rest
1| u,D->W+,b,B | 0| 0| 120
2| u,S->W+,b,B | 0| 0| 136
3| u,B->W+,b,B | 0| 0| 351
4| U,d->W-,b,B | 0| 0| 120
5| U,s->W-,b,B | 0| 0| 136
6| U,b->W-,b,B | 0| 0| 351
7| d,U->W-,b,B | 0| 0| 120
8| d,C->W-,b,B | 0| 0| 136
9| D,u->W+,b,B | 0| 0| 120
PgDn
F1-Help F2-Man F3-Model F4-Diagrams F5-Switches F6-Results F9-Ref F10-Quit


CalcHEP/symb
Delete,On/off,Restore,Latex,Ghosts
1/120
u
D
d
G
W+
b
B
u
G
d
D
u
D
d
G
W+
b
B
u
A
d
D
u
D
d
G
W+
b
B
u
Z
d
D
u
D
d
G
W+
b
B
W+
A
u
D
u
D
d
G
W+
b
B
W+
Z
u
D
u
D
d
G
W+
b
B
W+
h
u
D
F1-Help,F2-Man,PgUp,PgDn,Home,End,# ,Esc

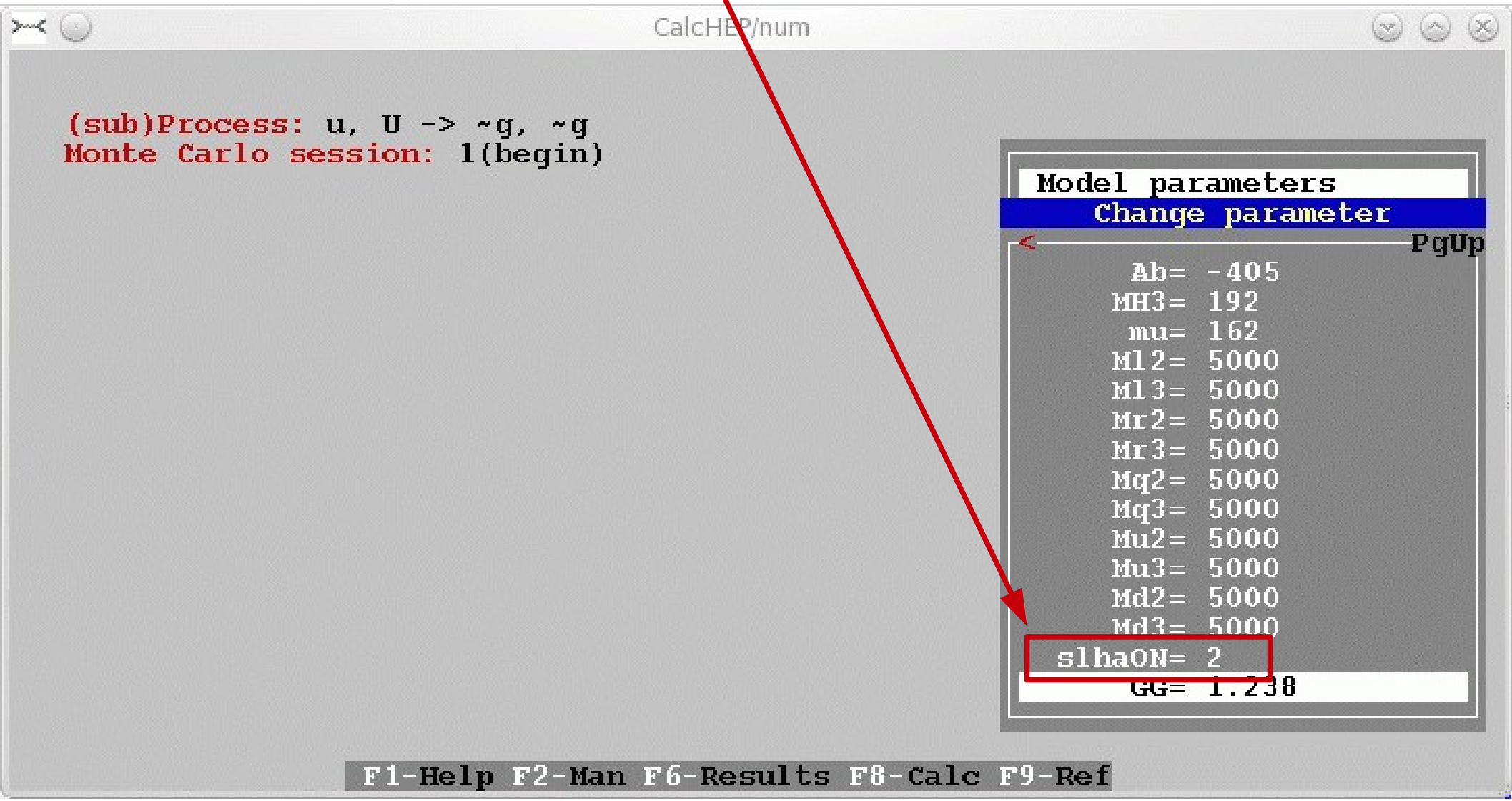

CalcHEP/symb
Model: Standard Model
Process: p,p -> W,b,B
Feynman diagrams
472 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.
Squared diagrams
5208 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.
0 diagrams are calculated.
View squared diagrams
Symbolic calculations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


CalcHEP/symb
Model: Standard Model
Process: p,p -> W,b,B
Feynman diagrams
472 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.
Squared diagrams
5208 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.
5208 diagrams are calculated.
0 Out of memory
C code
C-compiler
Edit Linker
REDUCE code
MATHEMATICA code
FORM code
Enter new process
F1-Help F2-Man F3-Model F4-Diagrams F5-Switches F6-Results F9-Ref F10-Quit


CalcHEP/symb
Model: Standard Model
Process: p,p -> W,b,B
Feynman diagrams
472 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.
Squared diagrams
5208 diagrams in 24 subprocesses are constructed.
0 diagrams are deleted.
5208 diagrams are calculated.
0 Out of memory
C code
C-compiler
Edit Linker
REDUCE code
MATHEMATICA code
FORM code
Enter new process
F1-Help F2-Man F3-Model F4-Diagrams F5-Switches F6-Results F9-Ref F10-Quit


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

# Option to read-write LHA file (MSSM case)



# Total cross section and distributions

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

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

Distributions

| Clr | Del | Size | Read | ErrMes |
|---|---|---|---|---|

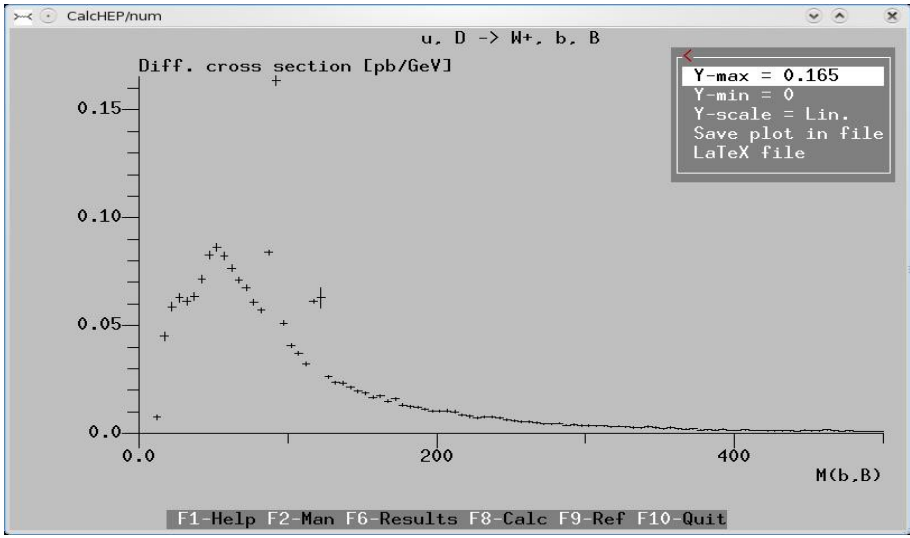
| Parameter_1 | <I> Min_1 | <I> Max_1 | <\|Parameter_2\|> Min_2 | <I> Max_2 |
|---|---|---|---|---|
| T(b) | 0 | 200 | | |
| T(B) | 0 | 200 | | |
| N(b) | -5 | 5 | | |
| N(B) | -5 | 5 | | |
| M(b,B) | 0 | 1500 | | |
| M(W+,b) | 0 | 1500 | | |
| T(b) | 0 | 1500 | M(b,B) | 0 1500 |

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

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

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

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



# Accessing your results

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

# protocol prt_*nn*

```
    CalcHEP kinematics module
 The session parameters:

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

#Physical_Parameters
    alfEMZ = 7.8180609999999E-03
    alfSMZ = 1.1720000000000E-01
.........................................
.........................................
#Cuts
*** Table ***
 Cuts
  Parameter  |> Min bound <|> Max bound <|
T(b)         |20           |
T(B)         |20           |
.........................................
.........................................
#Regularization
*** Table ***
 Regularization
 Momentum    |> Mass  <|> Width <| Power|
45           |MZ       |wZ       |2
45           |Mh       |wh       |2
.........................................
.........................................
#END
=====================================
 #IT   Cross section [pb]  Error %    nCall   chi**2
  1      2.0373E+00       3.30E+01    20000
  2      8.6164E+00       2.86E+01    20000
.........................................
.........................................
```

# Few words about LanHEP package

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

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

***The program for Feynman rules generation in momentum space***

**QCD as an example**

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

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

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

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

# Few words about LanHEP package

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

***This is the program for Feynman rules generation in momentum space***

**QCD as an example**

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

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

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

QCD Feynman rules generated by LanHEP in LaTeX format

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

# Features of LanHEP

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

# LanHEP installation

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

**tar -zxvf  lhep*xxx*.tar.gz**

**cd lhep*xxx***

**make**

**make clean**

# Running LanHEP

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

*File sm_tex processed, 0 sec.*

*File stand.mdl processed, 1 sec.*

# Future plans

➧ *Effective FR derivation for ExD models*

*recent e-mail from Andrei!*

```
model uedqwd/3.

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

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

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

spinor e:(electron, mass me=2000.511),
       e11:(electron1, mass me1=1000.0511),
       e1r:(electron1, mass me1=1000.0511), ....

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

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

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

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

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

CheckHerm.
CheckMasses.
```

# CalcHEP batch interface: results from CalcHEP in one shot!

- calchep_batch batch_file

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

## Main Features

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

batch_file

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

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

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

# CalcHEP batch interface: results from CalcHEP in one shot!

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

Home
Symbolic Results
Numerical Results
Events Library
Process Library
Help

Thank you for using CalcHEP!
Please cite arXiv:0000.0000

## CalcHEP Batch Details

### Standard Model(CKM=1)

**Done!**

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

# CalcHEP batch interface: results from CalcHEP in one shot!

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## Symbolic Sessions

### Standard Model(CKM=1)

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

# CalcHEP batch interface: results from CalcHEP in one shot!

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

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Thank you for using CalcHEP!
Please cite arXiv:0000.0000

## Numerical Sessions

### Standard Model(CKM=1)

**Done!**

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

# CalcHEP batch interface: results from CalcHEP in one shot!

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

**Standard Model(CKM=1)**

**Done!**

Home
Symbolic Results
Numerical Results
Events Library
Process Library
Help

Thank you for using CalcHEP!
Please cite arXiv:0000.0000

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

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

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

# CalcHEP batch interface: results from CalcHEP in one shot!

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

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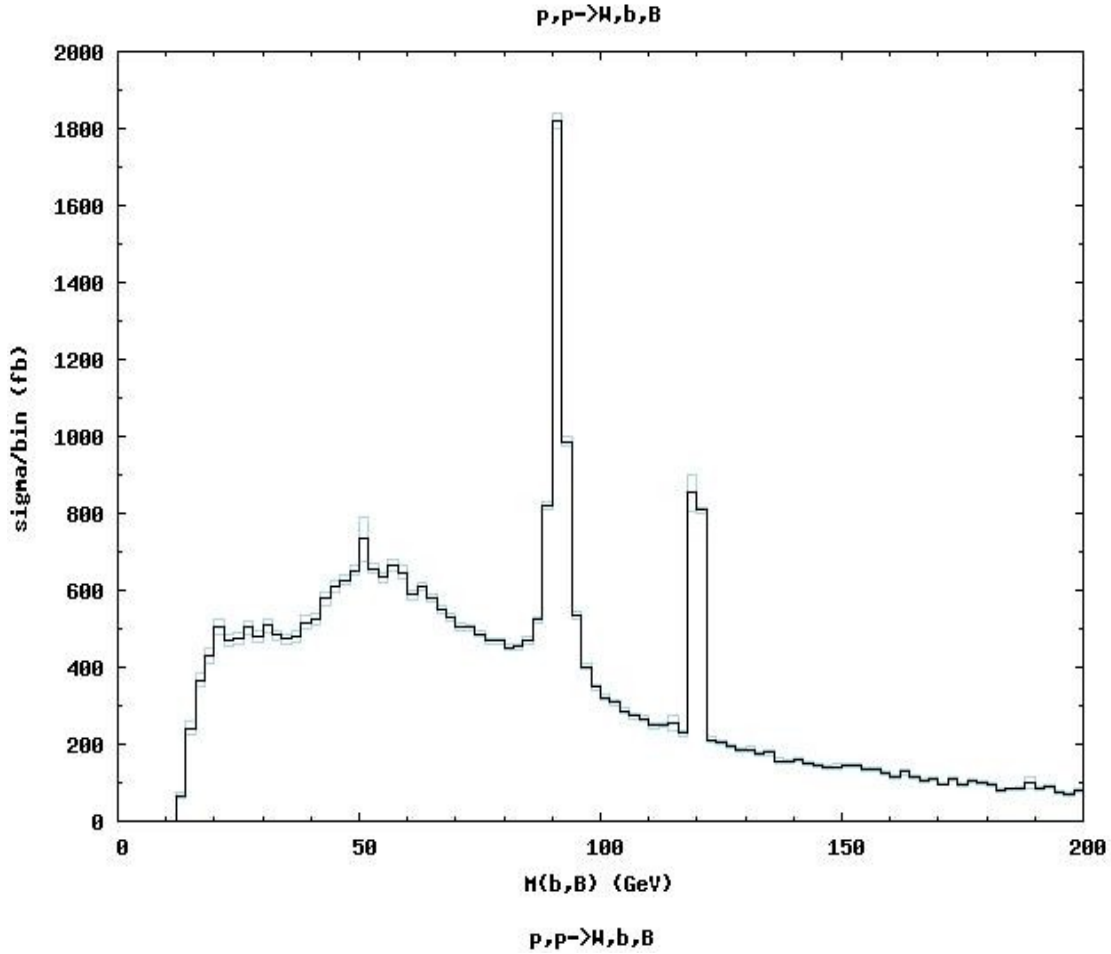
Please cite arXiv:0000.0000

**Distributions**



# CalcHEP batch interface: results from CalcHEP in one shot!

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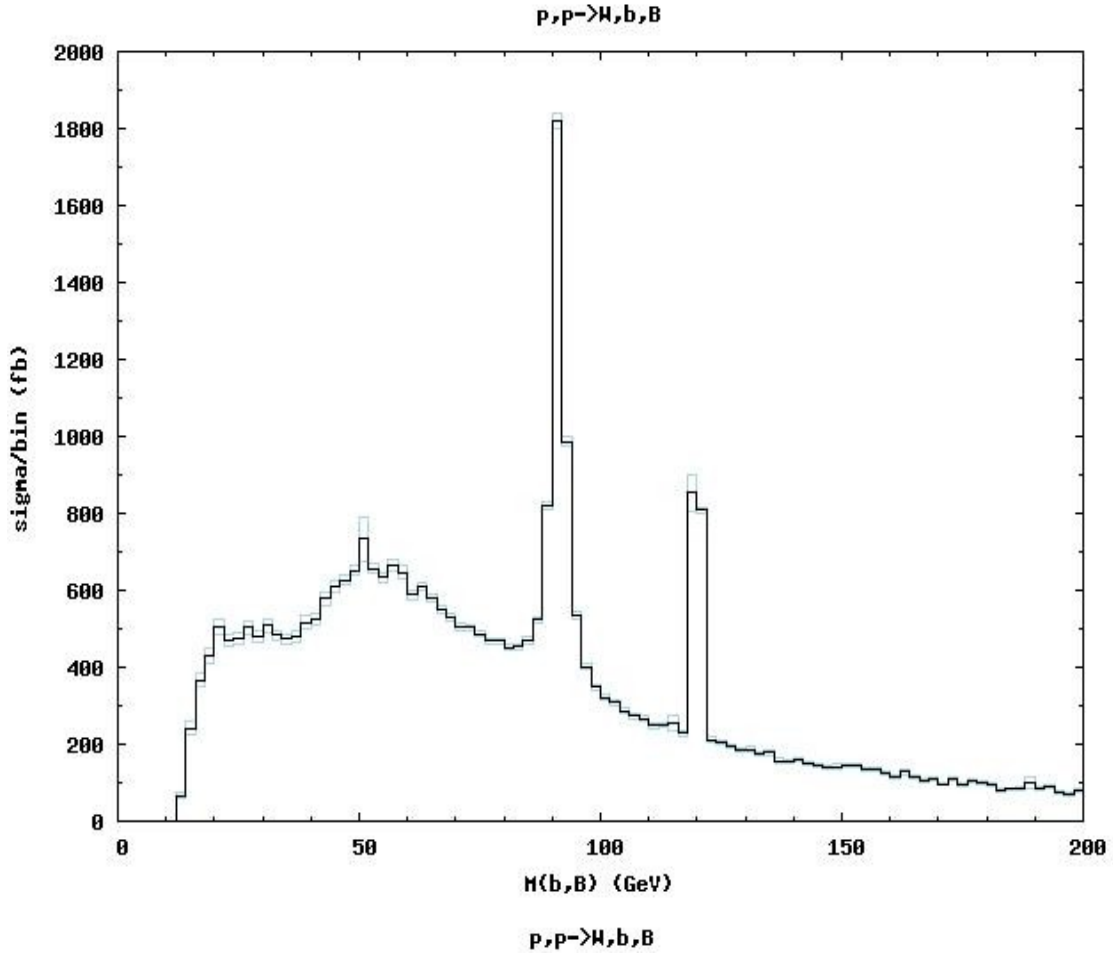
**Distributions**



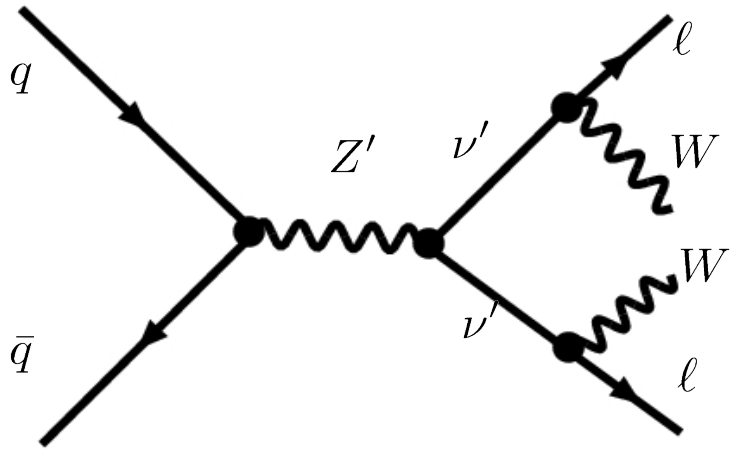

**The new version of CalcHEP (dev version) implements all properties of batch interface**

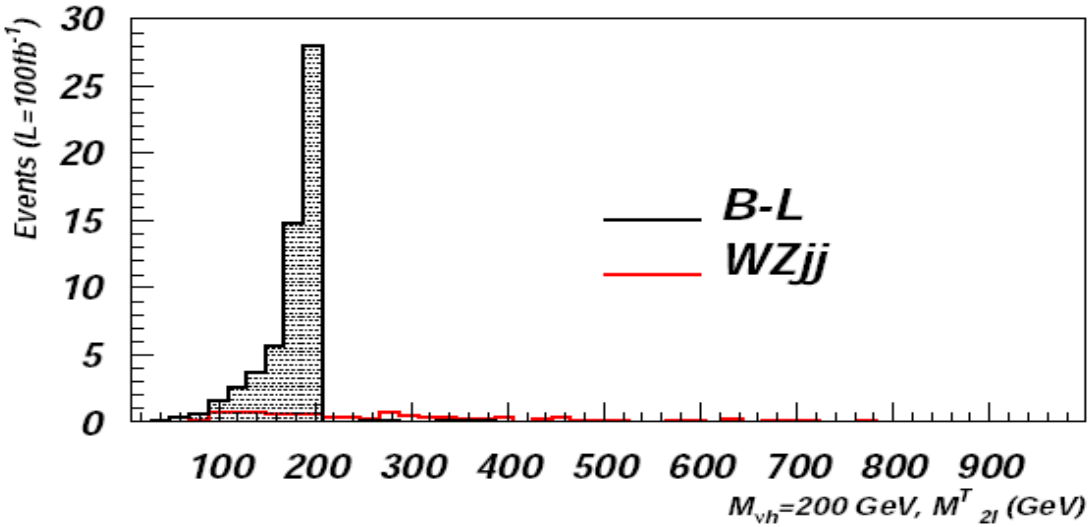
# Recent applications: B-L extension of SM

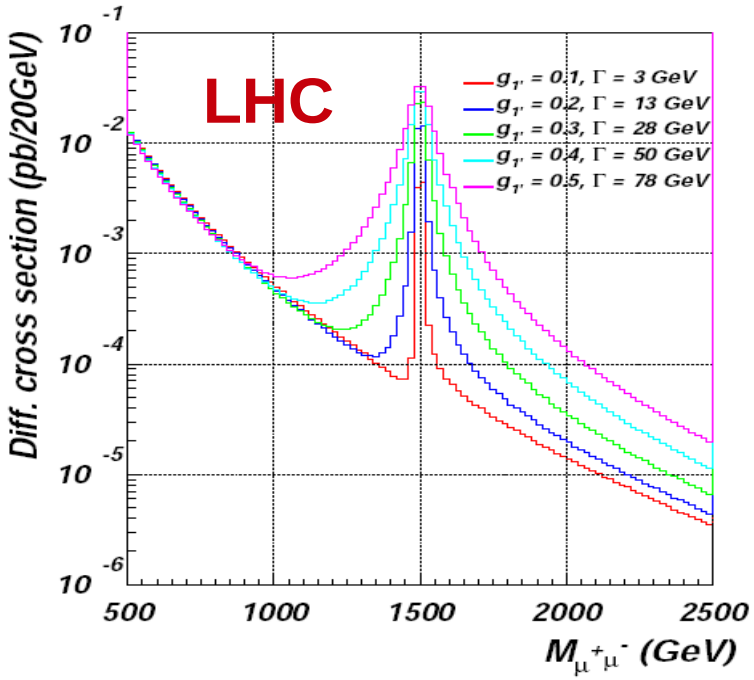
## Extra U(1)' : Z', heavy long leaving neutrino

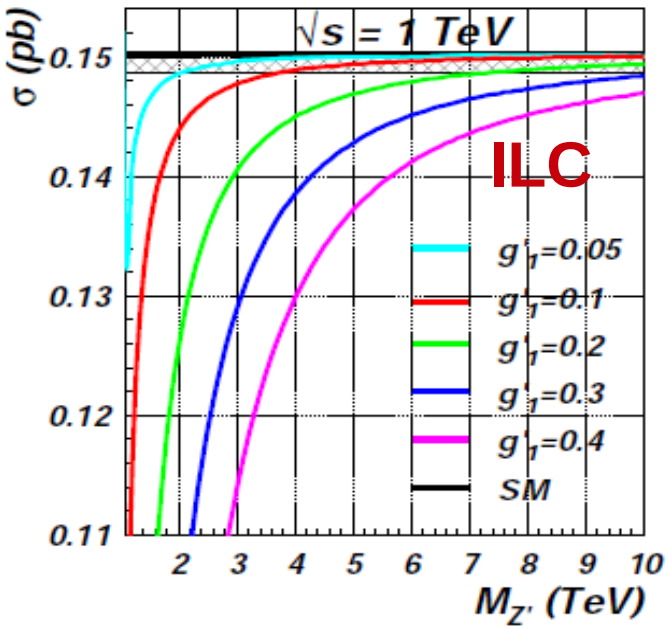
**(in collaboration with S. Moretti, L. Basso, M.Pruna, C. Shepherd)**

arXiv:0812.4313
arXiv:0903.4777



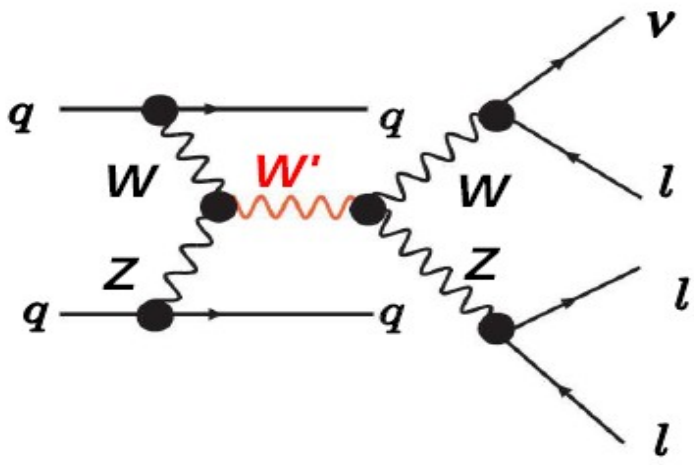
# Recent applications:

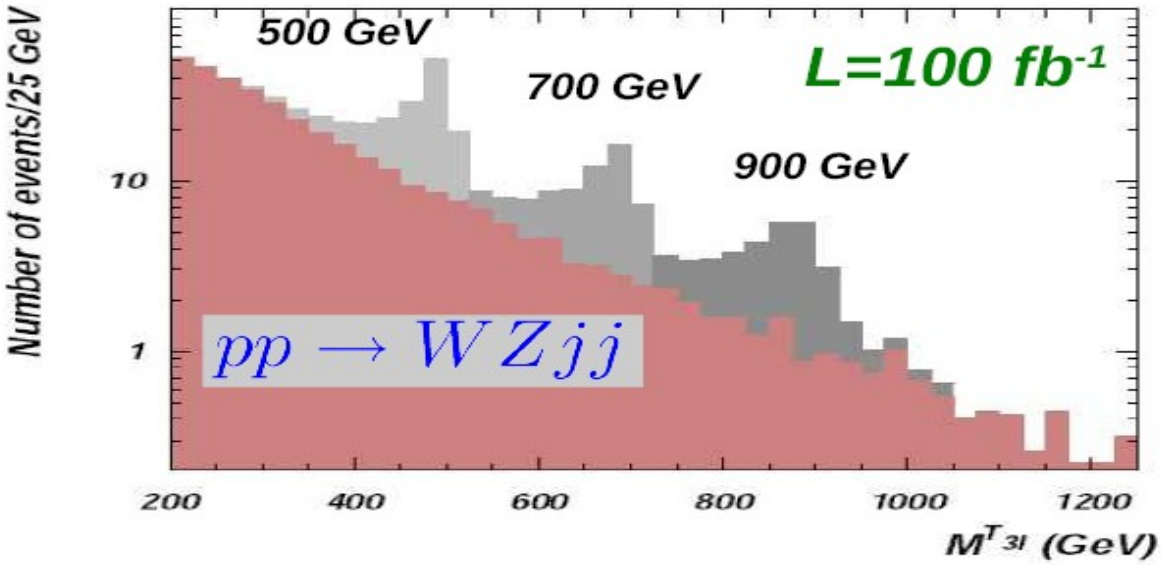
## W' 3-lepton signatures from 3-site Higgsless model

arXiv:0708.2588

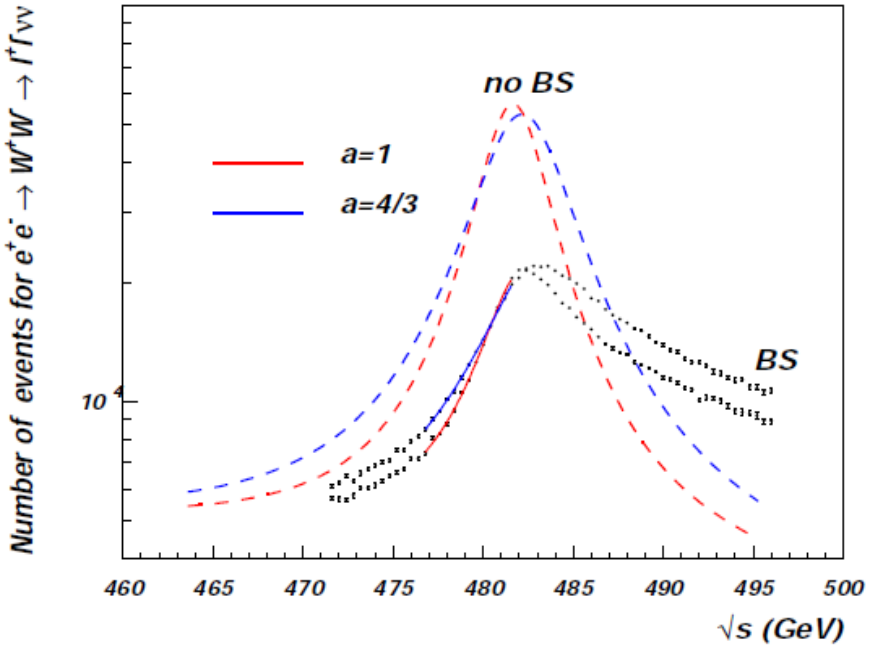
### LHC reach for WZ->W' process

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



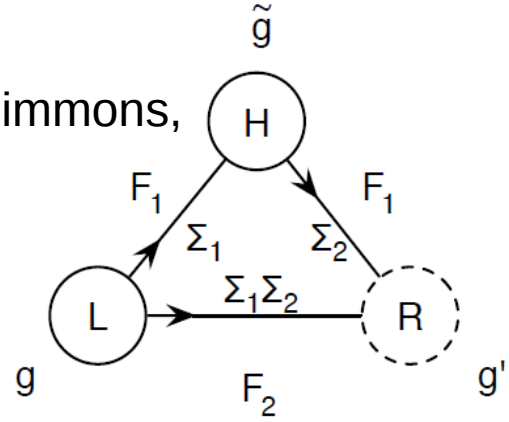

Z' line shape for $e^+e^- \to W^+W^- \to l^+l^-\nu\nu$, $\sqrt{s}$=500 GeV




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

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

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



# Recent applications: phenomenology of WalkingTechnicolor models

arXiv:0809.0793

*AB, Foadi, Frandsen, Järvinen, Pukhov, Sannino*

## LHC

$N_c = 3, N_f = 2$

*in the two-index symmetric*

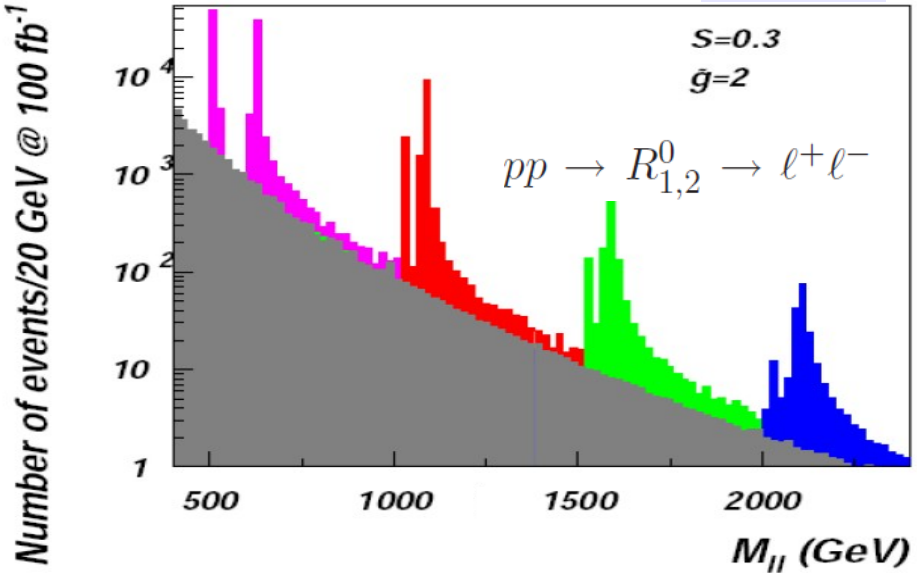
*$SU(2)_L$ X $SU(2)_R$ –> $SU(2)_V$*

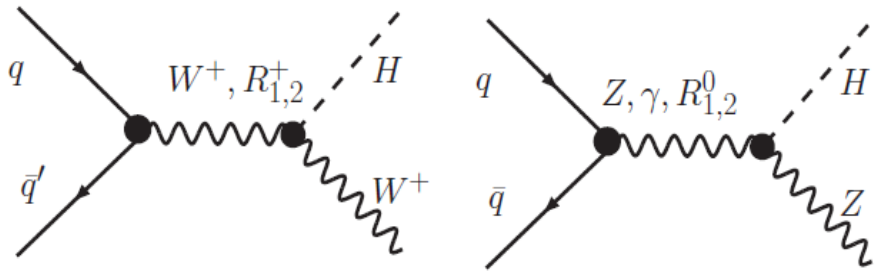
*two triplets of heavy mesons*

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

**and**

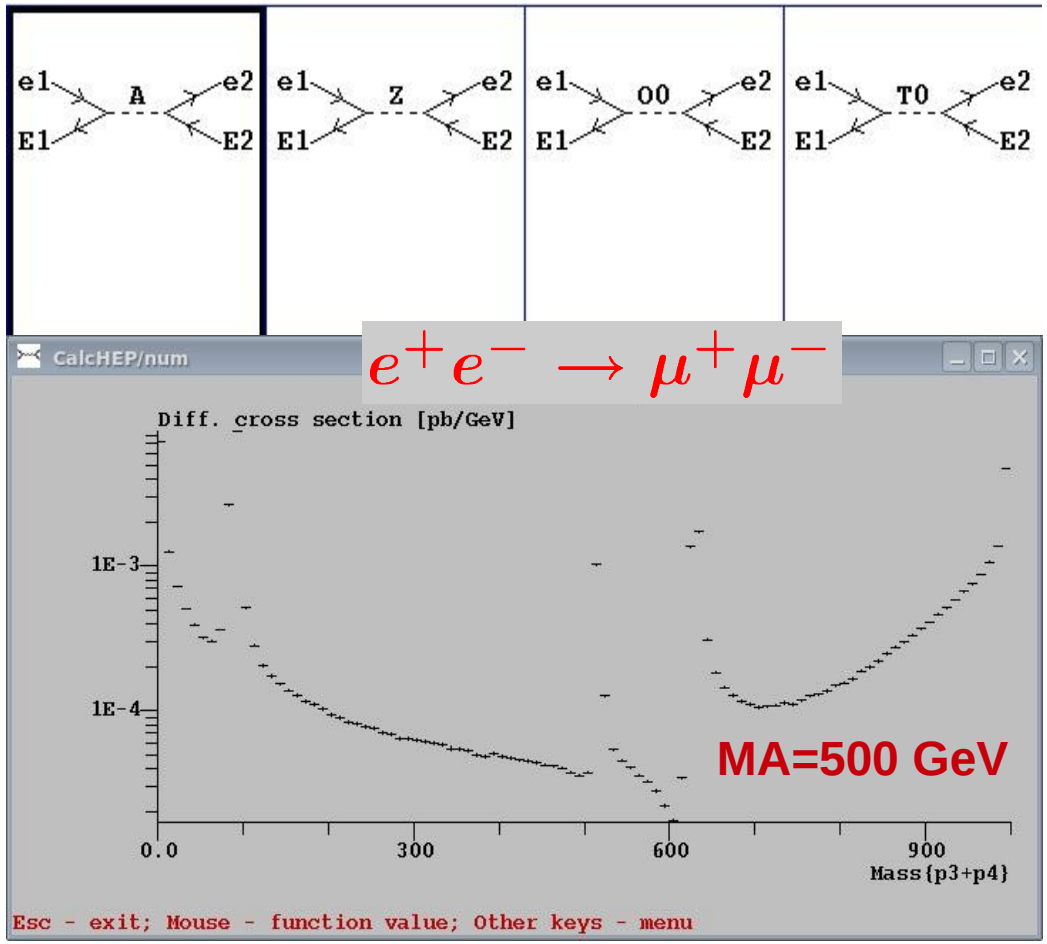
$R_1^0(R_2^0)$




## ILC@1TeV

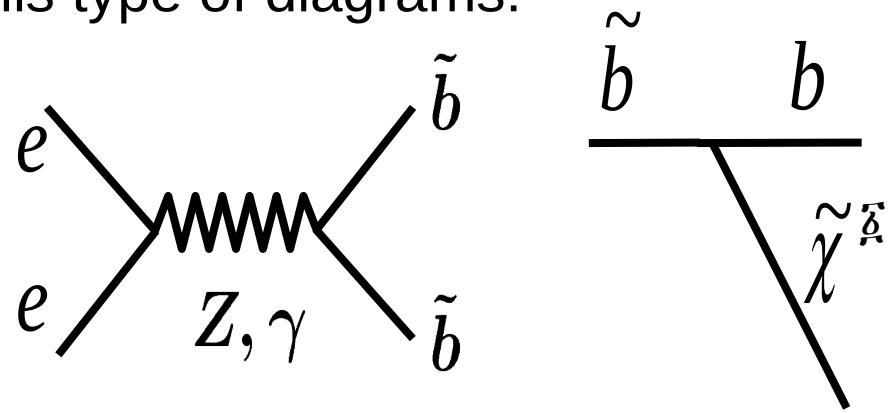
**(work in progress)**



# Recent applications: sbottom coannihilation scenario at ILC

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

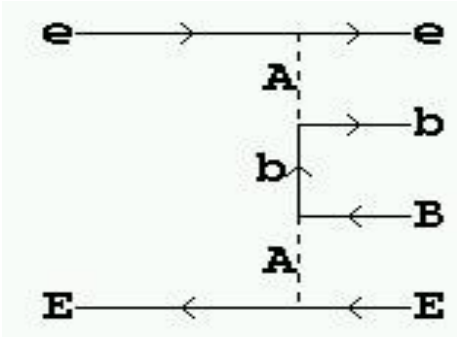
If sbottom and neutralino have a small mass split they can account for co-annihilation in early Universe through this type of diagrams:




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

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

background process




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

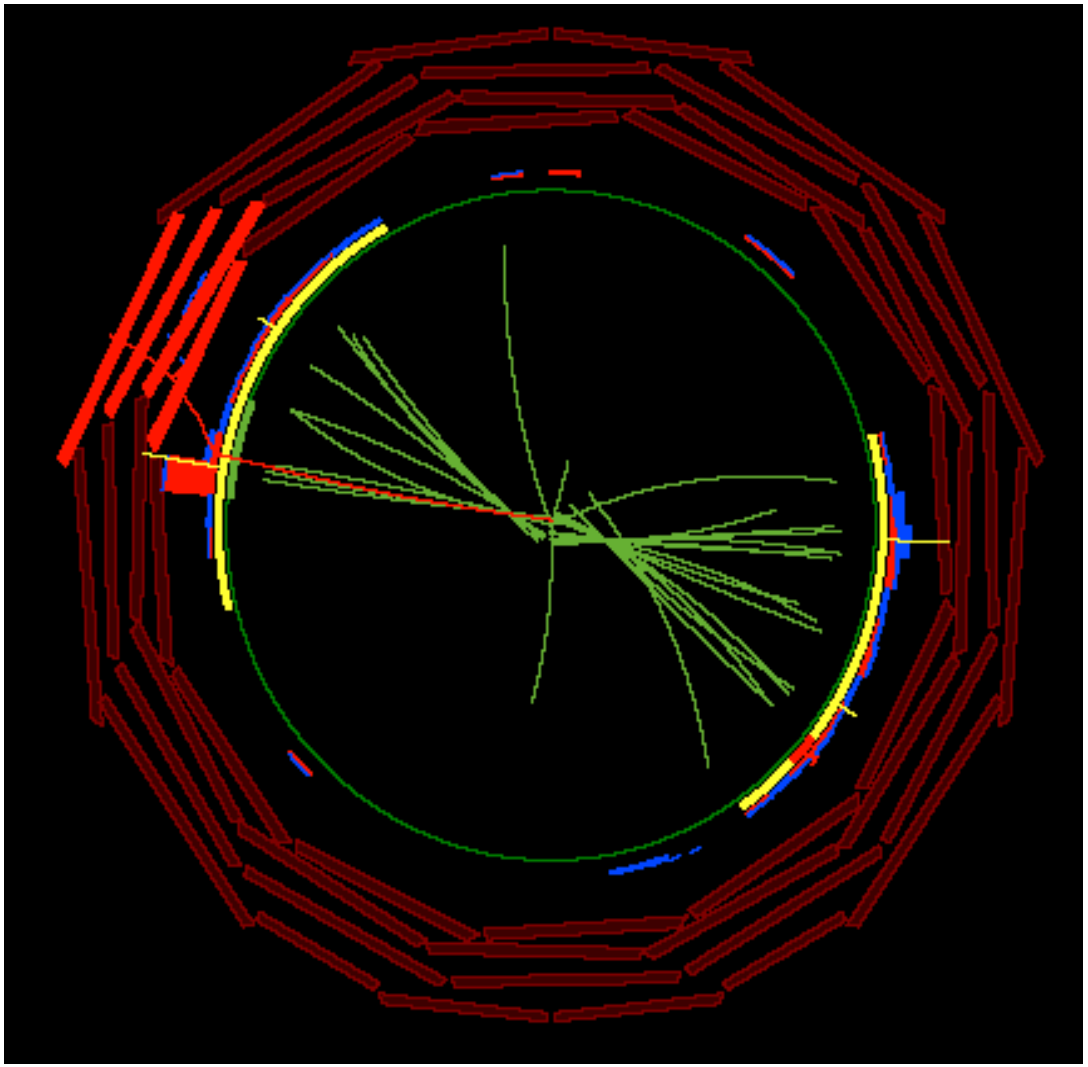
$$-m_e^2\frac{(E_1-E_3)^2}{E_1E_3}$$

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

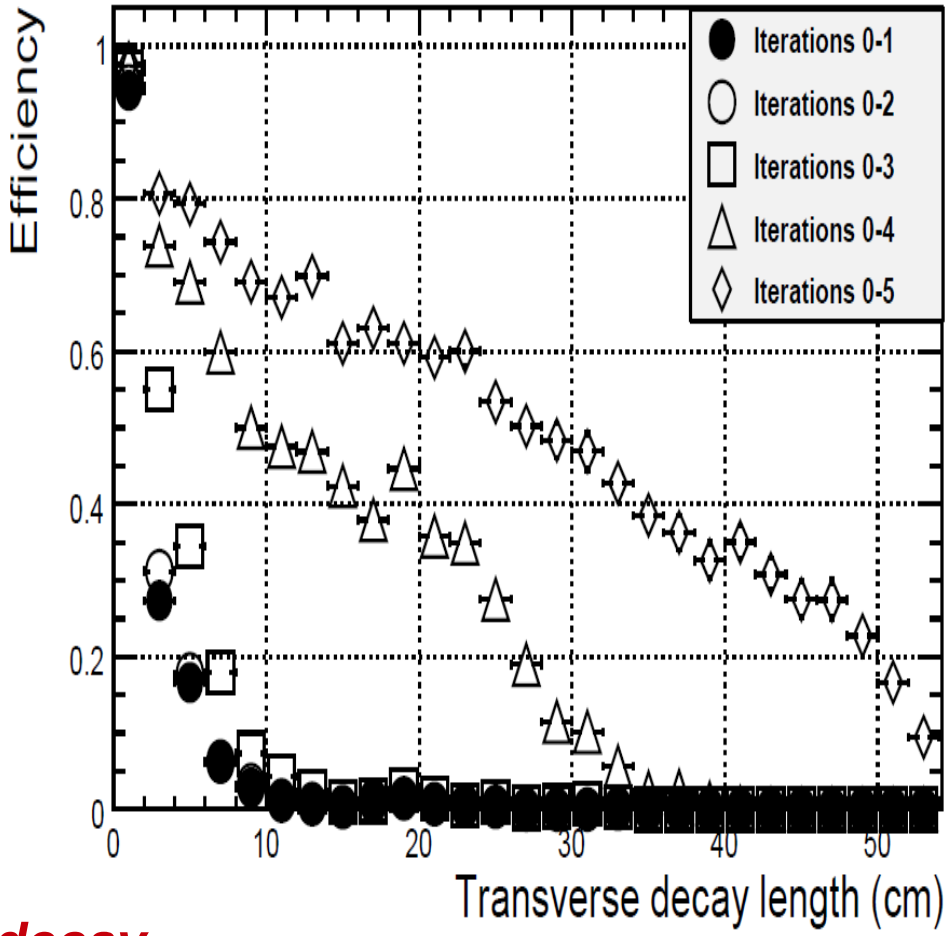
## *Ongoing project:*

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

***In collaboration with Ian Tomalin and Arnaud Gay***



***Improved tracking efficiency***

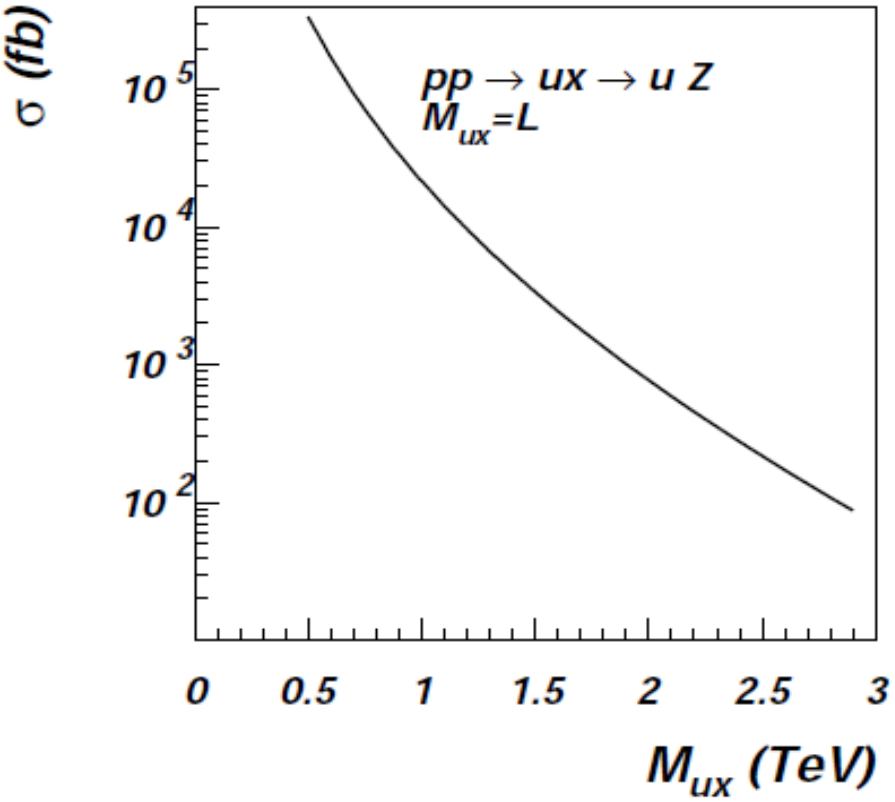


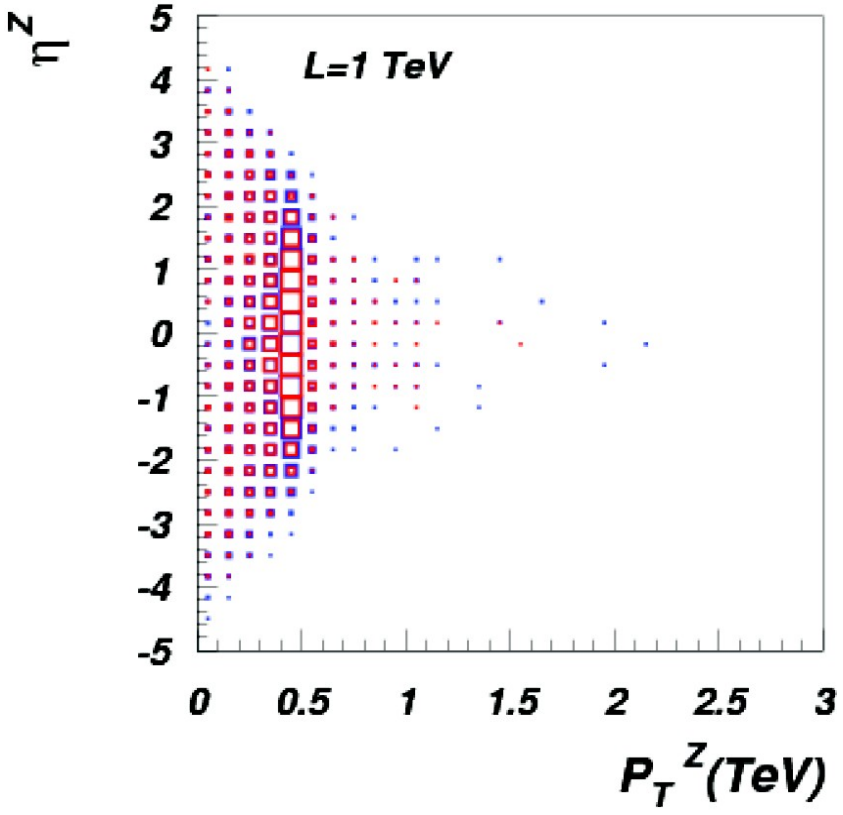

***2 displaced vertices from 2 heavy photons decay***

## *Ongoing project:*
# Boosted Z-bosons

***In collaboration with James Jackson and Claire Shepherd-Themistocleous***

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



## *Ongoing project:*
# Boosted Z-bosons

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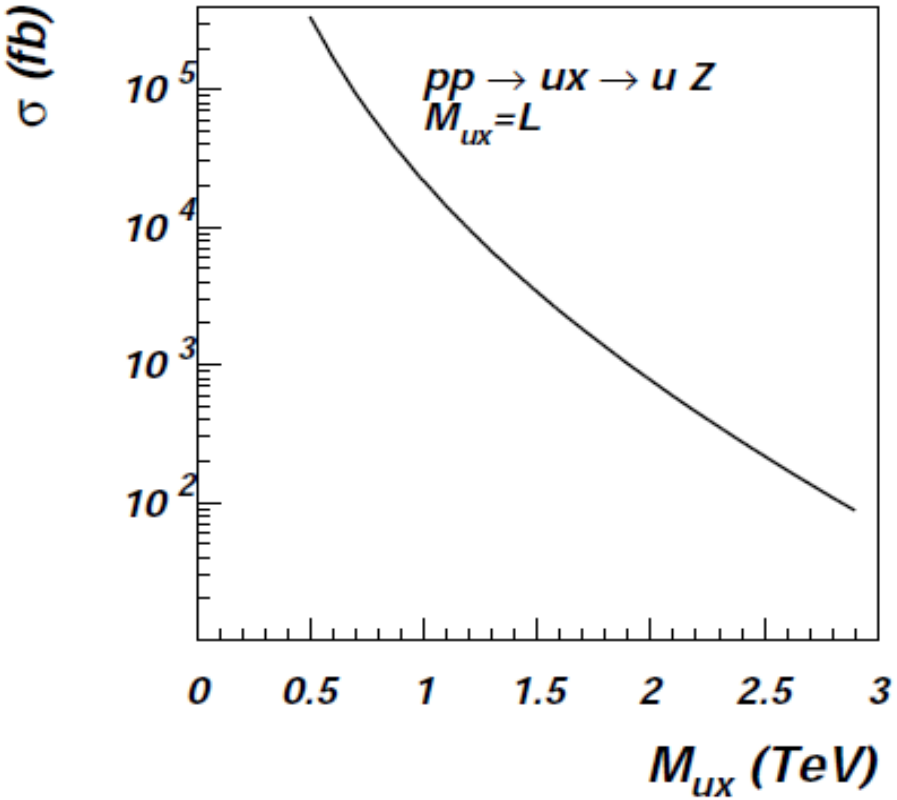
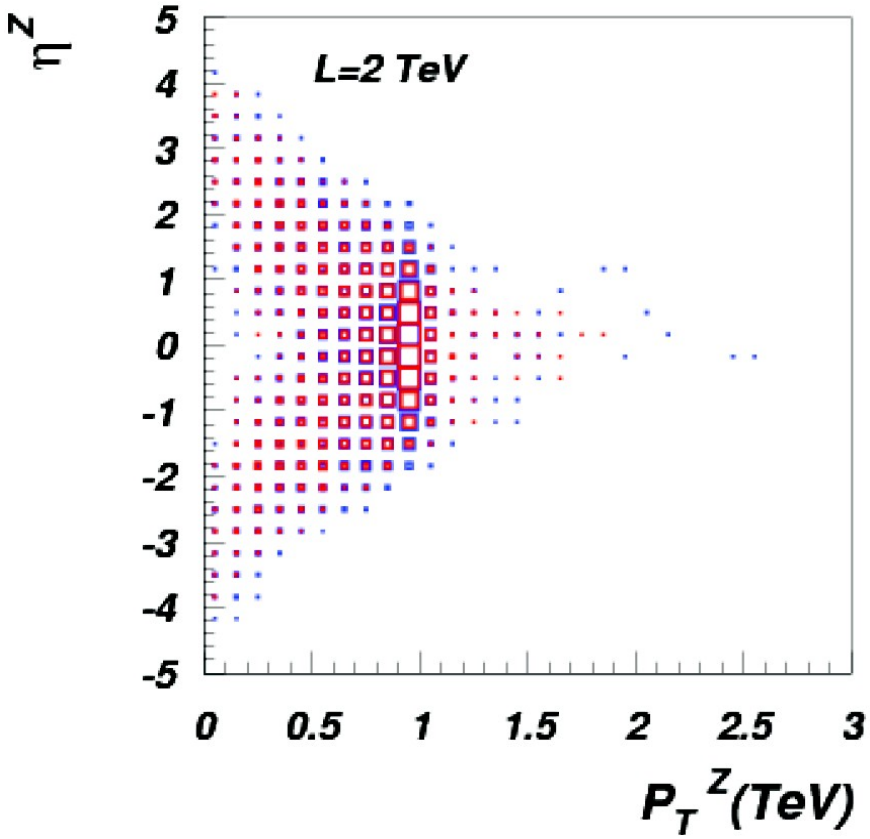
***Benchmark model:*** ***model with excited fermions with gauge interactions***



# *Ongoing project:*
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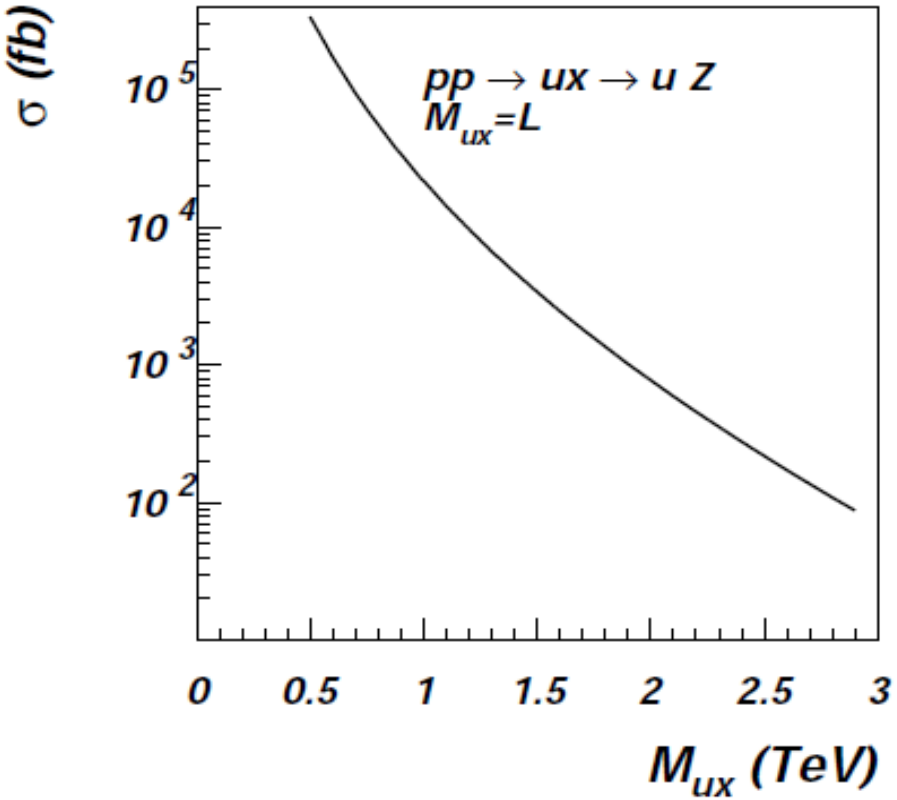
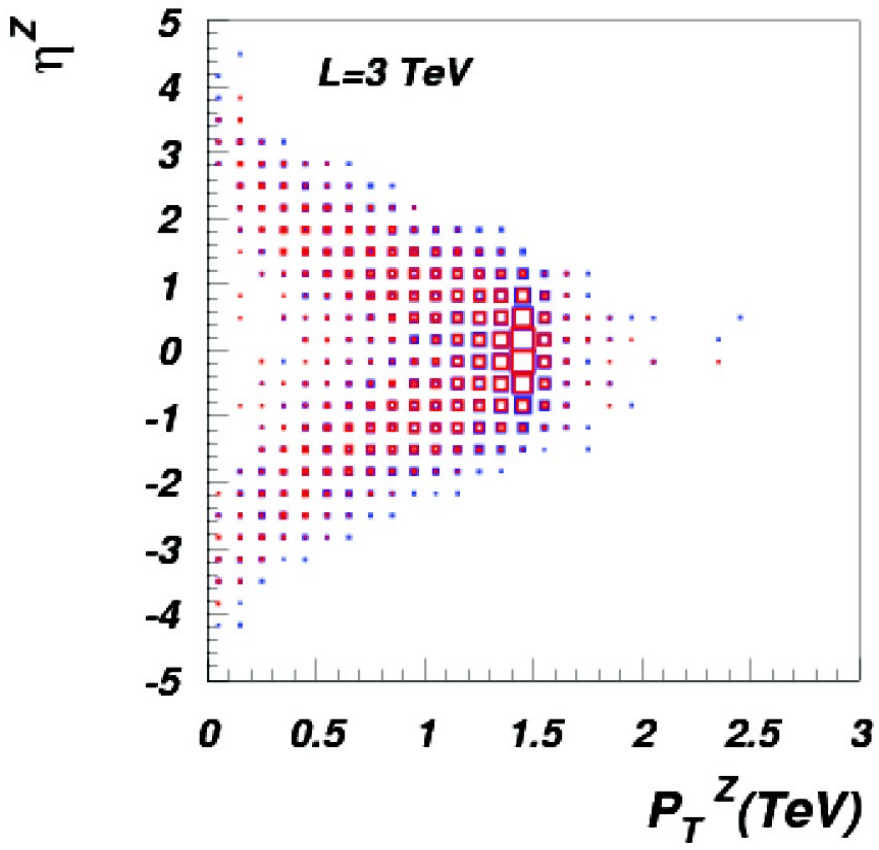


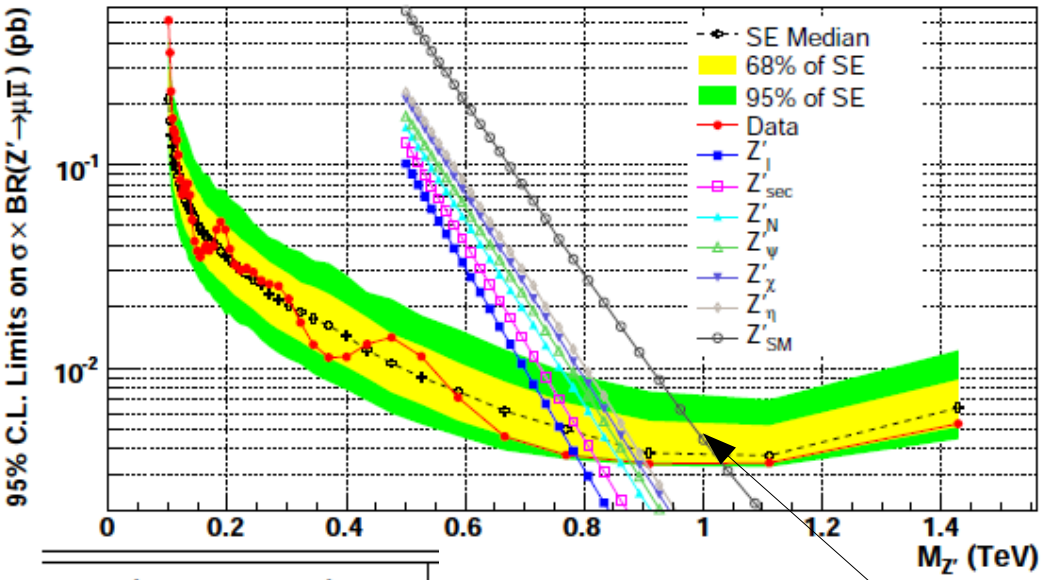

- ***Motivated by several promising candidates for New Physics such as***
  - *SUSY (cascase squark and gluinos decays)*
  - *Technicolor (W' -> WZ decays)*
- ***Study of multiparticle final states should be performed for efficiency estimation***

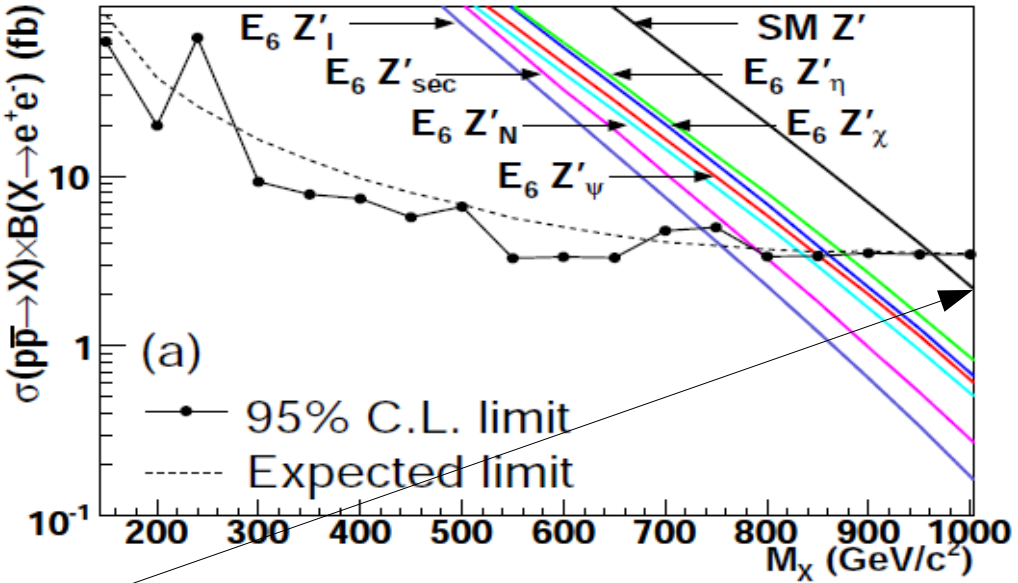
# One more remark on why experimentalists should talk more to theorists

arXiv:0811.0053 di-electrons

**CDF**

arXiv:0810.2059 di-muons




| $Z'$ model | $Z'$ mass limit |
|---|---|
| $Z'_I$ | 789 |
| $Z'_{sec}$ | 821 |
| $Z'_N$ | 861 |
| $Z'_\psi$ | 878 |
| $Z'_\chi$ | 892 |
| $Z'_\eta$ | 904 |
| $Z'_{SM}$ | 1030 |

**same point with cs different by factor 2!**

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

# Future plans for CalcHEP

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

# Final remarks

- **Main features of CalcHEP**
  - *easy model implementation (manual or with LanHEP/FeynRules)*
  - *will work with any generic model*
  - *convenient interface*
  - *batch mode*

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

  **from model builders to experimentalists!**

- **Powerful tool which**

  **should not be blindly trusted or blamed !**

# Summary

- **Lets Discuss EX <-> TH wish list and define common projects**
- **We have powerful tools**
  - CalcHEP/LanHEP are among them – for new physics studies, implementation of new models is easy: MSSM, NMSSM, LHT, UET, Walking Technicolor models have been already implemented (as well as many more!)
- **Connection to experiment is crucial**
  - Creating of model database
  - Model validation
  - Traceable tag for LHE events
- **Let's do our best to constructively combine our expertise!**