CompHEP and CompHEP-PYTHIA interface in High Energy Physics

Alexander Belyaev
Florida State University

OUTLINE

- ⋆ CompHEP: idea, structure and features
- ⋆ CompHEP-PYTHIA interface
- ⋆ Applications and examples

CompHEP software package

A.Pukhov, E.Boos, M.Dubinin, V.Edneral,V.Ilyin, D.Kovalenko, A.Kryukov, V.Savrin, S.Shichanin, A.Semenov

Skobeltsyn Institute of Nuclear Physics, Moscow State University

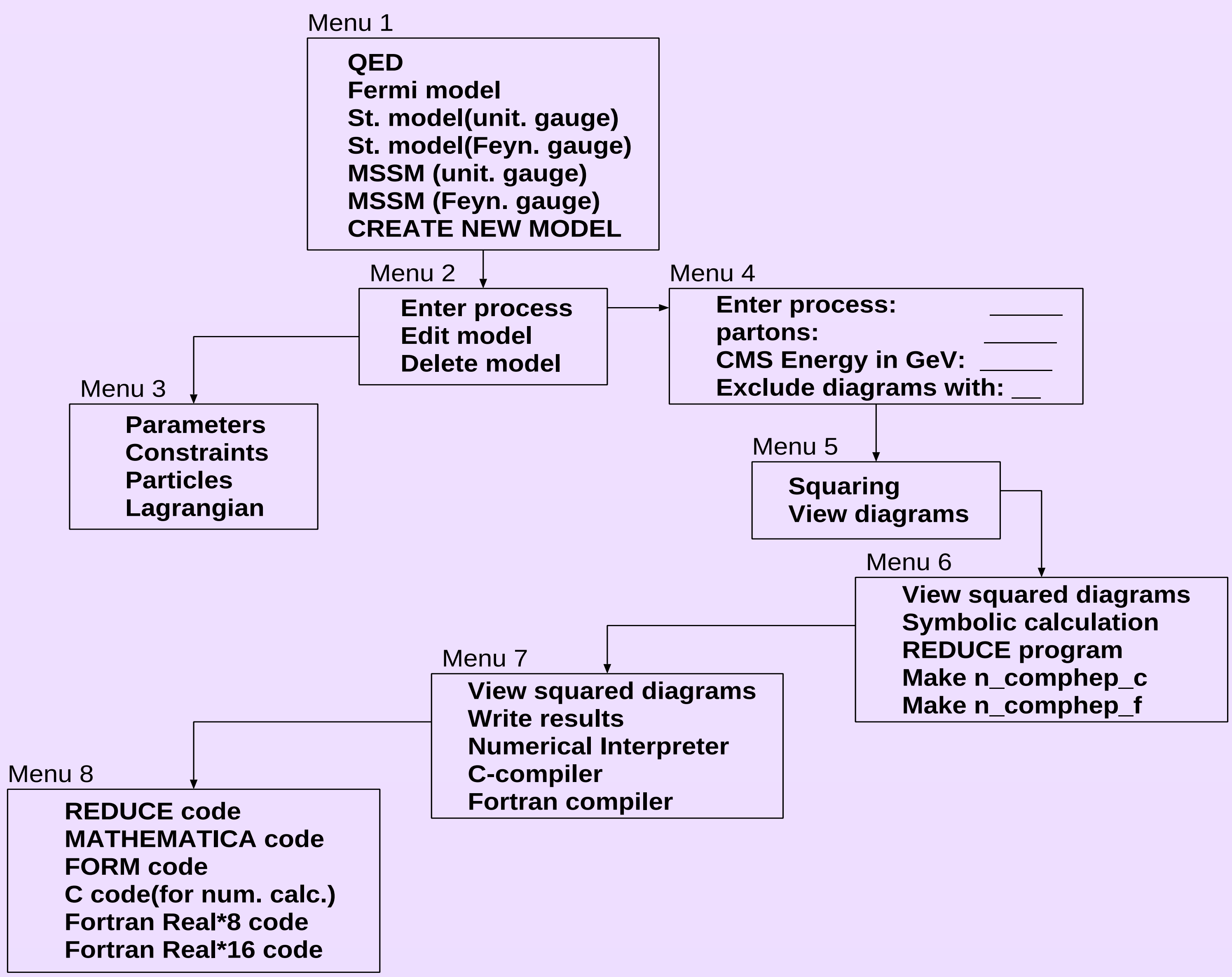
E. E. Boos *et al.*,SNUTP-94-116 (hep-ph/9503280) *http://theory.npimsu.su/~comphep*

- ⋆ CompHEP is a package for automatic calculations of elementary particle decay and collision processes. Tree approximation. The main idea: passing from the Lagrangian to the final distributions effectively with the high level of automation. The other packages: *FeynArt/FeynCalc* , *GRACE* , *HELAS* , *MADGRAPH* .
- ⋆ CompHEP is a menu-driven system with the context help.
- ⋆ Several built-in physical models: Standard Model and MSSM (SU(3)xSU(2)xU(1)) in the unitary and t'Hooft - Feynman gauges. The user can create the new model.
- ⋆ Two parts: symbolic and numerical.

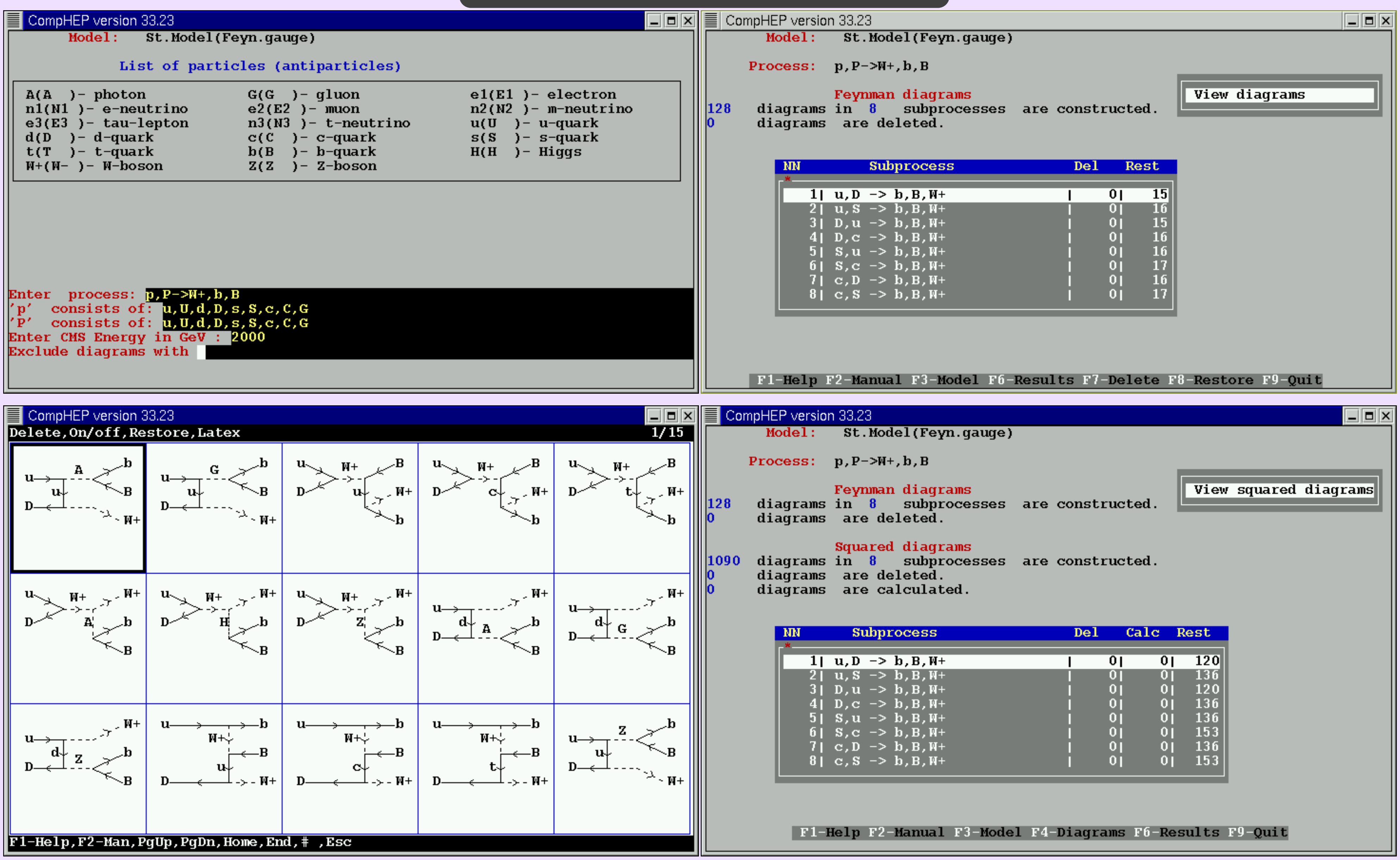
Symbolic part of CompHEP lets the user:

- ⋆ select process by specifying incoming and outgoing particles (decays and collisions)
- ⋆ generate, display and exclude Feynman diagrams
- ⋆ generate, display and exclude squared Feynman diagrams
- ⋆ calculate analytical expressions ($|M|^2$) by using the fast built-in symbolic calculator
- ⋆ save squared matrix elements in the $REDUCE$, $MATHEMATICA$ and $FORM$ codes
- ⋆ generate the optimized $FORTRAN$ (v33) and C (v33,v41) code for the squared matrix elements

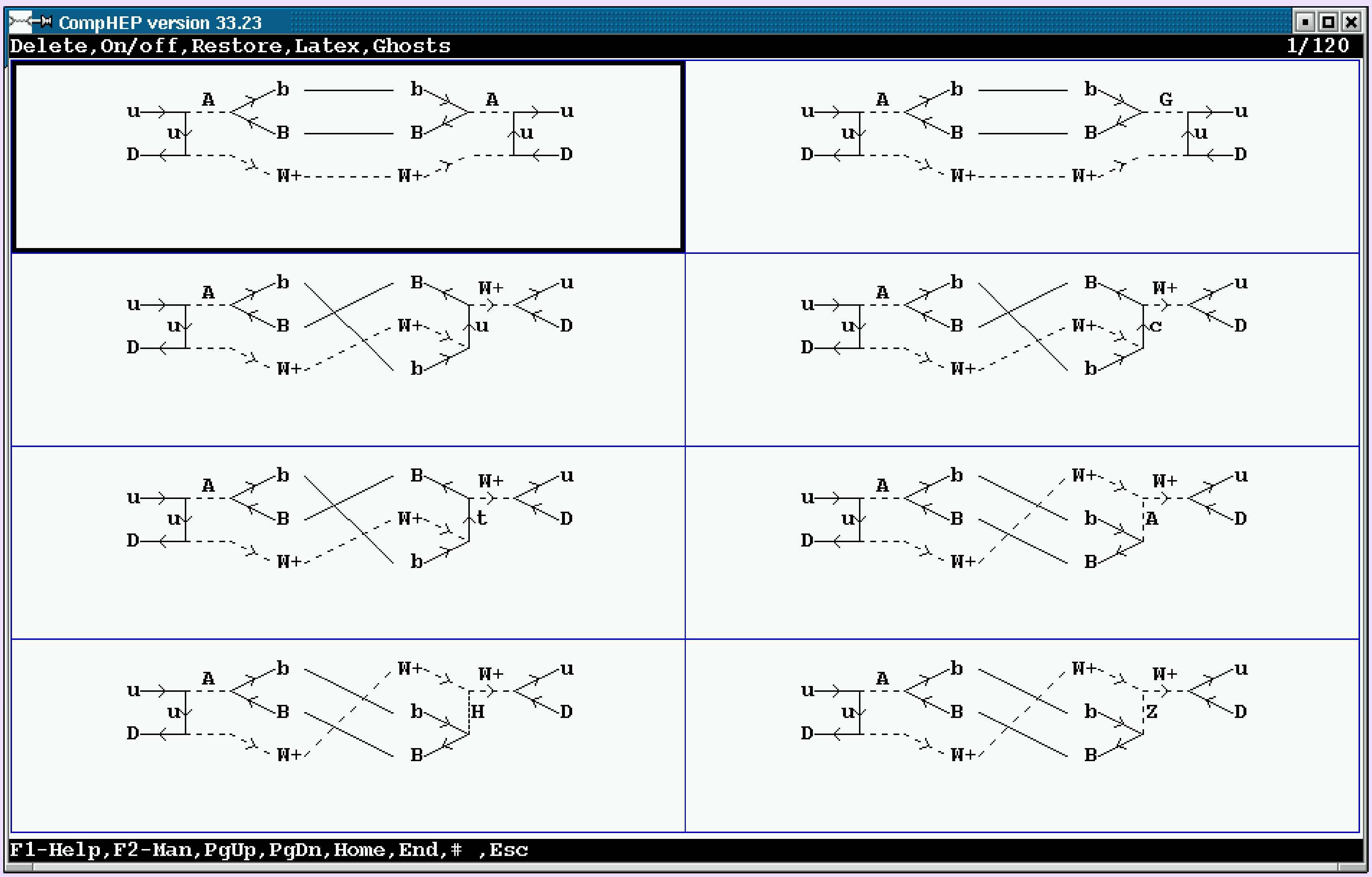
Symbolic part of CompHEP



$Wb\bar{b}$ process as an example



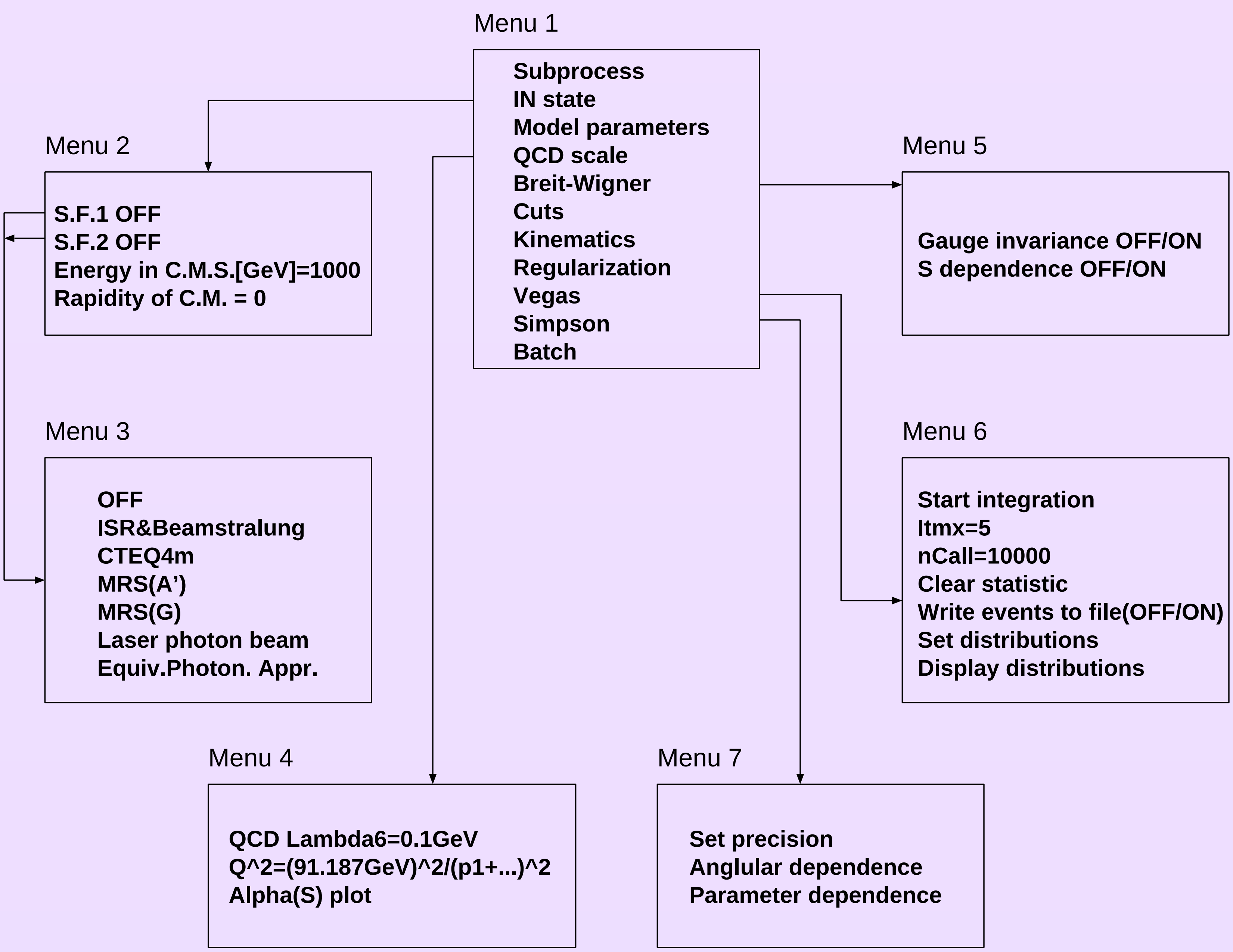
$Wb\bar{b}$ process as an example



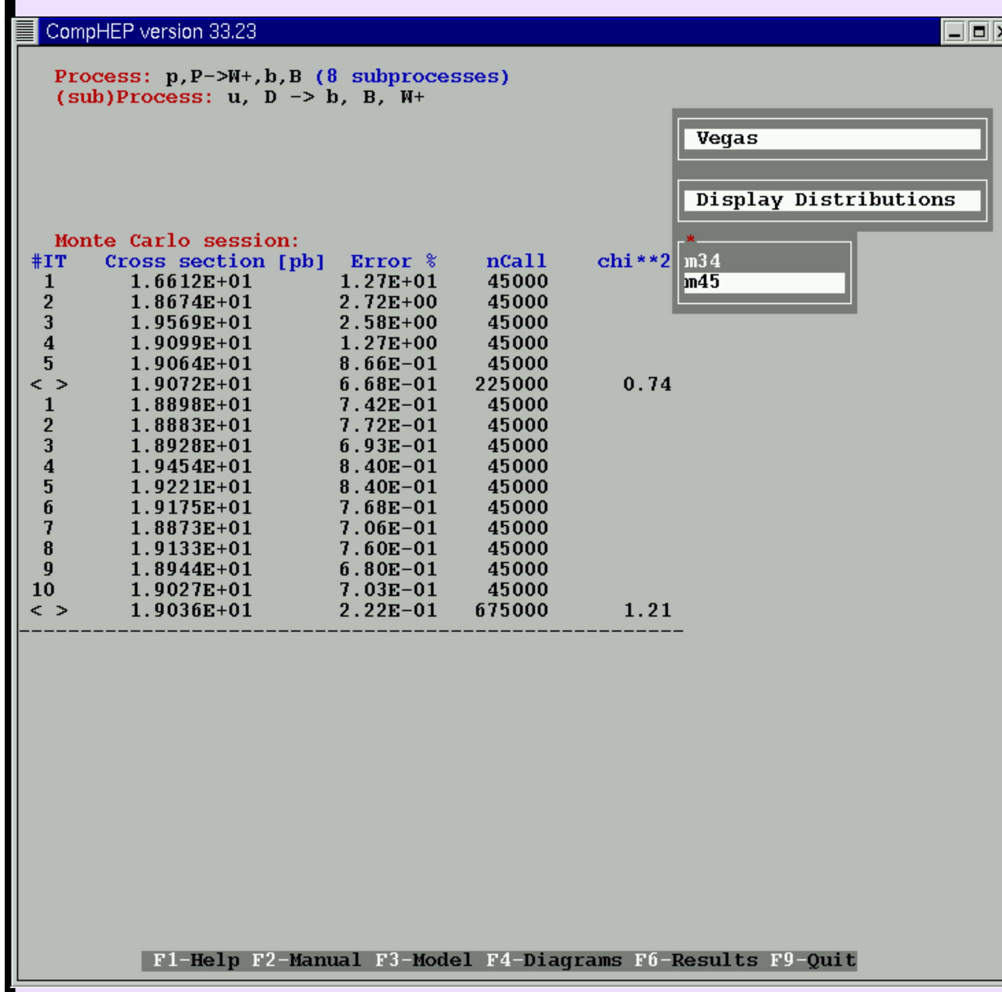
The numerical part of CompHEP offers to :

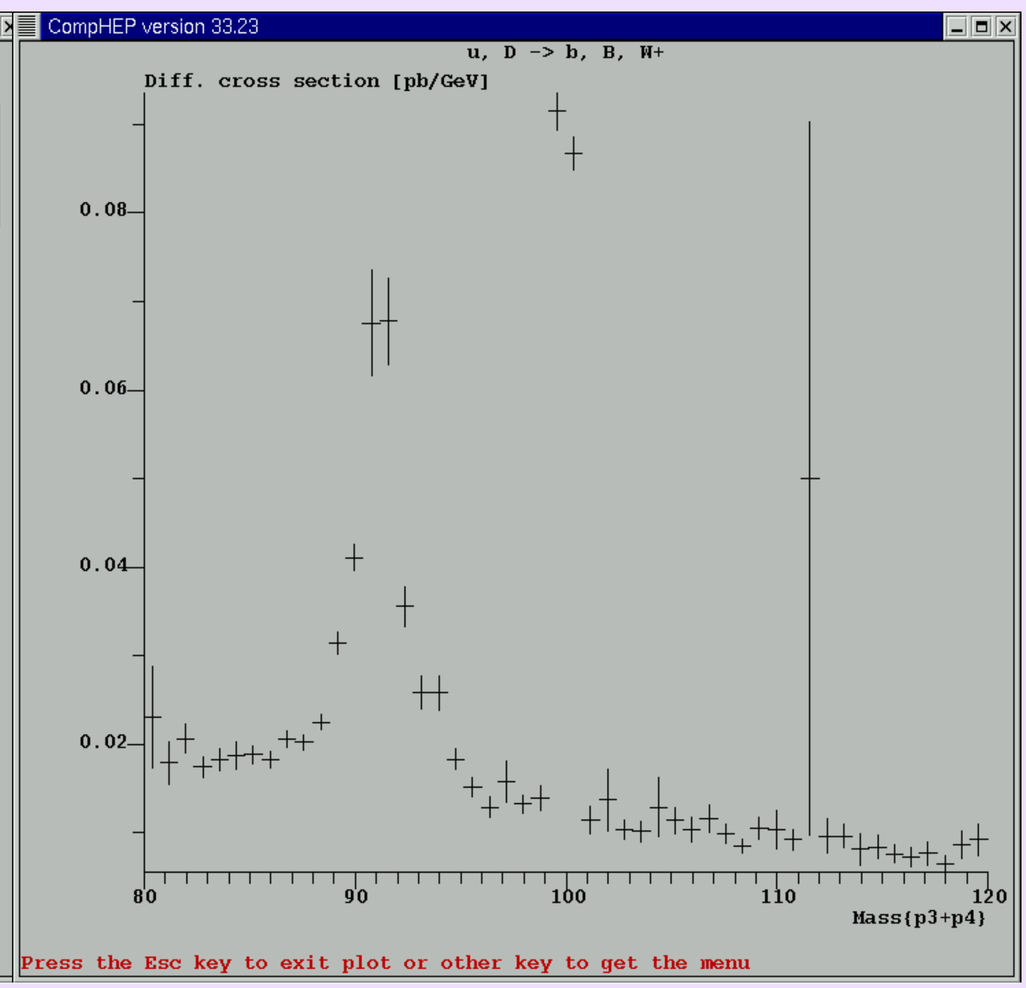
- ⋆ convolute the squared matrix element with structure functions and beam spectra($CTEQ$, MRS PDF , ISR electron beam spectrum, laser photon, WW spectrum)
- ⋆ modify any physical parameter
- ⋆ define kinematic scheme (phase space parameterization)
- ⋆ introduce various kinematical cuts
- ⋆ select the scale parameter for QCD
- ⋆ smooth sharp peak of squared matrix element
- ⋆ store the calculated matrix element values in file for subsequent event generation and generate events
- ⋆ fill distributions and create graphical and LaTeX output

The numerical part of CompHEP



The numerical part of CompHEP





Installation of CompHEP

★ Manual and Codes

CompHEP codes and manual are disposed on the following Web site

`http://theory.sinp.msu.ru/~comphep`

Also there is a mirror in DESY

`http://www.ifh.de/~pukhov`

★ Installation

- `tar -zxvf comphep_41.10.tar`
  As a result a directory comphep_41.10 will be created.
- In order to compile the CompHEP source code you need a C compiler with the X11 graphics library
- `./mk_all` command from the CompHEP root directory.

User installation of CompHEP

- ⋆ the environment variable COMPHEP should contain the corresponding path: in the case of *tcsh* the name of startup file is ~/*.tcshrc* or ~/*.cshrc* and the assignment is realized by the instruction

```
setenv COMPHEP <Path to CompHEP directory>
```

- ⋆ create your work directory say, *work* for the CompHEP session
- ⋆ `$COMPHEP/install`
- ⋆ sub-directories and files will in *work* directory:

  `models/` `tmp/` `results/` `comphep` `comphep.ini`

  models is used for files which describe models

  tmp is created for temporal files

  results is assigned for a CompHEP output
- ⋆ To start a CompHEP session: `./comphep`

  comphep.ini file allows to choose an appropriate text font, color(colorless) mode for the window and also switch on/off the sound signal.

Models of particle interactions. Parameters.

Description of particle interaction model in CompHEP consists of four parts. They are *parameters*, *constrains*, *particles*, and *vertices*.

CompHEP version 33.23

Parameters

Name	Value	> Comment
EE	0.31223	Elementary charge (alpha=1/128.9, on-shell, MZ point, PDG
GG	1.238	Strong coupling (LEP/SLD average alphas=0.122, PDG96)
SW	0.4730	sine of the electroweak mixing angle (PDG96)
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
Mt	1.777	tau-lepton mass (PDG96)
Mc	1.420	c-quark mass (pole mass, PDG96)
Ms	0.200	s-quark mass (pole mass, PDG96)
Mb	4.620	b-quark mass (pole mass, PDG96)
Mtop	175	t-quark mass (pole mass)
MZ	91.1884	Z-boson mass (PDG96)
MH	100	higgs mass
wtop	1.7524	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)
wH	0.004244	Higgs width (tree level 1->2x)

F1 F2 Top Bottom GoTo Find fAgain Zoom ErrMes

Models of particle interactions. Constrains

CompHEP version 33.23

Constraints 1

Name	Expression	Comment
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

F1 F2 Top Bottom GoTo Find fAgain Zoom ErrMes

Models of particle interactions. Particles

CompHEP version 33.23

Particles 1

Full name	A	A+	2*spin	mass	width	color	aux	>LaTex(A)<	>LaTeX(A+) <
photon	A	A	2	0	0	1	G	\gamma	\gamma
gluon	G	G	2	0	0	8	G	g	g
electron	e1	E1	1	0	0	1		e	\bar{e}
e-neutrino	n1	N1	1	0	0	1	L	\nu_e	\bar{\nu}_e
muon	e2	E2	1	Mm	0	1		\mu	\bar{\mu}
m-neutrino	n2	N2	1	0	0	1	L	\nu_\mu	\bar{\nu}_\mu
tau-lepton	e3	E3	1	Mt	0	1		\tau	\bar{\tau}
t-neutrino	n3	N3	1	0	0	1	L	\nu_\tau	\bar{\nu}_\tau
u-quark	u	U	1	0	0	3		u	\bar{u}
d-quark	d	D	1	0	0	3		d	\bar{d}
c-quark	c	C	1	Mc	0	3		c	\bar{c}
s-quark	s	S	1	Ms	0	3		s	\bar{s}
t-quark	t	T	1	Mtop	wtop	3		t	\bar{t}
b-quark	b	B	1	Mb	0	3		b	\bar{b}
Higgs	H	H	0	MH	wH	1		H	H
W-boson	W+	W-	2	MW	wW	1	G	W^+	W^-
Z-boson	Z	Z	2	MZ	wZ	1	G	Z	Z

F1 F2 Top Bottom GoTo Find fAgain Zoom ErrMes

Models of particle interactions. Vertices

Vertices 21

Clr-Rest-Del-Size

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
W+	W-	A		-EE	m1.m2*(p1-p2).m3+m2.m3*(p2-p3).m1+m3.m1*(p3-p1).m2
W+	W-	Z		-EE*CW/SW	m1.m2*(p1-p2).m3+m2.m3*(p2-p3).m1+m3.m1*(p3-p1).m2
W+	W-	Z	Z	-(EE*CW/SW)^ 2	2*m1.m2*m3.m4-m1.m3*m2.m4-m1.m4*m2.m3
W+	W+	W-	W-	(EE/SW)^ 2	2*m1.m2*m3.m4-m1.m3*m2.m4-m1.m4*m2.m3
W+	W-	A	Z	-EE^ 2*CW/SW	2*m1.m2*m3.m4-m1.m3*m2.m4-m1.m4*m2.m3
W+	W-	A	A	-EE^ 2	2*m1.m2*m3.m4-m1.m3*m2.m4-m1.m4*m2.m3
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
E2	e2	H		-EE*Mm/(2*MW*SW)	1
E3	e3	H		-EE*Mt/(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*Mtop/(2*MW*SW)	1
E1	e1	A		-EE	G(m3)
E2	e2	A		-EE	G(m3)
E3	e3	A		-EE	G(m3)
N1	e1	W+		EE/(2*Sqrt2*SW)	G(m3)*(1-G5)
N2	e2	W+		EE/(2*Sqrt2*SW)	G(m3)*(1-G5)
N3	e3	W+		EE/(2*Sqrt2*SW)	G(m3)*(1-G5)
E1	n1	W-		EE/(2*Sqrt2*SW)	G(m3)*(1-G5)
E2	n2	W-		EE/(2*Sqrt2*SW)	G(m3)*(1-G5)
E3	n3	W-		EE/(2*Sqrt2*SW)	G(m3)*(1-G5)
E1	e1	Z		-EE/(4*SW*CW)	G(m3)*(1-G5)-4*(SW^ 2)*G(m3)
E2	e2	Z		-EE/(4*SW*CW)	G(m3)*(1-G5)-4*(SW^ 2)*G(m3)
E3	e3	Z		-EE/(4*SW*CW)	G(m3)*(1-G5)-4*(SW^ 2)*G(m3)
N1	n1	Z		EE/(4*SW*CW)	G(m3)*(1-G5)
N2	n2	Z		EE/(4*SW*CW)	G(m3)*(1-G5)

F1-F2-Top-Bottom-GoTo-Find-Zoom-ErrMes

Input of the process

- The syntax for the input is:

  `P1[,P2] -> P3,P4 [,...,[N*x]]`

  'P1'..'P4' are particle names, N is a number of particles

  `u,U -> G,G` — annihilation of the u-quark and $\bar{u}$-quark into two gluons

- Example of inclusive processes: `u,U -> G,G,2*x` – all processes of annihilation of the u- and $\bar{u}$-quark into two gluons + two arbitrary particles

- If the program finds an unknown name among the in-particles it will try to consider it as a name of composite particle: `e,p -> 3*x`

  `Is 'p' a composite particle Y/N ?`

  A possible input is: `'p' consists of:`u, U, d, D, G

- For a collision process, the total energy of colliding particles in the CMS is demanded:

  `Enter Sqrt(S) in GeV:` *300*

- CompHEP generates only those channels where $\sum m_i < \sqrt{s}$

Diagrams

- ⋆ Incoming particles – on the left side of diagrams, the outgoing – on the right.
- ⋆ Spin $0, \frac{1}{2}, 1$ particles — dotted, solid, and dashed line correspondingly. The arrow indicates the direction of particle (not anti-particle) propagation.
- ⋆ CompHEP produces only one representative of a set of diagrams For example, CompHEP creates only one diagram for the $e1, E1$ -> A, A process (all textbooks present two diagrams) – momenta are not assigned to the outgoing particles on the step of diagrams generation.
- ⋆ CompHEP does not generate diagrams with Faddeev-Popov and Goldstone ghosts. Such diagrams are restored on the step of squared diagram evaluation.
- ⋆ Vertices with a complicated color structure(e.g. the four-gluon one) are implemented by means of unphysical tensor field – does not appear in the constructed diagrams. A contribution of the four-gluon vertex is restored when squared diagrams are evaluated.

Some details of the numerical session

- ⋆ In_state function gives the user an option to choose structure functions for incoming particles. The GeV units are assumed.
- ⋆ The $Model\_parameters$ function allows the user to assign a new value to any independent parameter involved. QCD strong coupling parameter will be reset according to the rules defined by the $QCD\ scale$ menu function.
- ⋆ QCD scale CompHEP substitutes the QCD strong coupling constant as a function of the $\Lambda^{(6)}$ parameter and the Q^2 scale value. User can change a numerical value of $\Lambda^{(6)}$ or the Q^2 scale definition. For example: the input '13' will be treated as $Q^2 = |(p1 - p3)^2|$. If $Q^2$is defined as a constant, the corresponding value of $\alpha = GG^2/(4\pi)$is displayed on the screen. The $\alpha(s)$ plot for a user-defined region of s is available.

Some details of the numerical session

- ⋆ Breit-Wigner propagator The propagator of virtual particle has a pole at $p^2 = m^2$, inside the phase space volume this leads to a non-integrable singularity. The general solution – high order corrections: $\frac{1}{p^2 - m^2 - i \cdot \Gamma(p^2) \cdot m}$, $\Gamma(m^2)$ is the particle width (reversed mean life time)
  - ⧫ Γ value is essential near the pole point $p^2 = m^2$: $\Gamma(p^2) = \Gamma(m^2) = const.$ It corresponds to the position OFF of *'S dependence'* switch.
  - ⧫ $\Gamma(p^2) = \Gamma(m^2) \cdot \sqrt{p^2}/m$ —*'S dependence'* is ON
- ⋆ gauge invariance and gauge symmetry:
  in any order of perturbation theory, but intervention of higher order terms to the lowest order expression via the BW-propagator can break it.
  $Gauge\ invariance$ – ON: diagram which does not contain the Breit-Wigner propagator is multiplied by factor $\frac{(p^2 - m^2)^2}{(p^2 - m^2)^2 + (width(p^2) \cdot m)^2}$ Symbolic summation of all diagram contributions at a common denominator expression: allows to keep all gauge-motivated cancellations but the factor kills a contribution of non-resonant diagrams in the resonance point.

Implementation of models of particle interactions

⋆ PARAMETERS The Table *Parameters* – three fields:

- *Name* for an identifier of the parameter. Up to 6 characters. The first character must be a letter, others – letters or digits. CompHEP identifiers are case sensitive. Reserved: `i`,`Sqrt2`, `p1,p2,p3,...` , **G5**
- *Value* for a numerical value of parameter;
- *Comment* for brief description of a parameter.

⋆ CONSTRAINTS – three fields:

- *Name* for the constrained parameter.
- *Expression* algebraic formula composed of: integer numbers, identifiers enumerated in the *Parameters* Table,
  (), arithmetic operators +, -, /, *, ^, $sqrt()$

For raising to a power the second operand must be an integer

⋆ *Comment* for brief description of parameters.

★ PARTICLES Each row in the *Particles* Table describes a particle – anti-particle pair. The rows consist of 10 fields:

1. *Full name* for a full name of particle. (not processed anywhere)

2&3. *"A"* and *"A+"* containing designations of the particle and anti-particle, respectively. Any character is allowed. The name may contain up to three symbols (started from '~'). For a neutral particle the *"A"* and *"A+"* fields must be identical.

4. *2*Spin* – doubled particle spin: *0* for scalar, *1* for spinor and *2* for vector particles. Neutral spinor particle is treated as a Majorana one.

5. *Mass* for a mass identifier or symbol '*0*'.

6. *Width* for a particle decay width. It must contain an identifier defined in the first two tables or '*0*';

7. *Color* for a dimension of the color SU(3) group representation. You have to choose: *1*, *3*, *8*.

8. Aux for an auxiliary field which allows to modify particle propagators. If the Aux field is empty the standard expressions for propagators are substituted:

(a) spin 0 case:

$$< 0|T[A(p_1), A^+(p_2)]|0 >= ScPr(p_1, p_2, M) =$$

$$\frac{\delta(p_1 + p_2)}{(2\pi)^4 i(M^2 - p_1^2)} \;\; ;$$

(b) spin 1/2 case:

$$< 0|T[A(p_1), A^+(p_2)\,\gamma_0]|0 >= (\hat{p}_1 + M)\, ScPr(p_1, p_2, M) \;\; ,$$

where $\hat{p} = p^\mu \gamma_\mu$, "A^+" – Hermitian conjugation of "A"

(c) spin 1 case:

$$< 0|T[A^{m_1}(p_1),\ (A^{m_2})^+(p_2)]0 >=$$

$$-(g^{m_1 m_2} + p_1^{m_1}\ p_2^{m_2}/M^2) \times ScPr(p_1, p_2, M) \;\; .$$

Zero mass vector particle must be marked as a *gauge* one using the Aux field (see below).

Possible objects for the Aux field are:

'l','L' is permitted for massless fermions (2*spin = 1) only. The propagator is changed to $\frac{\hat{p}_1(1+\gamma_5)}{2}\,ScPr(p_1,p_2,M)$

'r','R' $\frac{\hat{p}_1(1-\gamma_5)}{2}\,ScPr(p_1,p_2,M)$

''* to describe a point-like interaction (e.g. electroweak 4-fermion interaction model); In this case $ScPr(p_1,p_2,M)$ is replaced to $\frac{\delta(p_1+p_2)}{(2\pi)^4 i\; M^2}$.

In the case of vector particle we also remove $p_1^{m1}p_2^{m2}$ term in the propagator numerator.

'G','g' is permitted for vector (2*spin=2) particle. In this case the propagator of vector particle accepts the Feynman form $-g^{m_1 m_2}\,ScPr(p_1,p_2,M)$;

9&10. *LaTeX(A)* and *LaTeX(A+)* for particle and anti-particle designations in the LaTeX format. They are substituted in the LaTeX image of Feynman diagrams generated by CompHEP . The names are used in the mathematical mode.

Vertices

- ⋆ The first four fields $A1$, $A2$, $A3$, $A4$ include the names of the interacting particles.
- ⋆ The last two fields *'Factor'* and *'LorentzPart'* define a vertex itself

  Let S be the action, then a functional derivative of S over fields is represented as:

$$\frac{\delta S}{\delta A1_{[m1]}(p1)\,\delta A2_{[m2]}(p2)\,\delta A3_{[m3]}(p3)\,[\delta A4_{[m4]}(p4)]} =$$

$$(2\pi)^4\delta(p1+p2+p3\,[+p4])\,[\gamma_0]\ \times ColorStructure \times Factor \times LorentzPart$$

  p and m denote 4-momenta and Lorentz indices. $A4$, $p4$, and $m4$ appear only in the case of four particles. In the case of anti-commuting fields the right-side derivatives are assumed.

  The Fourier transformation is defined by $A(x) = \int \exp(-ikx) A(k)\, d^4k$. *'Factor'* must be a rational monomial constructed of the model identifiers, integer numbers and imaginary unity. *'LorentzPart'* must be a tensor or Dirac γ-matrix expression.

  Coefficients of this expression are polynomials of the model identifiers and scalar products of momenta: $p1.p2$ is $g_{\mu\nu}p_1^{\mu}p_2^{\nu}$; $p1.m2$ is $p_1^{m_2}$; $m1.m2$ is $g_{m_1 m_2}$

Vertices

- γ-matrix with index $'m' \to G(m)$, $p_\mu \gamma^\mu = \hat{p} \to G(p)$
- Anti-commutation relations for γ matrices is $G(v1)\,G(v2) + G(v2)\,G(v1) = 2\ v1.v2$, where $v1, v2$ are momenta or indices.
- The γ_5 matrix is denoted by $G5$. It is defined by equation $\gamma_5 = i\ \gamma_0\gamma_1\gamma_2\gamma_3$ CompHEP interprets the anti-particle spinor field as the Hermitian conjugated particle field, rather than the Dirac conjugated one.
- Above the Majorana spinor was defined as a Hermitian self-conjugated one: $\{\psi = \psi^+, \psi = C\bar{\psi}^T\} \to C = -\gamma_0$ (C-conjugation)
- After substitution $C \to -\gamma_0$ all possible vertices could be written as $A1(p1)\,\gamma_0\,G(v1)\,G(v2)\ldots G(vn)\,A2(p2)$, where $A1$ and $A2$ are some spinor fields, γ_0 is substituted by CompHEP automatically (case of a spinor vertex)
- Equation to check the symmetry in the case of fermion vertex:
  $A1(p1)\,\gamma_0\,G(v1)\,G(v2)\ldots[G5]\ldots G(vn)\,A2(p2) =$
  $A2(p2)\,\gamma_0\,(-G(vn))\ldots[G5]\ldots(-G(v2))\,(-G(v1))\,A1(p1)$.
  It may be useful also to check the Lagrangian self-conjugation property.

Vertices

$ColorStructure$ is substituted by CompHEP automatically.

- For a colorless particle vertex it is equal to 1.
- For $(3 \times \bar{3})$ and for (8×8) vertices the unity tensor is substituted.
- If CompHEP meets a vertex with three particles in the adjoint representation $(8 \times 8 \times 8)$, it substitutes $-i\, f(a1, a2, a3)$, where $f^{\alpha_1}_{\alpha_2 \alpha_3}$ are the structure constants of SU(3). Color indices $a1, a2, a3$ are taken in the same order as they appear in the particle columns.
- For the $(3 \times \bar{3} \times 8)$ vertex CompHEP substitutes $\frac{1}{2}\lambda(\bar{i}, i, a)$, where $\lambda(\bar{i}, i, a)$ are the Gell-Mann matrices.
- More complicated color structures are not implemented yet, but it is possible to construct them by means of unphysical particles (Aux='*') or tensor ghosts.

Vertices. Example: 3-gluon vertex

$S_{3G} = -\frac{g}{2}\int(\partial_\mu G^\alpha_\nu - \partial_\nu G^\alpha_\mu) f^\alpha_{\beta\gamma} G^\beta_\mu G^\gamma_\nu d^4x = -g\int \partial^{\mu_2} G^{\alpha_1}_{\mu_1} g^{\mu_1\mu_3} f_{\alpha_1\alpha_2\alpha_3} G^{\alpha_2}_{\mu_2} G^{\alpha_3}_{\mu_3} d^4x$
where G^α_μ is the gluon field, g is the strong coupling constant.
Applying the Fourier transformation we get $S_{3G} =$
$(2\pi)^4 g \int \delta(p_1+p_2+p_3)\; i\; f_{\alpha_1\alpha_2\alpha_3} \times p_1^{\mu_2} g^{\mu_1\mu_3} G^{\alpha_1}_{\mu_1}(p_1) G^{\alpha_2}_{\mu_2}(p_2) G^{\alpha_3}_{\mu_3}(p_3) d^4p_1 d^4p_2 d^4p_3$
This vertex contains three identical fields, so the calculation of functional derivatives gives us six terms:
$\frac{\delta S_{3g}}{\delta G^{\alpha_1}_{\mu_1}(p_1)\delta G^{\alpha_2}_{\mu_2}(p_2)\delta G^{\alpha_3}_{\mu_3}(p_3)} = (2\pi)^4\delta(p_1+p_2+p_3)\; i\; f_{\alpha_1\alpha_2\alpha_3} \times g(p_1^{\mu_2} g^{\mu_1\mu_3} -$
$p_3^{\mu_2} g^{\mu_1\mu_3} + p_2^{\mu_3} g^{\mu_1\mu_2} - p_1^{\mu_3} g^{\mu_1\mu_2} + p_3^{\mu_1} g^{\mu_2\mu_3} - p_2^{\mu_1} g^{\mu_2\mu_3}) \Rightarrow$
$Factor \cdot LorentzPart =$
$-g\left((p_1^{\mu_2} - p_3^{\mu_2}) g^{\mu_1\mu_3} + (p_2^{\mu_3} - p_1^{\mu_3}) g^{\mu_1\mu_2} + (p_3^{\mu_1} - p_2^{\mu_1}) g^{\mu_2\mu_3}\right)$

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

Vertices. Example:Quark-gluon interaction

The interaction of a gluon with a quark is described by the $S_{QqG} = g\int G^{\alpha}_{\mu}(x)\bar{q}(x)\gamma^{\mu}\hat{t}_{\alpha}q(x)\,d^4x$ After the Fourier transformation and substituting $\bar{q} = q^{+}\gamma^{0}$ we get

$S_{QqG} = g(2\pi)^4\int\delta(p_1+p_2+p_3)\times G^{\alpha}_{\mu}(p_3)q^{+}(p_1)\gamma^0\gamma^{\mu}\hat{t}_{\alpha}q(p_2)\,d^4p_1d^4p_2d^4p_3$;

$$\frac{\delta S_{QqG}}{\delta q^{+}_{i}(p_1)\delta q^{j}(p_2)\delta G^{\alpha}_{\mu}(p_3)} = g(2\pi)^4\delta(p_1+p_2+p_3)(\hat{t}_{\alpha})^{i}_{j}\gamma^0\gamma^{\mu_3}\ .$$

The factor $(2\pi)^4\delta(p_1+p_2+p_3)(\hat{t}_{\alpha})^{i}_{j}\gamma^0$ is substituted by CompHEP automatically. Thus, the quark-gluon interaction is implemented in the CompHEP *Vertex* table as the following record:

A1	A2	A3	A4	Factor	Lorentz part
Q	q	G		GG	G(m3)

where q and Q are designations for a quark and a corresponding anti-quark.

Vertices. Example:Neutrino as a Majorana fermion

In the Standard Model only the left component of massless neutrino takes part in interactions. One can describe neutrino by a Majorana field which has the same number of degrees of freedom as a left Dirac one. For Dirac neutrino $Z\nu\bar{\nu}$ interactions take form: $L_{Z\nu\bar{\nu}} = \frac{e}{4\sin\Theta_w\cos\Theta_w} Z_\mu \bar{\Psi}_\nu \gamma^\mu (1-\gamma^5)\Psi_\nu$

CompHEP 's $Vertex$ table record is:

n1	N1	Z		EE/(4*SW*CW)	G(m3)*(1-G5)

To rewrite Dirac neutrino in terms of a Majorana fermion let us perform the substitution $\Psi_\nu = \frac{1}{2}(1-\gamma^5)\psi_l + \frac{1}{2}(1+\gamma^5)\psi_r$, where ψ_l and ψ_r are Majorana fermions. Omitting Lagrangian for ψ_r one gets:

$L_{Z\nu\nu} = -\frac{e}{4\sin\Theta_w\cos\Theta_w} Z_\mu \bar{\psi_l} \gamma^\mu \gamma^5 \psi_l$

we can rewrite it in the CompHEP notations:

MN	MN	Z		-EE/(2*SW*CW)	G(m3)*G5

Vertices. Example: Beyond the SM – Leptoquarks

Example of Lagrangian which contains the matrix of C-conjugation. Such matrix appears in interactions violating the fermion number. Let Ψ_e and Ψ_u be the fermion fields of electron and u-quark, interacting with the scalar complex leptoquark field F

$$L = \lambda \Psi_u^c (1+\gamma^5) \Psi_e F + \lambda \bar{\Psi}_e (1+\gamma^5) \bar{\Psi}_u^c F^+$$

where $\bar{\Psi}_e^c = C \bar{\Psi}_e^T = -\gamma^0 \bar{\Psi}_e^T$ and $\Psi_u^c = \Psi_u^T C = -\Psi_u^T \gamma^0$. So, the Lagrangian can be presented in the form

$$L = -\lambda \Psi_u^T \gamma^0 (1+\gamma^5) \Psi_e F + \lambda \Psi_u^+ \gamma^0 (1+\gamma^5) \Psi_e^+ F^+ \ .$$

Direct implementation of the definition above gives us the $Vertex$ table

A1	A2	A3	A4	Factor	Lorentz part
u	e1	F		-lambda	(1+G5)
E1	U	F+		lambda	(1+G5)

Vertices. Example: Beyond the SM – Anomalous WtB coupling

SM WtB interaction:

$$L_{WtB^{SM}} = \frac{g}{2\sqrt{2}} W_\nu^- \bar{b}\gamma^\nu(1-\gamma^5)t + h.c.$$

Let us introduce additional term:

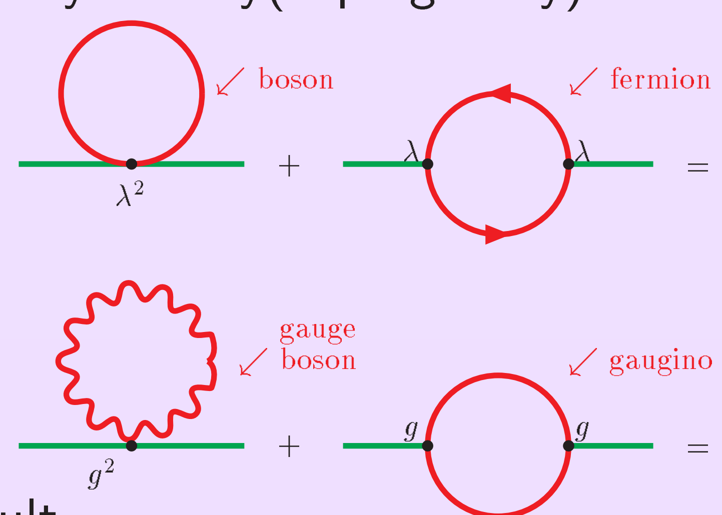
$$L_{WtB^R} = A_R \frac{g}{2\sqrt{2}} W_\nu^- \bar{b}\gamma^\nu(1+\gamma^5)t + h.c.$$

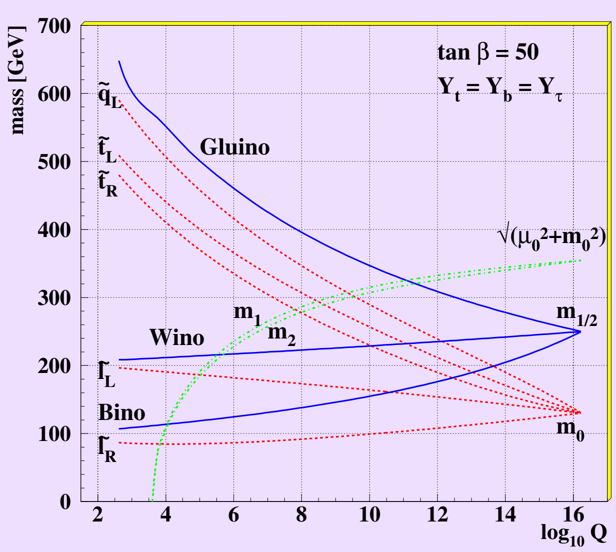
It will lead to additional term in the table:

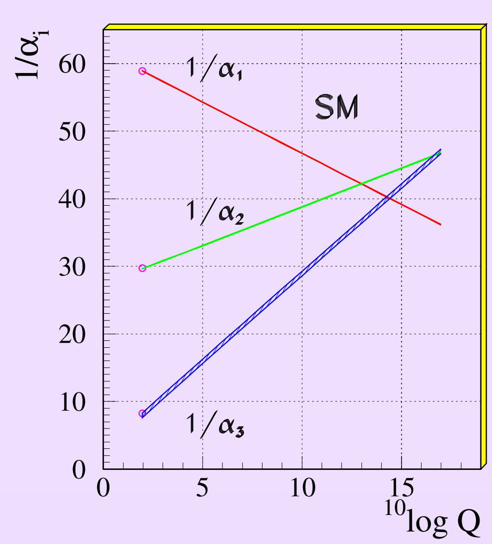
B	t	W-		EE/(2*sqrt2*SW)	G(m3)*((1-G5)+AR*(1+G5))
t	B	W+		EE/(2*sqrt2*SW)	G(m3)*((1-G5)+AR*(1+G5))

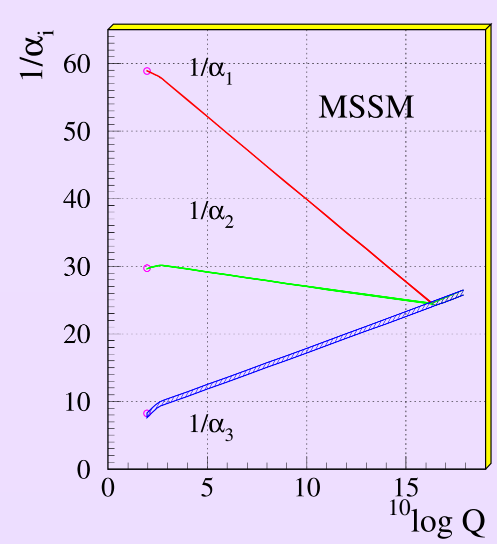
MSSM within CompHEP . Why the Supersymmetry is attractive?

- ⋆ Extension of space-time symmetry. Local supersymmetry(supergravity) includes Einstein's general relativity
- ⋆ Provides link to gravity
- ⋆ Solution of naturalness problem, cancellation of quadratic divergences
- ⋆ Provides the unification of gauge couplings
- ⋆ Electroweak symmetry breaking is derived result









MSSM: Lagrangian and particle content (1)

Superfield	Bosons		Fermions		$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge							
$\mathbf{G^a}$	gluon	g^a	gluino	$\tilde{g}^a$	8	0	0
$\mathbf{V^k}$	Weak	$W^k \quad (W^\pm, Z)$	wino, zino	$\tilde{w}^k \quad (\tilde{w}^\pm, \tilde{z})$	1	3	0
$\mathbf{V'}$	Hypercharge	$B \ (\gamma)$	bino	$\tilde{b}(\tilde{\gamma})$	1	1	0
Matter							
$\mathbf{L_i}$	sleptons	$\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons	$L_i = (\nu, e)_L$	1	2	-1
$\mathbf{E_i}$	sleptons	$\tilde{E}_i = \tilde{e}_R$	leptons	$E_i = e_R$	1	1	2
$\mathbf{Q_i}$	squarks	$\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks	$Q_i = (u, d)_L$	3	2	1/3
$\mathbf{U_i}$	squarks	$\tilde{U}_i = \tilde{u}_R$	quarks	$U_i = u_R^c$	3*	1	$-4/3$
$\mathbf{D_i}$	squarks	$\tilde{D}_i = \tilde{d}_R$	quarks	$D_i = d_R^c$	3*	1	2/3
Higgs							
$\mathbf{H_1}$	Higgses	H_1	higgsinos	$\tilde{H}_1$	1	2	-1
$\mathbf{H_2}$	Higgses	H_2	higgsinos	$\tilde{H}_2$	1	2	1

MSSM: Lagrangian and particle content (2)

Two parts: SUSY generalization of the Standard Model, and SUSY breaking:

$$\mathcal{L} = \mathcal{L}_{SUSY} + \mathcal{L}_{Breaking}, \quad \text{where} \quad \mathcal{L}_{SUSY} = \mathcal{L}_{Gauge} + \mathcal{L}_{Yukawa}$$

$$\mathcal{L}_{Gauge} = \sum_{SU(3),SU(2),U(1)} \frac{1}{4}\left(\int d^2\theta \; TrW^{\alpha}W_{\alpha} + \int d^2\bar{\theta} \; Tr\bar{W}^{\dot{\alpha}}\bar{W}_{\dot{\alpha}}\right) +$$

$$\sum_{Matter} \int d^2\theta d^2\bar{\theta} \; \Phi_i^{\dagger} e^{g_3\hat{V}_3 + g_2\hat{V}_2 + g_1\hat{V}_1}\Phi_i, \;\; \mathcal{L}_{Yukawa} = \int d^2\theta \, (\mathcal{W}_R + \mathcal{W}_{NR}) + h.c$$

R-parity – "$R = (-1)^{3(B-L)+2S}$ +" charge for all ordinary particles and a "$-$" charge to their superpartners
($i, j = 1-3$ are the $SU(2)$ and $a, b = 1-3$ are the generation indices).

$$W_R = \epsilon_{ij}(y^U_{ab}Q^j_a U^c_b H^i_2 + y^D_{ab}Q^j_a D^c_b H^i_1 + y^L_{ab}L^j_a E^c_b H^i_1 + \mu H^i_1 H^j_2),$$

$$W_{NR} = \epsilon_{ij}(\lambda^L_{abd}L^i_a L^j_b E^c_d + \lambda^{L\prime}_{abd}L^i_a Q^j_b D^c_d + \mu'_a L^i_a H^j_2) + \lambda^B_{abd}U^c_a D^c_b D^c_d$$

MSSM within CompHEP . The implementation

A.Belyaev, A.V.Gladyshev, A.V.Semenov; IFT – P.075/97, `hep-ph/hep-ph/9712303`

http://thsun1.jinr.ru/~comphep/ *http://theory.sinp.msu.ru/~semenov/*

- ⋆ notations of paper J.Rosiek (Phys. Rev. **D41** (1990) 3464)
- ⋆ Feynman rules generation has been done using LanHEP program
- ⋆ mSUGRA Assumptions:
  - ⧫ Universality of the soft breaking parameters at the GUT scale ($\sim 10^{16}$ GeV)
  - ⧫ diagonal form of Yukawa matrices and trilinear parameters
  - ⧫ gauge couplings unification
- ⋆ Independent parameters left: m_0 – universal scalar mass; $m_{1/2}$ – universal gaugino mass; $sign(\mu)$ – sign of Higgs mixing parameter A - the initial value of trilinear soft parameter B parameter – usually expressed via $\tan\beta$, the ratio of vevs of two Higgses

Full name	P	aP	2*spin	mass	width	color	aux
photon	A	A	2	0	0	1	G
Z boson	Z	Z	2	MZ	wZ	1	G
gluon	G	G	2	0	0	8	G
W boson	W+	W-	2	MW	wW	1	G
neutrino	n1	N1	1	0	0	1	L
electron	e1	E1	1	0	0	1	
mu-neutrino	n2	N2	1	0	0	1	L
muon	e2	E2	1	Mm	0	1	
tau-neutrino	n3	N3	1	0	0	1	L
tau-lepton	e3	E3	1	Mt	0	1	
u-quark	u	U	1	0	0	3	
d-quark	d	D	1	0	0	3	
c-quark	c	C	1	Mc	0	3	
s-quark	s	S	1	Ms	0	3	
t-quark	t	T	1	Mtop	wtop	3	
b-quark	b	B	1	Mb	0	3	
Light Higgs	h	h	0	Mh	wh	1	
Heavy higgs	H	H	0	MHH	wHh	1	
3rd Higgs	H3	H3	0	MH3	wH3	1	
Charged Higgs	H+	H-	0	MHc	wHc	1	
chargino 1	~1+	~1-	1	MC1	wC1	1	
chargino 2	~2+	~2-	1	MC2	wC2	1	
neutralino 1	~o1	~o1	1	MNE1	wNE1	1	
neutralino 2	~o2	~o2	1	MNE2	wNE2	1	

Name	Value	Comment	Name	Value	Comment	Name	Value	Comment
EE	0.31333	$\sqrt{4\pi\alpha_{em}}$	TB	41.2	$\tan\beta$	wSe1	7.70	$\Gamma(\tilde{e}_1)$
GG	1.117	$\sqrt{4\pi\alpha_s}$	hx	-220	μ	MSe2	806	$m_{\tilde{e}_2}$
SW	0.474	$sin\theta_W$	ls1	0	A_L^1	wSe2	3.39	$\Gamma(\tilde{e}_2)$
s12	0.221	CKM	ls2	0	A_L^2	MSmu1	804	$m_{\tilde{\mu}_1}$
s23	0.04	CKM	ls3	4.62	A_τ	wSmu1	7.70	$\Gamma(\tilde{\mu}_1)$
s13	0.0035	CKM	us1	0	A_U^1	MSmu2	806	$m_{\tilde{\mu}_2}$
MZ	91.187	M_Z	us2	0	A_U^2	wSmu2	3.39	$\Gamma(\tilde{\mu}_2)$
Zn11	0.152	Z_N^{11}	us3	106	A_t^3	MStau1	557	$m_{\tilde{\tau}_1}$
Zn12	0.060	Z_N^{12}	ds1	0	A_D^1	wStau1	27.5	$\Gamma(\tilde{\tau}_1)$
Zn13	-0.953	Z_N^{13}	ds2	0	A_D^2	MStau2	695	$m_{\tilde{\tau}_2}$
Zn14	-0.255	Z_N^{14}	ds3	3.32	A_b	wStau2	36.5	$\Gamma(\tilde{\tau}_2)$
Zn21	0.681	Z_N^{21}	wZ	2.502	$\Gamma(Z)$	MSne	801	$m_{\tilde{\nu}_e}$
Zn22	-0.172	Z_N^{22}	wW	2.094	$\Gamma(W)$	wSne	10.8	$\Gamma(\tilde{\nu}_e)$
Zn23	0.274	Z_N^{23}	Mm	0.1057	m_μ	MSnmu	801	$m_{\tilde{\nu}_\mu}$
Zn24	-0.657	Z_N^{24}	Mt	1.777	m_τ	wSnmu	16.3	$\Gamma(\tilde{\nu}_\mu)$
Zn31	-0.092	Z_N^{31}	Mc	1.3	m_c	MSntau	801	$m_{\tilde{\nu}_\tau}$
Zn32	-0.983	Z_N^{32}	Ms	0.2	m_s	wSntau	35.4	$\Gamma(\tilde{\nu}_\tau)$
Zn33	-0.107	Z_N^{33}	Mtop	175	m_t	MSu1	831	$m_{\tilde{u}_1}$
Zn34	0.117	Z_N^{34}	wtop	1.442	$\Gamma(t)$	wSu1	55.8	$\Gamma(\tilde{u}_1)$
Zn41	0.710	Z_N^{41}	Mb	4.3	m_b	MSu2	830	$m_{\tilde{u}_2}$
Zn42	0.025	Z_N^{44}	Mh	110	m_h	wSu2	48.0	$\Gamma(\tilde{u}_2)$
Zn43	-0.072	Z_N^{43}	wh	0.088	$\Gamma(h)$	MSd1	835	$m_{\tilde{d}_1}$
Zn44	0.700	Z_N^{44}	MHH	273	m_H	wSd1	157.5	$\Gamma(\tilde{d}_1)$
Zm11	0.918	Z_-^{11}	wHh	18.6	$\Gamma(H)$	MSd2	831	$m_{\tilde{d}_2}$
Zm12	0.397	Z_-^{12}	MH3	273	m_A	wSd2	46.9	$\Gamma(\tilde{d}_2)$

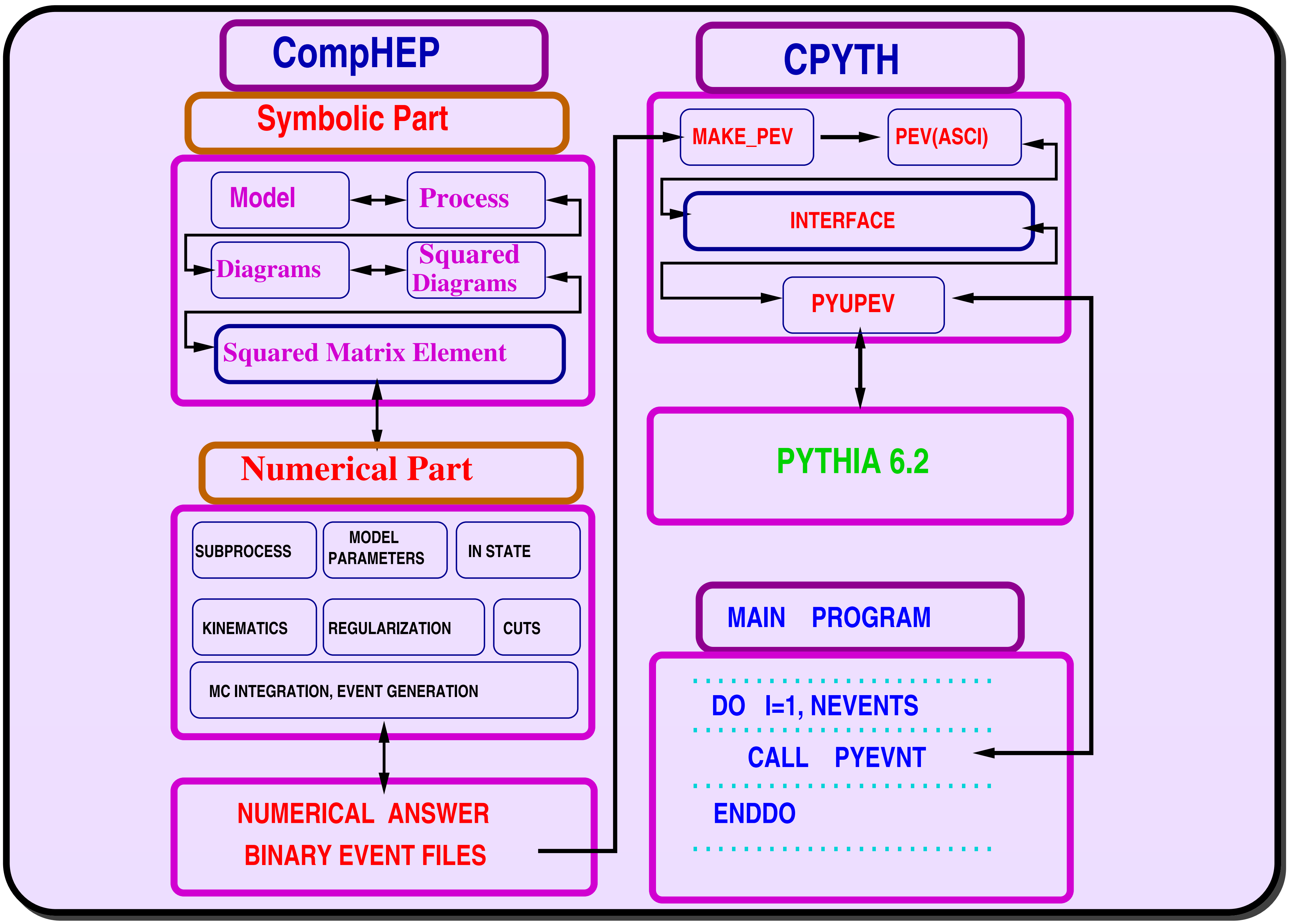
CompHEP-PYTHIA interface

A.S. Belyaev, E.E. Boos, A.N. Vologdin, M.N. Dubinin, V.A. Ilyin, A.P. Kryukov, A.E. Pukhov, A.N. Skachkova, V.I. Savrin, A.V. Sherstnev, S.A. Shichanin

hep-ph/0101232, presentation of V.A. Ilyin at ACAT2000

/afs/cern.ch/cms/physics/PEVLIB

- ⋆ CompHEP ⇒ multi-body final state process
- ⋆ events from CompHEP ⇒ input for PYTHIA, ISAJET, HERWIG
- ⋆ We propose to separate the *matrix element* and *decay/showers/hadronization* steps of the computations:
- ⋆ it allows to develop/implement new options in these two steps
- ⋆ it gives a possibility to input parton events in different programs for the second step (PYTHIA, ISAJET, HERWIG etc)
- ⋆ CompHEP plays a role of generator of generators


CompHEP
Symbolic Part
Model
Process
Diagrams
Squared Diagrams
Squared Matrix Element
Numerical Part
SUBPROCESS
MODEL PARAMETERS
IN STATE
KINEMATICS
REGULARIZATION
CUTS
MC INTEGRATION, EVENT GENERATION
NUMERICAL ANSWER
BINARY EVENT FILES
CPYTH
MAKE_PEV
PEV(ASCI)
INTERFACE
PYUPEV
PYTHIA 6.2
MAIN PROGRAM
DO I=1, NEVENTS
CALL PYEVNT
ENDDO

```
>./PGEN.exe | more



                         Event listing (summary)

    I particle/jet KS     KF  orig    p_x      p_y      p_z       E        m

    1 !p+!         21    2212    0    0.000    0.000 1000.000 1000.000    0.938
    2 !pbar-!      21   -2212    0    0.000    0.000-1000.000 1000.000    0.938
 ==============================================================================
    3 !u!          21       2    1    0.191    0.764  480.893  480.894    0.000
    4 !dbar!       21      -1    2    0.016    0.351   -6.669    6.679    0.000
    5 !u!          21       2    3    0.191    0.764  480.893  480.894    0.000
    6 !dbar!       21      -1    4    0.016    0.351   -6.669    6.679    0.000
    7 !b!          21       5    0    4.830   -1.804    3.641    7.822    4.620
    8 !bbar!       21      -5    0   -1.680    9.784   52.166   53.303    4.620
    9 !W+!         21      24    0   -2.943   -6.865  418.416  426.447   82.031
 ==============================================================================
   10 (W+)         11      24    9   -2.943   -6.865  418.416  426.447   82.031
   11 mu+           1     -13   10  -39.809    9.479  175.617  180.322    0.106
   12 nu_mu         1      14   10   36.866  -16.343  242.799  246.125    0.000
   13 (b)       A  12       5    7    4.830   -1.804    3.641    7.822    4.620
   14 (bbar)    V  11      -5    8   -1.680    9.784   52.166   53.303    4.620
   15 (ud_1)    A  12    2103    1   -0.191   -0.764  519.101  519.102    0.771
   16 (uu_1bar) V  11   -2203    2   -0.016   -0.351 -993.325  993.325    0.771
 ==============================================================================
```

$jjbb$ process

This is important background for Hbb SUSY process. It involves 126 diagrams, therefore quark flavor simplification is important in this case.

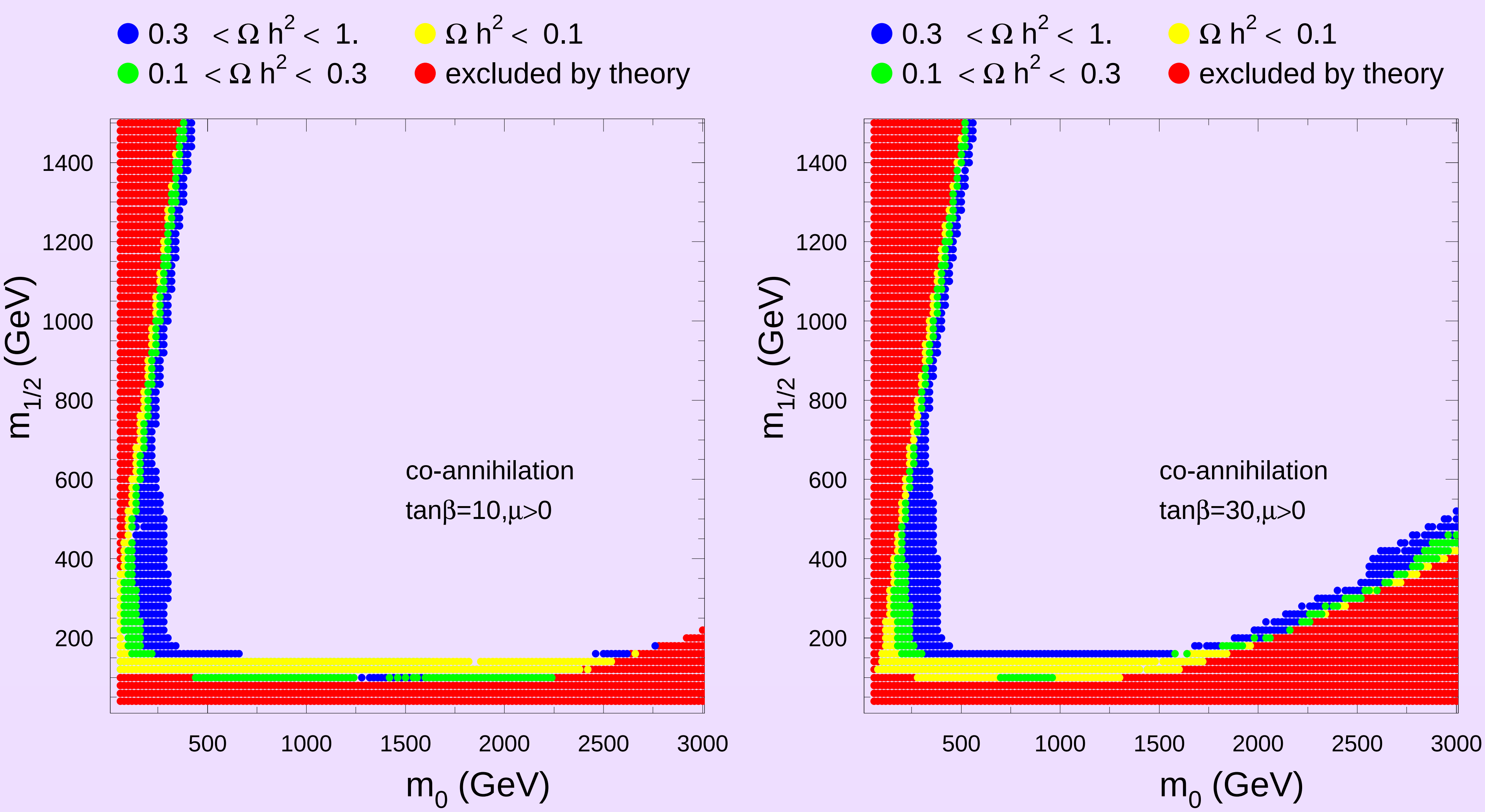
```
--------------------------------
u ,u -> u ,u ,b ,B 1    0.155E+03
u ,U -> s ,S ,b ,B 2    0.107E+02
u ,U -> c ,C ,b ,B 3    0.104E+02
u ,U -> d ,D ,b ,B 4    0.105E+02
u ,U -> u ,U ,b ,B 5    0.990E+03
u ,U -> G ,G ,b ,B 6    0.487E+03
U ,u -> s ,S ,b ,B 7    0.435E+00
U ,u -> c ,C ,b ,B 8    0.422E+00
U ,u -> d ,D ,b ,B 9    0.432E+00
U ,u -> u ,U ,b ,B 10   0.172E+02
U ,u -> G ,G ,b ,B 11   0.171E+02
U ,U -> U ,U ,b ,B 12   0.152E+03
d ,d -> d ,d ,b ,B 13   0.914E+02
d ,D -> s ,S ,b ,B 14   0.399E+01
d ,D -> c ,C ,b ,B 15   0.391E+01
d ,D -> d ,D ,b ,B 16   0.272E+03
d ,D -> u ,U ,b ,B 17   0.401E+01
d ,D -> G ,G ,b ,B 18   0.174E+03
D ,d -> s ,S ,b ,B 19   0.677E+00
D ,d -> c ,C ,b ,B 20   0.665E+00
D ,d -> d ,D ,b ,B 21   0.311E+02
D ,d -> u ,U ,b ,B 22   0.679E+00
D ,d -> G ,G ,b ,B 23   0.278E+02
D ,D -> D ,D ,b ,B 24   0.894E+02
--------------
```

```
s ,s -> s ,s ,b ,B 1    0.935E+01
s ,S -> s ,S ,b ,B 2    0.100E+02
s ,S -> c ,C ,b ,B 3    0.239E+00
s ,S -> d ,D ,b ,B 4    0.248E+00
s ,S -> u ,U ,b ,B 5    0.248E+00
s ,S -> G ,G ,b ,B 6    0.985E+01
S ,s -> s ,S ,b ,B 7    0.996E+01
S ,s -> c ,C ,b ,B 8    0.241E+00
S ,s -> d ,D ,b ,B 9    0.246E+00
S ,s -> u ,U ,b ,B 10   0.246E+00
S ,s -> G ,G ,b ,B 11   0.989E+01
S ,S -> S ,S ,b ,B 12   0.940E+01
c ,c -> c ,c ,b ,B 13   0.195E+01
c ,C -> s ,S ,b ,B 14   0.604E-01
c ,C -> c ,C ,b ,B 15   0.215E+01
c ,C -> d ,D ,b ,B 16   0.606E-01
c ,C -> u ,U ,b ,B 17   0.606E-01
c ,C -> G ,G ,b ,B 18   0.231E+01
C ,c -> s ,S ,b ,B 19   0.604E-01
C ,c -> c ,C ,b ,B 20   0.215E+01
C ,c -> d ,D ,b ,B 21   0.609E-01
C ,c -> u ,U ,b ,B 22   0.609E-01
C ,c -> G ,G ,b ,B 23   0.230E+01
C ,C -> C ,C ,b ,B 24   0.199E+01
--------------
```

More about CompHEP application

- ⋆ MCDB at FNAL and CERN based on the CompHEP's parton-level events
- ⋆ user can easy create/modify his own model
- ⋆ covers QCD,top, Higgs, SUSY, RPV SUSY, technicolor, EXD, compositeness(recent paper), LQ
- ⋆ even was used for relic density calculation in SUGRA, SO(10) and gaugino-mediated models [Baer,Balazs,A.B. JHEP(02)]
  - ♦ initial state: $\widetilde{Z}_1$, $\widetilde{Z}_2$, $\widetilde{W}_1$, $\tilde{e}_1$, $\tilde{\mu}_1$, $\tilde{\tau}_1$, $\tilde{t}_1$ and $\tan\beta_1$
  - ♦ $relativistic$ thermal averaging
  - ♦ exact calculations: CompHEP – over 1000 subprocesses
  - ♦ weak scale parameters from supersymmetric models are generated using ISAJET and interfaced with the squared matrix elements from CompHEP

Neutralino relic density in cMSSM



Neutralino relic density in cMSSM