CalcHEP a package for automatic computation in HEP.

A.Pukhov, SINP MSU, Russia

CalcHEP is a package for computation of Feynman diagrams, integration over multi-particle phase space, and partonic level event generation.

It is restricted by tree level calculations but from other side can be applied to any model of particle interaction.

There are two versions of this soft
CompHEP: http://theory.sinp.msu.ru/comphep
presented by Boos, Dubinin, Bunichev, Dudko, Edneral, Kryukov, Ilyin, Savrin, Sherstnev, Semenov.

and CalcHEP: http://theory.sinp.msu.ru/˜ pukhov/calchep.html
presented by me.

In general both versions have the same facilities, but some details now after 5 years of independent development are different. In this talk I present my version of this soft, CalcHEP.

General features 1

The main idea prescribed into CalcHEP is to make available the passing on from Lagrangians to final distributions effectively with a high level of automation. The *beta release* ***of this soft was a program for registration of appellations in Supreme Court or Russia Federation. Thus from the beginning it was a menu driven system with service at the level of office programs written 15 yeas ago. Later on the special efforts were done to force it to work in non interactive*** *batch* ***regime. The program has a menu sensitive HELP and is accompanied by documentation.***

The computation technique used in CaclHEP also is very old. Calchep is based on method of symbolic calculation of squared diagrams. Calculated diagrams are transformed into C-code. The squaring significantly increases the number of diagram which itself increase factorial in number of legs. Because of it CalcHEP is restricted by $2 -> 4$ ***processes, but for this type of procesees is works as fast as other modern programs.***

General features 2

The existing of symbolic step makes CalcHEP very convenient for installations of new models. CalcHEP now is a very popular tool for investigation of BSM physics.

In the same time a lot of effors were done to support interface with other programs used in High Energy physics.
i) interface with *CERN PDFLIB* ***library, interface with modern*** *CTEQ* ***and*** *MRST* ***parton distributions;***
ii) interface with HERWIG and PHYTHIA.
iii) inteface with SUSY spectrum generators *Isajet, SuSpect, SoftSusy, Spheno, NMHdecay, CPSUPERH;*

Interface is realized in such a way that external code is not obligatory.

CalcHEP can be used as a generator of codes of matrix elements for other projects. Here the main example is the *MicrOMEGAs* ***package where matrix elements generated by CalcHEP are used for prediction of Dark Matter.***

Why it works? (Internal symbolic calculator)

CalcHEP has very efficient *symbolic calculator*. **It analizes each diagram and creates representation of symbolic expressions optimazed for the given diagram. For example, for 6 legs diagrams we typicaly have 10 independent scalar products with maximum power 4. Then monom of scalar products**

$$p_1{\cdot}p_2^{n_1}\, p_1{\cdot}p_3^{n_2}\, p_1{\cdot}p_4^{n_3}\, p_1{\cdot}p_5^{n_4}\, p_2{\cdot}p_3^{n_5}\, p_2{\cdot}p_4^{n_6}\, p_2{\cdot}p_5^{n_7}\, p_3{\cdot}p_4^{n_8}\, p_3{\cdot}p_5^{n_9}\, p_4{\cdot}p_5^{n_{10}}$$

is presented by one number (for 32 bits computer)

$$N = n_1 + 5(n_2 + 5(n_3 + 5(n_4 + 5(n_5 + 5(n_6 + 5(n_7 + 5(n_8 + 5(n_9 + 5n_{10}))))))))$$

Multiplication of two monoms corresponds to summatiom of the corresponting numbers. To present Lorentz and spinor structures the ideas realized in the package Dirac (A. Grozin) were used. They are presented by some arrays which are as short as possible according to number of Lorentz indixes and γ matrices in the given diagram.

At this step CalcHEP is about 10 times faster than standard packages for symbolic calculations.

Why it works? (t'Hooft-Feynman gauge)

CalcHEP can work in two gauges, the *physical* **one**

$$T[V_\mu(k_1), V_\nu(k_2)] \approx \delta(k_1 - k_2)\left(g_{\mu\nu} - \frac{k_1 k_2}{M^2}\right)/(k_1^2 - M^2)$$

and the *t'Hooft-Feynman* **one**

$$T[V_\mu(k_1), V_\nu(k_2)] \approx \delta(k_1 - k_2) g_{\mu\nu}/(k_1^2 - M^2)$$

In the second case we get shorter symbolic expressions, but additions diagrams with Goldstone. In the t'Hooft-Feynman gauge all auxiliary states have the same masses as the corresponding physical particle. The contribution of all unphysical states including 2 Faddeev-Popov ghosts, Goldstone and time-like vector state has to be zero according to gauge invariance. If we add this zero to the sum over physical states it will improve density matrix for vector particles

$$\left(g_{\mu\nu} - \frac{k_1 k_2}{M^2}\right) \quad \rightarrow \quad g_{\mu\nu}$$

Why it works? (t'Hooft-Feynman gauge 2)

Thus including diagram with ghost and gondstone states in the place of virtual and external vector particles CalcHEP solves the problem of ultra-violet diagram cancellation caused by gauge invariance. To realize such trick in framework of amplitude method one has to treat vector boson as a state with 7 'polarization' states.

Each additional diagram has the same denominators as the mother diagram where auxiliary fields are replaced on initial vector boson. Calchep sums all of them together with mother diagram and the size of resulting symbolic expression is about the same as the size of each term.

Diagrams self cancelation and width implementation.

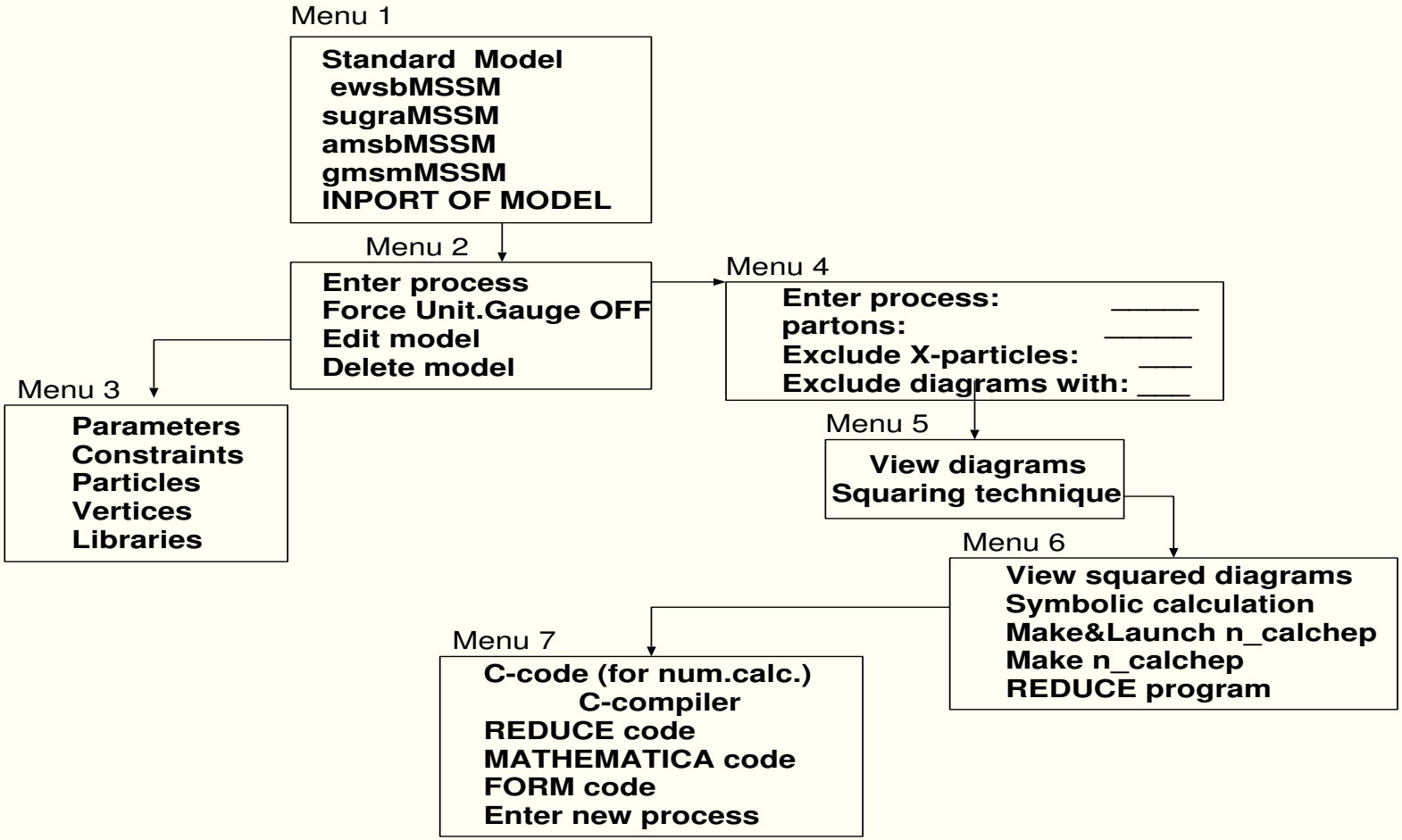
In the unitary gauge we have diagram calcelation and calculation becames unstable in case of particle widths implementation which breaks gauge invarience. The problem can be solved (?) by restoring zero width propagator far from the pole. Other solution is the multiplication of non-pole diagrams on factors like

$$\frac{(p^2 - M^2)^2}{(p^2 - M^2)^2 + (M \cdot w)^2}$$

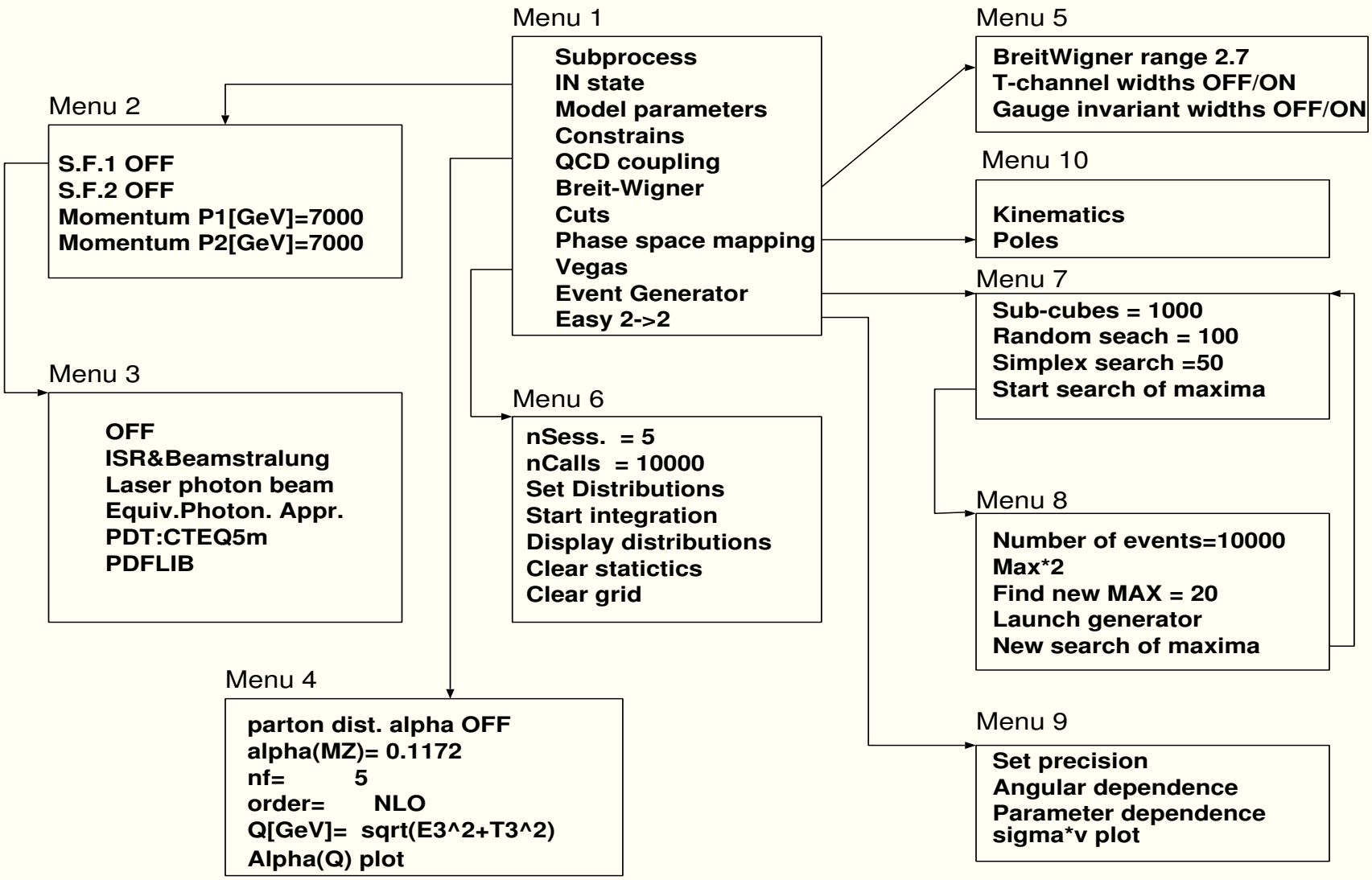
which corresponds to substitution of width in common denominator after symbolic sumation of all diagrams. CalcHEP has the corresponding option.

Symbolic part

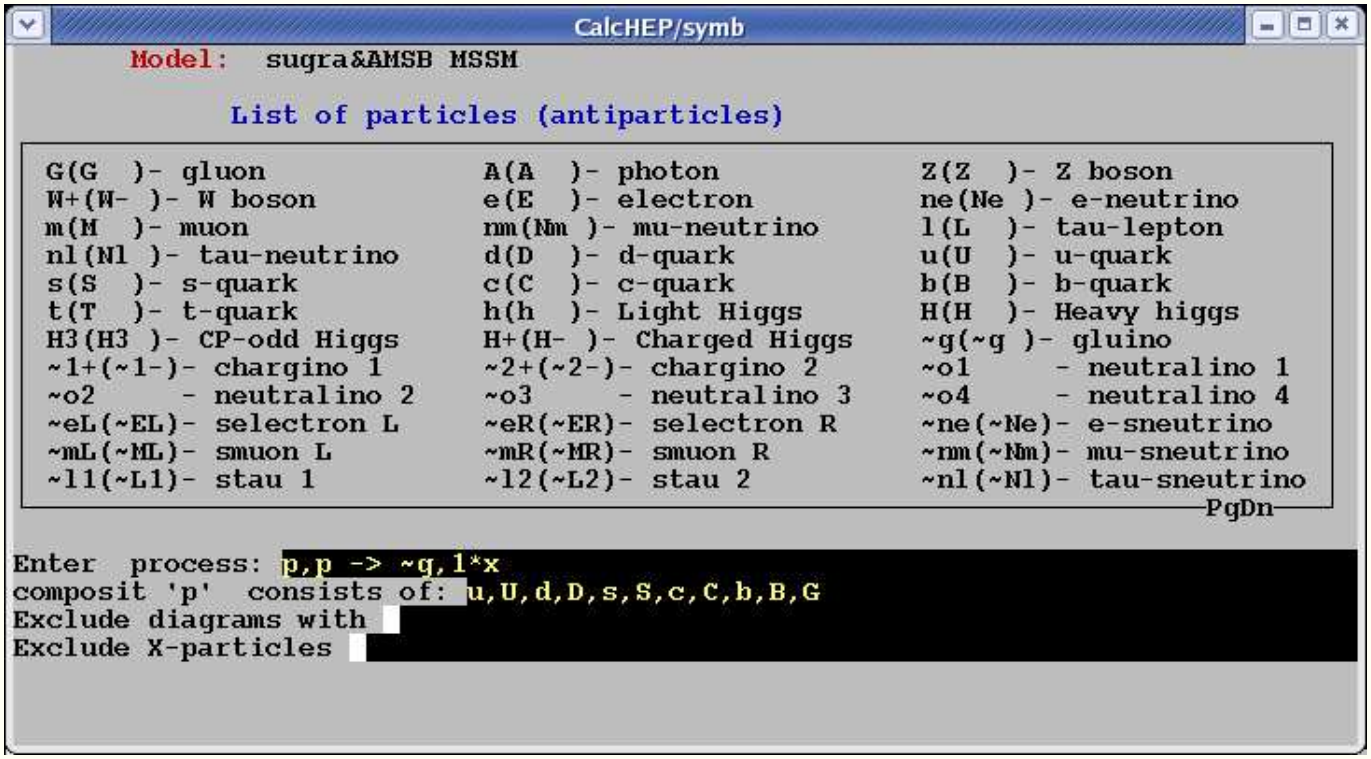
Calchep symbolic session is intended to generate C-code of matrix elements which are linked with tools for numerical calculations.



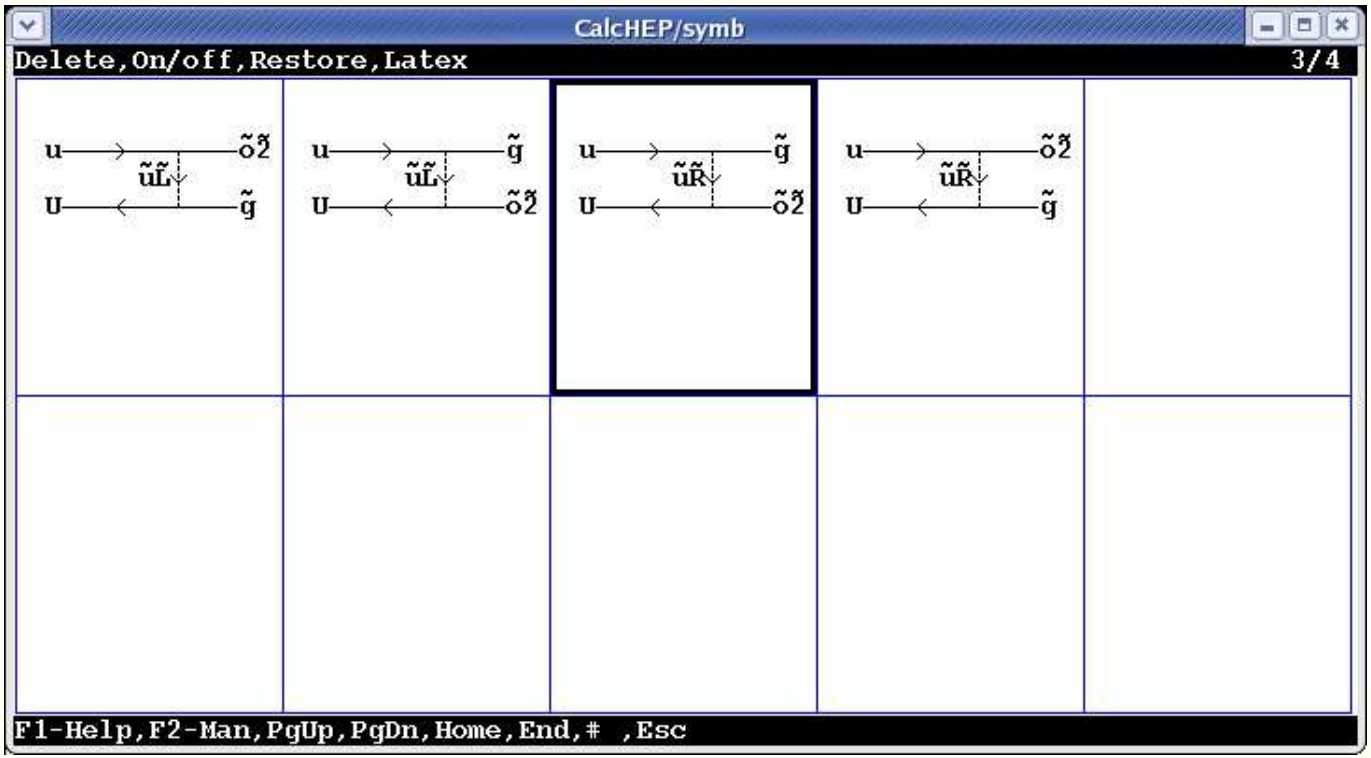
Numerical part.



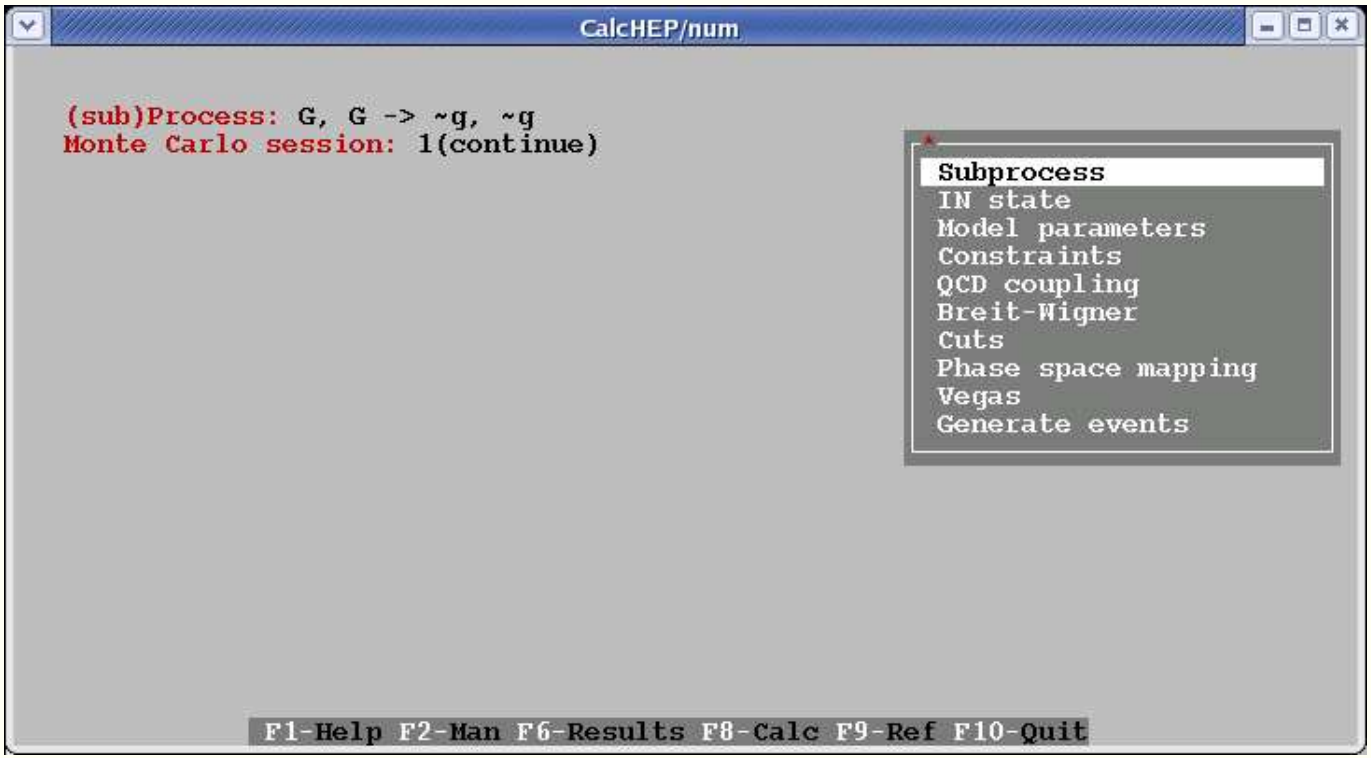
How it looks. 1



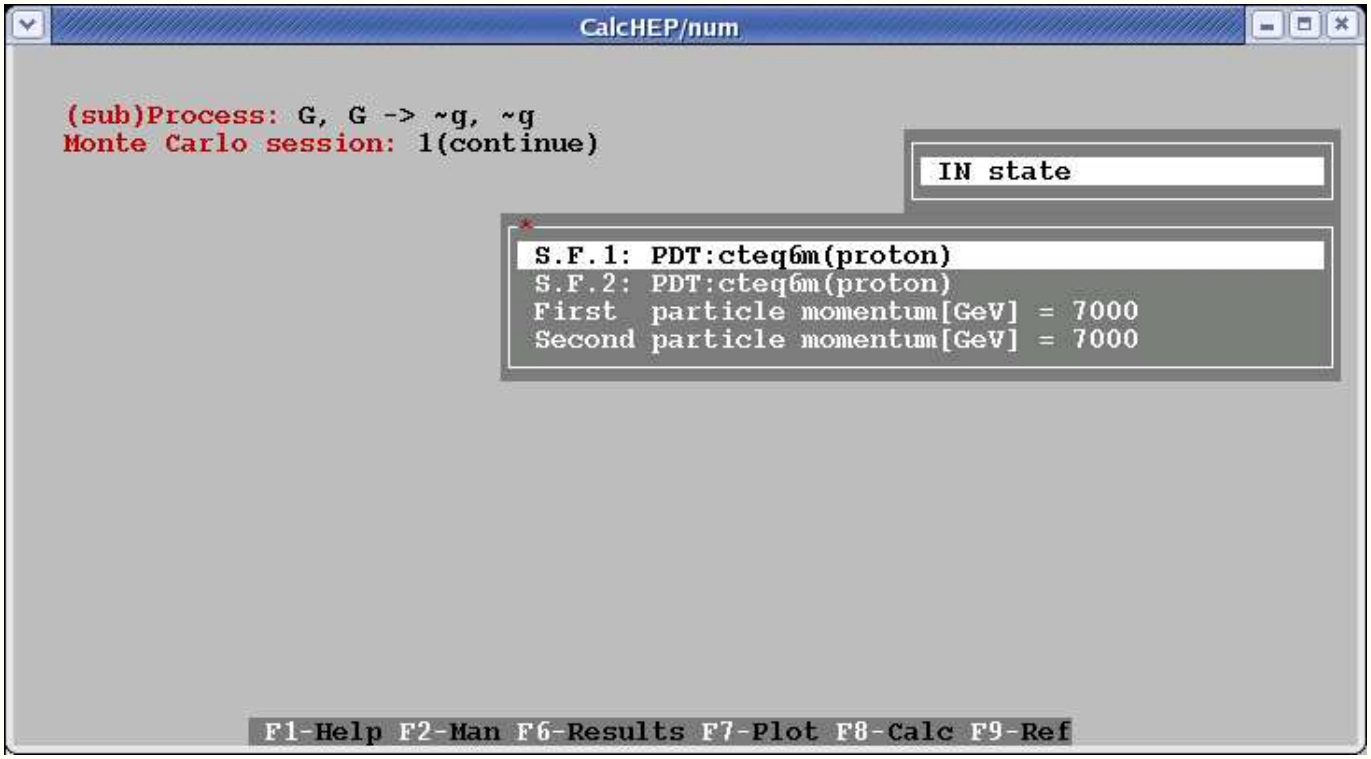
How it looks. 2



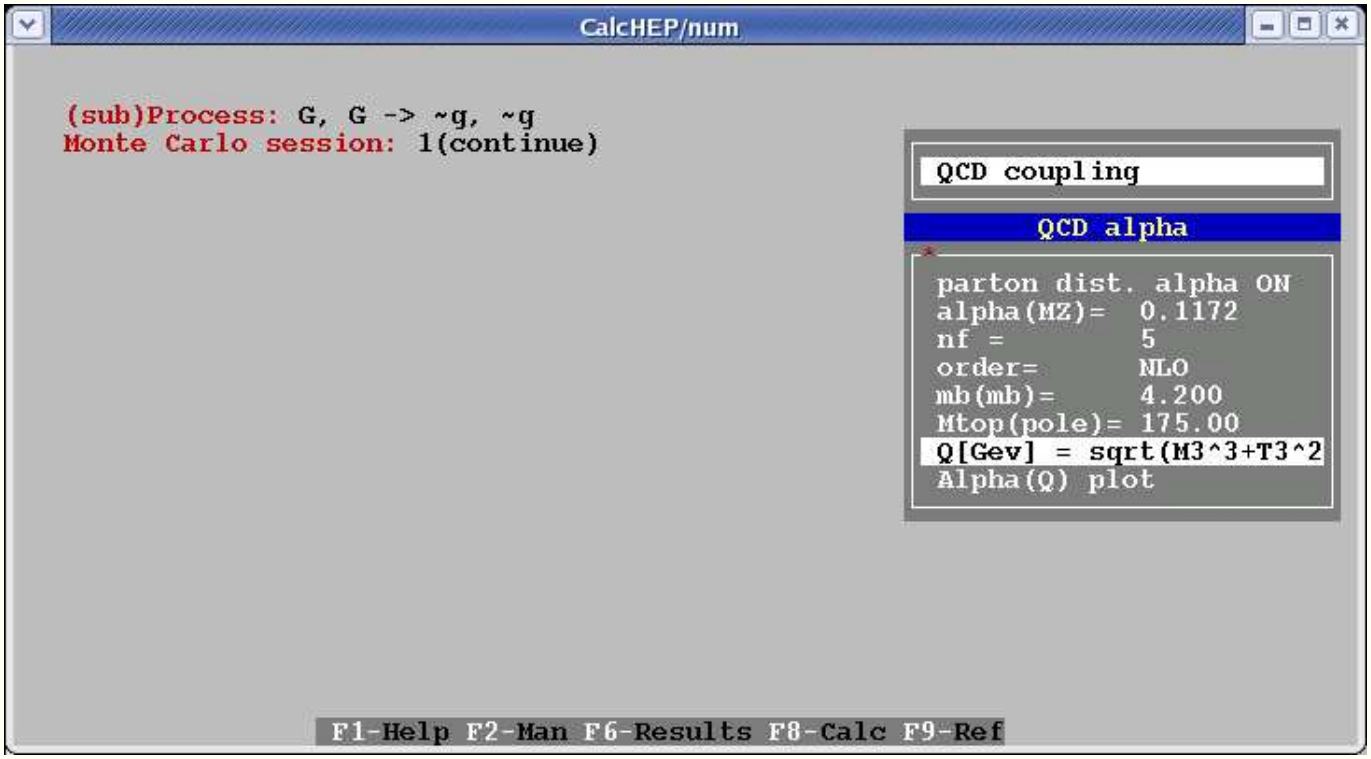
How it looks. 3



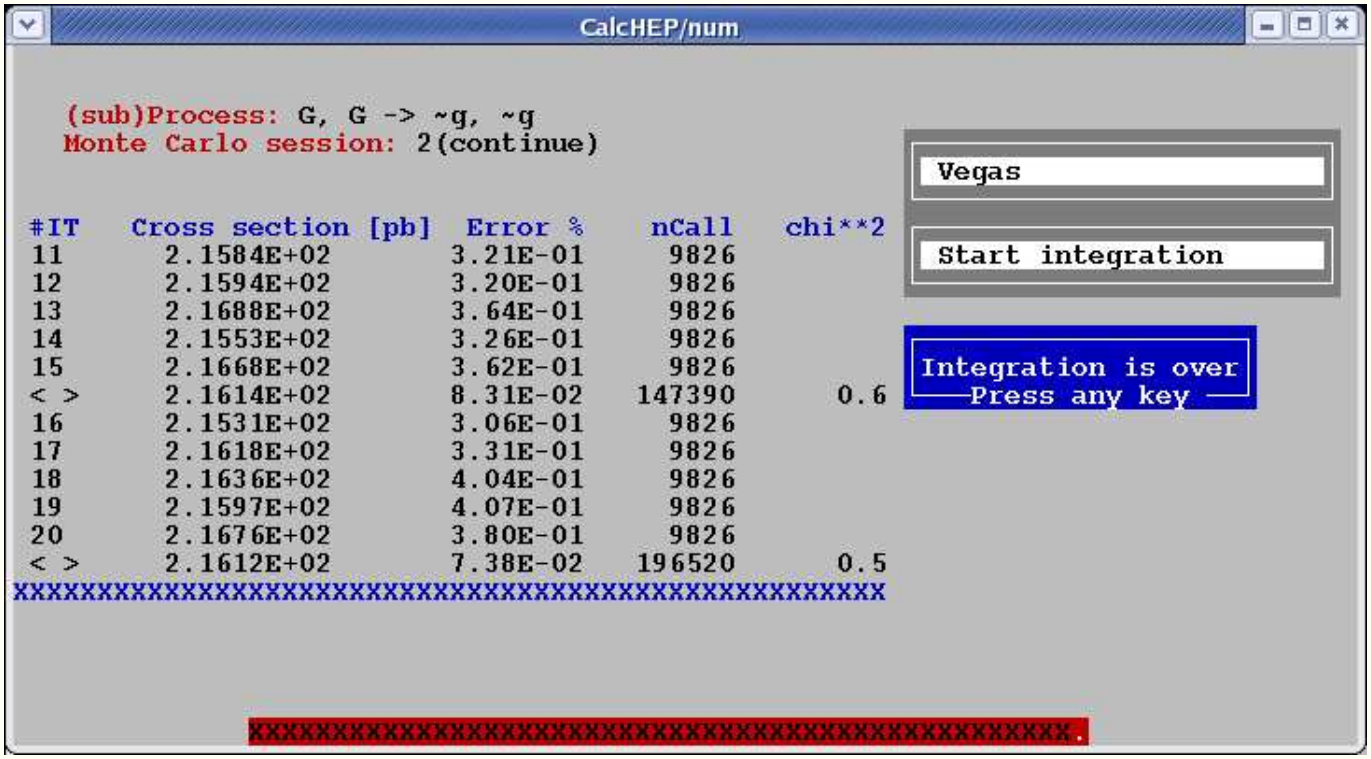
How it looks. 4



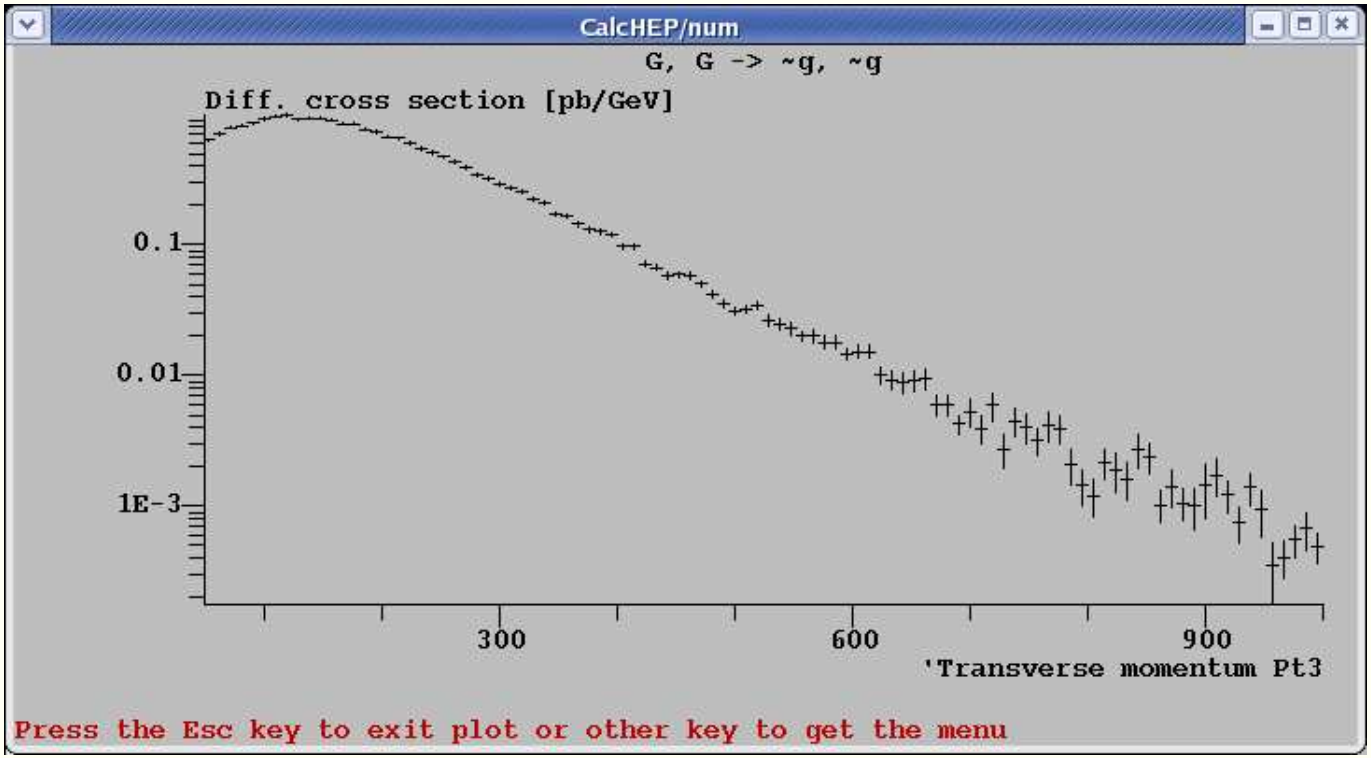
How it looks. 5



How it looks. 6



How it looks. 7



Model structure.

The model is presented by four files:

Variables

Name	Value	Comment
alfEMZ	0.0078180608	MS-BAR electromagnetic alpha(MZ)
alfSMZ	0.1172	Strong coupling constant
SW	0.481	MS-BAR sin of the Weinberg angle
MZ	91.1884	Z mass
Ml	1.777	mass of tau lepton
MbMb	4.23	b-quark mass
tb	10	Tangent beta
mZero	450	scalar masses at GUT
mGrav	60000	Gravitino mass
sgn	1	sign of mu

```
            Constraints
  Name  |> Expression
 smOk   |saveSM(MbMb,Mtp,SW,alfSMZ,alfEMZ,MZ,Ml)
 ambsOk|suspectAMSB(mZero,mGrav,tb,sgn)*one(smOk)
 *Mh    |Mh(ambsOk)
%wh     |wh(ambsOk)
```

The dummy parameters `smOk` ***and*** `ambsOk` ***are used to show dependences caused by implicit parameters.***

Star before `Mh` ***is a signal that*** `Mh` ***will be attached to C code even if does not contribute to matrix element.***

`suspectAMSB` ***is external function which has to be passed to linker.***

Particles

Full name	P	aP	number	2*spin	mass	width	color	aux
gluon	G	G	21	2	0	0	8	G
photon	A	A	22	2	0	0	1	G
Z boson	Z	Z	23	2	MZ	wZ	1	G
W boson	W+	W-	24	2	MW	wW	1	G
b-quark	b	B	5	1	Mb	0	3	
t-quark	t	T	6	1	Mt	wt	3	
Light Higgs	h	h	25	0	Mh	!wh	1	
Heavy higgs	H	H	35	0	MHH	!wHh	1	

There is a way to force automatic width calculation. "!wh" is a signal that code for `h->2*x` ***will be generated and added to the main matrix element.***

The presence of PDG number as particle attribute simplifies the interface with other packages. For instance Pythia and parton distribution codes. In the last case the 81 and 83 PDG code are used for d' and s' states which diagonalize CKM matrix. CalcHEP automataly correct parton distribution for such states. See details in hep-ph/0004194(CompHEP) and hep-ph/0412191(CalcHEP)

Vertices

P1	P2	P3	P4	Factor	dLagrangian/dA(p1)dA(p2)dA(p3)
A	H+	H-		-EE	m1.p2-m1.p3
A	W+	W-		-EE	m1.p3*m2.m3-m2.p3*m1.m3- ...
B	b	A		EE/3	G(m3)
B	b	G		GG	G(m3)
G	G	G.t		GG/Sqrt2	m1.M3*m2.m3-m1.m3*m2.M3
T	b	W+		EE/2/Sqrt2/SW	G(m3)*(1-G5)
T	b	W+.f		-i*EE/2/Sqrt2/MW/SW	Mb*(1+G5)-Mt *(1-G5)
A.C	W-.c	W+		-EE	p1.m3

G.t - point-like auxiliary tensor particles for 4-gluon vertex.

A.c/A.C - Faddev Popov ghosts

W+.f - goldstone

Generation of model files by Lanhep.

Lanhep package written by Andrei Semenov

A. Semenov. Nucl.Inst.\&Meth. A393 (1997) p. 293.
A.~Semenov, preprint LAPTH-884/01, 2001 (hep-ph0208011).
http://theory.sinp.msu.ru/~semenov/lanhep.html

solves the problem of generation of CalcHEP tables. Lanhep input is easy readable files. The package performs *let* ***substitutions,*** *where* ***cycles, dummy indexes convolution, work with fields multiplets, check of generated mass matrix, and recognizes appearance of mixing matrices.***

The first SUSY implementation in Lanhep terms was done by

A.~Belyaev, A.~Gladyshev, A.~Semenov,
preprint IFT--P--093--97 (hep-ph/9712303).

For example, in MSSM

```
%% SU(2) DD terms
let s_q1  = {~uL,~dL }, s_Q1=anti(s_q1).

let a1=g*s_Q1*tau*s_q1/2,
    a2=g*s_Q2*tau*s_q2/2,
    a3=g*s_Q3*tau*s_q3/2,
    a4=g*s_L1*tau*s_l1/2,
    a5=g*s_L2*tau*s_l2/2,
    a6=g*s_L3*tau*s_l3/2,
    a7=g*s_H1*tau*s_h1/2,
    a8=g*s_H2*tau*s_h2/2.

lterm  -(a1+a2+a3+a4+a5+a6+a7+a8) ** 2 / 2.
```

FF terms coming from superpotential:

```
lterm ( -df(superW,Ai,Aj)*Fi*Fj/2 + AddHermConj
where
 Ai=s_h1,Fi=f_h1; Ai=s_h2,Fi=f_h2; Ai=s_n, Fi=f_N;
 Ai=s_l1,Fi=f_l1; Ai=s_l2,Fi=f_l2; Ai=s_l3,Fi=f_l3;
 Ai=s_r1,Fi=f_r1; Ai=s_r2,Fi=f_r2; Ai=s_r3,Fi=f_r3;
 Ai=s_q1,Fi=f_q1; Ai=s_q2,Fi=f_q2; Ai=s_q3,Fi=f_q3;
 Ai=s_u1,Fi=f_u1; Ai=s_u2,Fi=f_u2; Ai=s_u3,Fi=f_u3;
 Ai=s_d1,Fi=f_d1; Ai=s_d2,Fi=f_d2; Ai=s_d3,Fi=f_d3)
where
 Aj=s_h1,Fj=f_h1; Aj=s_h2,Fj=f_h2; Aj=s_n, Fj=f_N;
 Aj=s_l1,Fj=f_l1; Aj=s_l2,Fj=f_l2; Aj=s_l3,Fj=f_l3;
 Aj=s_r1,Fj=f_r1; Aj=s_r2,Fj=f_r2; Aj=s_r3,Fj=f_r3;
 Aj=s_q1,Fj=f_q1; Aj=s_q2,Fj=f_q2; Aj=s_q3,Fj=f_q3;
 Aj=s_u1,Fj=f_u1; Aj=s_u2,Fj=f_u2; Aj=s_u3,Fj=f_u3;
 Aj=s_d1,Fj=f_d1; Aj=s_d2,Fj=f_d2; Aj=s_d3,Fj=f_d3.
```

A very usefull tool.

Batchs calculation

Initially CalcHEP was desined for work in interactive sessions. Later on it was recognized that batch calculations also are needed. This problem was solved by the following trick.

In the end of interactive session launched with option "+blind", for example,

```
calchep  +blind
```

program writes on the screen the sequence of pressed keys. Let we enter the process `e,E->W+,W-`*, perform symbolic calculation and write C code for matrix elements. Then output should be*

```
{{e,E->W+,W-{{[{[{{{{0
```

In principle, one can decode it,

```
{ - Enter ;      [ - Down key
```

To force CalcHEP to repeat this session one can call

```
bin/s_calchep -blind "{{e,E->W+,W-{{[{[{{{{0"
```

This command can be embedded into some script with `$1` *(script argument) instead of* `e,E->W+,W-`*. It gives us a tool to generate codes for different processes.*

The same trick works for numerical sessions too. Several scripts are presented in CalcHEP/bin directory
s_blind
set_param, set_momenta
run_vegas,
pcm_cycle, name_cycle, subproc_cycle
prep_gen, gen_events

If one starts them without parameters they explain which input parametes are expected.

There is a package LHCFast based on CalcHEP batch calculations.

Generation of libraries.

Suppose we have to create a library of matrix elements.

The names of global functions initially generated have suffix `_ext`***. Replacing this suffix by the*** `sed` ***command we can collect in one project several codes generated separately. To simplify interface routine all global functions and variables are attached to one structure***

```
struct CalcHEP_interface
{
  int nvar, nfunc;       // number of variables and functions
  char ** varName;       // names of parameters
  double* va;            // values of parameters
  int nin, nout, nprc;  // numbers on in-partiucles, out-particle,subprocesses
  char* (*pinf)(int, int , double*,long * PDG); // information about particles
  int (*calcFunc)(void);  double * BWrange;     // calculation of function
  double (*sqme)(int , double*, int*);          // calculation SQME
  .....
} interface_ext;
```

Shared libraries, dynamic loading.

New library of matrix element can be compiled as** shared **and loaded in runtime. This trick is widely used in micrOMEGAs package, because we don't know a'priori which co-annihilation channels are contribute to Dark Matter. Also we give micrOMEGAS users a possibility to accompany evaluation of Dart Matter with calculation of other cross sections. It looks like:

```
cc=newProcess("e,E->2*x","eE_2x");
procInfo1(cc,&ntot,&nin,&nout);
assignVal("tb",10.);
procInfo2(cc,nsub,names,masses);
cs= cs22(cc,nsub,Pcm,cosmin,cosmax,&err);
```

This scheme can be used for cross section calculation in any other project.

micrOMEGAs_2.0, Dark Matter calculation.

micrOMEGAs is a project for Dark Matter calculation based on CalcHEP models. In the beginning it was MSSM.

`G.~Belanger, F.~Boudjema, A.~Pukhov, A.~Semenov,  hep-ph/0405253`

New version micrOMEGAs_2.0 is intended for Dark Matter calculation in any model realized in CalcHEP. It is assumed that particles can be separated on *odd* ***and*** *even* ***and that such parity is conserved. Then in general the lightest*** *odd* ***particle in stable and can be considered as a candidate of Dark Matter.***

The micrOMEGAs_2 directory contents

`calchep\  sources\  MSSM\  NMSSM\  micro_make*    README`

The command

```
micro_make <new_project>
```

creates template of directory for new project with all needed structure inside. The user has to add the model in CalcHEP notations, add library for external functions and specify *odd* ***particles. The list of odd particles can be presented by the user***

```
OddPrtclsSTR OddPrtcls[NODD]=
{/* pname, apname, mass, width, spin*2;,cdim */
 {"~o1","~o1","MNE1","wNE1",1,1}
,{"~o2","~o2","MNE2","wNE2",1,1}
,{"~1+","~1-","MC1","wC1",1,1}
......
}
```

Or will be constructed by default from the particles whose name is started from tilde.

Interface with Pythia.

Interface with Pythia is realized via two Les Houches accords.

GENERIC USER PROCESS INTERFACE FOR EVENT GENERATORS, hep-ph/0109068
SUSY LES HOUCHES ACCORD, hep-ph/0311123

According to the first one we fill PYTHIA COMMON blocks. Because PDG numbers are presented from the beginning in CalcHEP particle description, no interface problems appear.

On the next step we have to teach PYTHIA to decay BSM particles. It is realized via SLHA and CalcHEP option to calculate `1->2` ***widths and branchings and write down them in SLHA format. This SLHA format. Alternatively the SLHA file generated by spectrum calculator can be used.***

```
DECAY        36     2.79446481E-06   # Lightest pseudoscalar
     6.68305122E-02    2          15        -15   # BR(A_1 -> tau tau)
     5.98727072E-04    2           4         -4   # BR(A_1 -> c cbar)
     9.27202388E-01    2           5         -5   # BR(A_1 -> b bbar)
     0.00000000E+00    2           6         -6   # BR(A_1 -> t tbar)
```

Particle masses are passed via `BLOCK MASS`***. This approach was restricted by SUSY applications until Peter Scands adds to PYTHIA an option to add new particle to the particle list***

```
BLOCK QNUMBERS 1000045 # ~chi_50
  1    0  # 3 times electric charge
  2    2  # number of spin states (2S+1)
  3    1  # color rep (1: singlet, 3: triplet, 8: octet)
  4    0  # Particle/Antiparticle distinction (0=own anti)
```

After this implementation we in principle have a tool for automatic calculation from Lagrangian to event generation for BSM physics.

New project for interface with Pythia and other hardonization ge

I am going to accomany CalcHEP event generator with decay generator also based on CalcHEP. The program should automaticaly detect outgoing BSM particles and decay them on SM ones trying subsequently $X \longrightarrow 2 * x$, $X \longrightarrow 3 * x$, *and* $X \longrightarrow 4 * x$ *channels.*

The codes for decays will be generated automatically and in runtime linked to main process like it done in micrOMEGAs.

It also gives a possibility to keep correct momentum distribution for decay particles.

We need a standard way for registration of new particles in hadronization generators.

List of BSM implementations.

During development of micrOMEGAS package we have implemented

MSSM based on SuSpect/Isajet/SoftSUSY/SPHENO.

NMSSM based NMHDecay

MSSM with CP violation based on CPSuperHiggs.

There are realization of extra dimension models in notations of CalcHEP/CompHEP

G. Servant, K. Agashe ... - the LZP model.

K.Matchev ... -the UED model.

The leptoquark model was implemented together with A.Belyaev and C.Leroy, R. Mediyev (hep-ph:/0502067)

The Little Higgs model : A.Birkedal et al `hep-ph/0603077`.