Calculation of DM properties in extensions of Standard Model

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MicrOMEGAs package is intended for calculation of DM signals like DM relic density, results of direct and indirect detection experiments, neutrino telescope, and collider search.

Feynman rules for generic SM extension can be realized in micrOMEGAs to calculate DM signals for different experiments.

ICTP-SAIFR, São Paulo, Brazil

October 14-18 2019

Introduction

In the last 30 years we have made great progress both in physics of elementary particles and astrophysics.

Standard Model was finally confirmed by discovery of Higgs Particle.

Gravitational waves were recently detected.

Inflation theory gives us an understanding of flatness and homogeneous of Universe.

Fluctuation of temperature of microwave background radiation allows us to calculate density of DM particles. This density in turn leads to noticeable contribution to structure formation of Universe which agrees with observed structure of clusters of galaxies. In the same time DM density contributes to rate of Universe expansion at MeV temperatures which affects the primordial nucleosynthesis. We need CP-violation to explain baryogenesis.

But in the Standard Model we don't have DM particles, we don't have strong enough CP violation terms and we don't have a suitable potential which leads to inflation. So we have a challenge to construct a Beyond Standard Model which is able to explain cosmological/astrophysical observations.

We expect that understanding DM will show us the way beyond the SM.

Cold DM density in Universe.

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

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

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

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

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

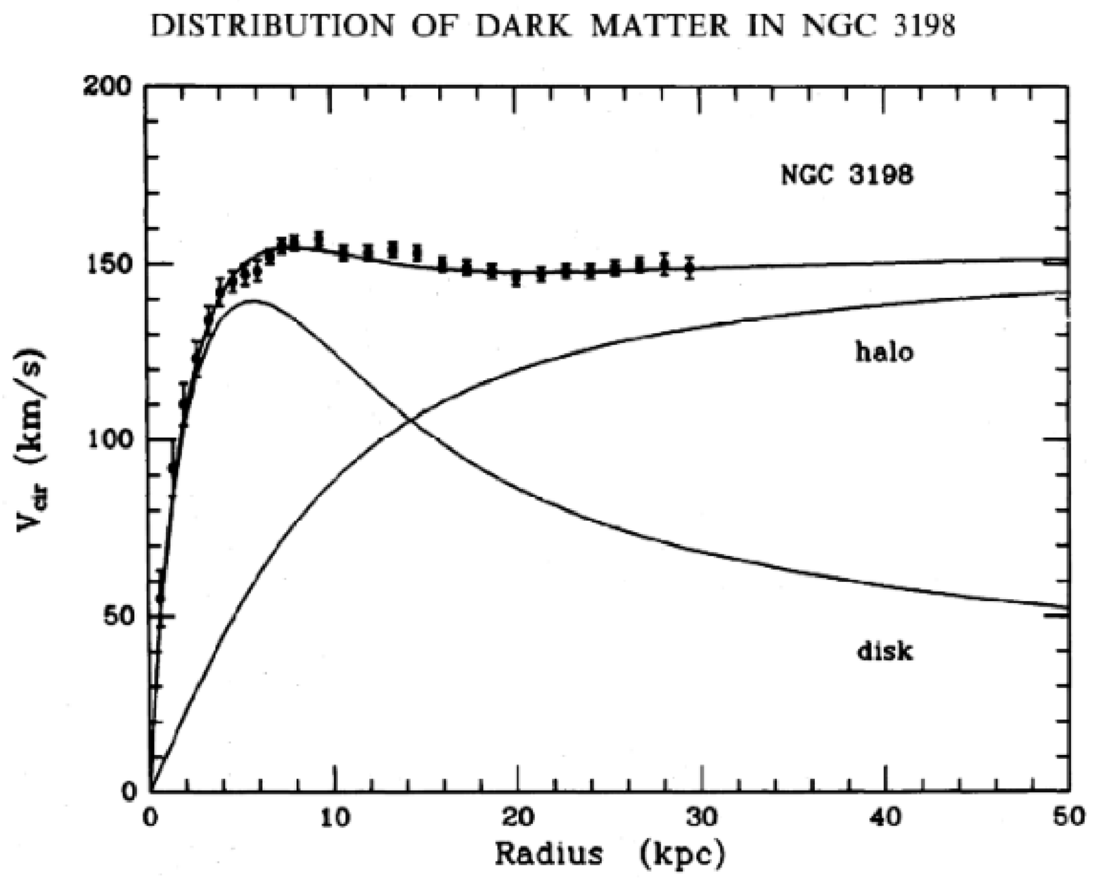
ρ_{cr}=10.537h^2 GeV/m^3 so ρ_{dm}= 1.11 GeV/m^3

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

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

Dark matter in spiral galaxies.

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



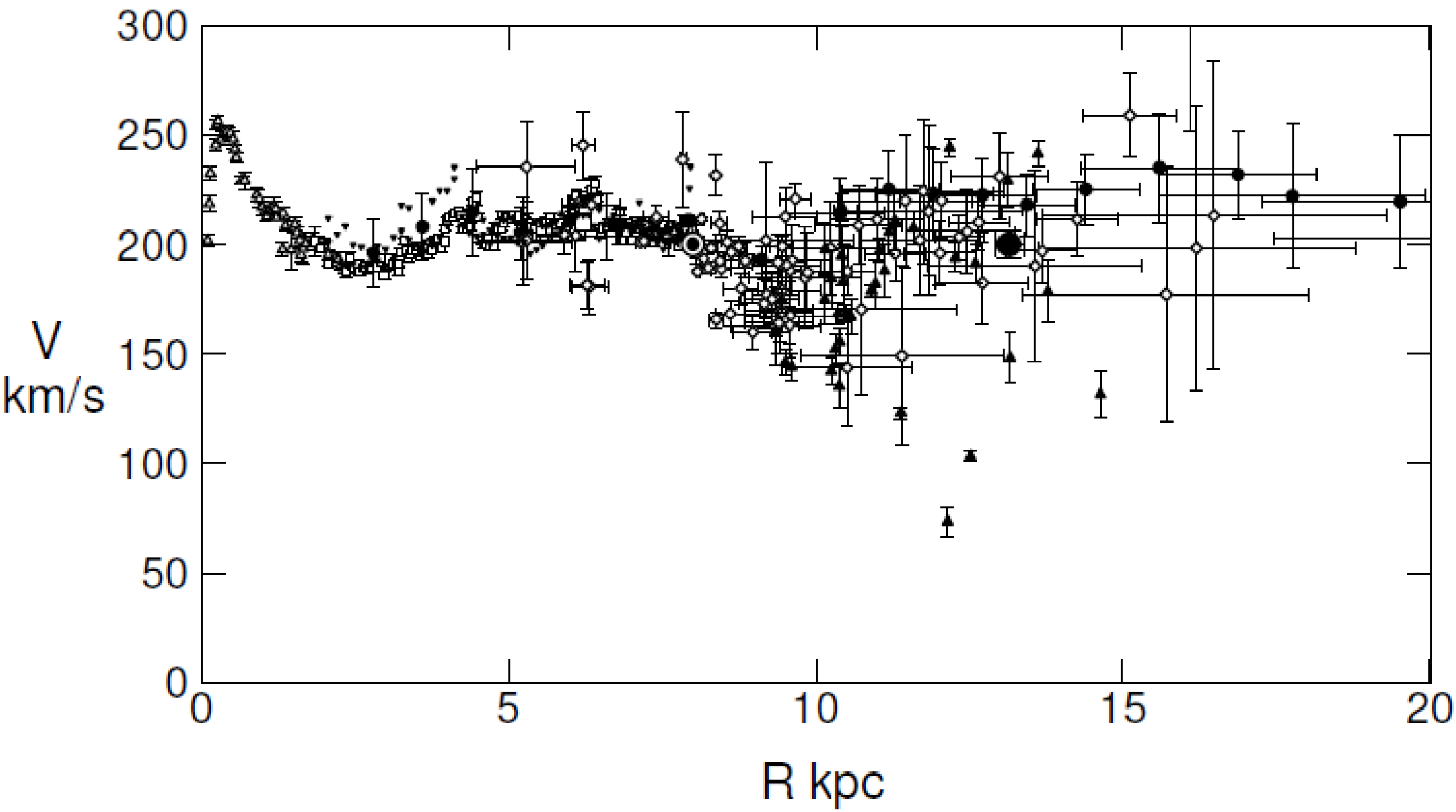
Flat rotation curve corresponds to DM density profile

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

Typical DM profile Navaro, Frenk, and White

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

Dark Matter in Milky Way



DM density at Sun orbit is estimated as

ρ(Rsun=8.5kp) = 0.1-0.7 GeV/cm^3

Central value ρ=0.3 GeV/cm^3

DM velocity distribution should be close to Maxwell

$$\frac{1}{\pi^{3/2} v_{rot}^3} e^{-(v/v_{rot})^2} d^3 v$$

Dark Matter search experiments

Up to now we see only gravitational evidence for Dark Matter.

- Direct detection : Several types of experiments search for DM with underground detectors (2018-2019): Xenon1T, DarkSide-50, PICO-60, CRESST-III. In the last 3 years lower limit on DM-nucleon cross section has decreased by factor 5 .
- Neutrino telescopes. Dark Matter can be captured by Sun. Neutrinos produced in result of DM annihilation in the center of Sun reach Earth, interact with rocks/ice and produce μ. So, we expect enhancement of μ in Sun direction. Super Kamiokande, IceCube, Baksan
- Indirect detection. Dark Matter in Milky Way halo can annihilate producing $e+, p^-$ which can be detected in space satellite experiments PAMELA, AMS-2 or photons Fermi-LAT, H.E.S.S.
- Accelerator search. Search of monojet events whose momenta is compensated by invisible DM particles. Or events with particles which accompany DM like s-quarks: LHC

MicrOMEGAs Package

Operation system Linux or Darwin. In principle it should work on any UNIX platform.

Language C (C99).
Own code size 14Mb
Included packages :

CalcHEP for matrix element generation
LanHEP for model generation
LoopTools for Dm,Dm → gamma, gamma(Z)
SuSpect, NMSSMTools, CpsuperH spectrum calculation for specific models
Lilith for Higgs physics

All together 76Mb
Downloaded in runtime:

HiggsBounds/HiggsSignals for Higgs physics
SMODELS - for collider analyses

Needed compilers: gcc, gfortran
Language for user main code: C/C++

Installation of micrOMEGAs package

micrOMEGAS site

http://lapth.in2p3.fr/micromegas

Click *Download and Install* *(left -top part of the screen)*

And then *DOWNLOAD* *(right-top part of the screen)*

The name of received file should be

micromegas_5.0.8.tgz

For this lecture load

http://theory.sinp.msu.ru/~pukhov/micromegas_5.0.20.tgz

Unpack it by **tar -xvzf micromegas_5.0.20.tgz**

It should create directory **micromegas_5.0.20/** which occupies about 40 Mb of disk space. You will need more disk space after compilation of specific models and generation of matrix elements.

In case of problems and questions

email: micro.omegas@lapp.in2p3.fr

File structure of micrOMEGAs package.

Makefile
CalcHEP_src/ generator of matrix elements
sources/ micrOMEGAs own codes
man/
manual_5.0.tex, manual_5.0.pdf
description of micrOMEGAs routines
Packages/
SuSpect_2.41 NMSSMTools_4.7.1 CpsuperH2.3,
LoopTools-2.1 external packages

model directories:

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

To compile micrOMEGAS use 'gmake' or 'make'

To clean use [g]make clean

Before compilation check existence of **X11** header files

*/usr/*include/X11/*.h

If they are absent install one of the packages

libX11-devel for Fedora/Scientific, Darwin(MAC)
libX11-dev for Ubuntu/Debian
xorg-x11-devel for SUSE

Without them you can not see plots created by micrOMEGAs.

Structure of MODEL directory

Makefile
main.c files with main program for given model
lib/ directory for routines specific routines model
Makefile
*.c,***F,***cpp source codes
alib.a compiled library
work/ CalcHEP working directory intended for matrix element generation
models/ model specification
vars1.mdl **func1.mdl** **prtcls1.mdl** **lgrng1.mdl** **extlib1.mdl**
so_generated/ directory to store generated matrix elements
./**calchep** executable file for interactive CalcHEP sessions

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

[g]make main=XXX.c => executable XXX
[g]make main=YYY.cpp => executable YYY

[g]make is equivalent to **[g]make main=main.c**

Module structure of main programs

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

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

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

```
#define MASSES_INFO              // Display information about mass spectrum
#define CONSTRAINTS              // Display B->s,gamma, Bs->mu,mu, …
#define LILITH                   // Checks Higgs decays
//#define HIGGSBOUNDS            // HiggsBounds  check Higgs decays
#define OMEGA                    // Calculate relic density
#define INDIRECT_DETECTION       // Signals of DM annihilation in galaxy hallo
#define CDM_NUCLEON              // Calculate amplitudes and cross-sections for  CDM-
                                    nucleon  collisions
#define CDM_NUCLEUS              // Calculate number of events for 1kg*day and recoil
                                   energy distribution  for various nuclei.  Testing
                                   Xenon1T,  DarkSide,PICO,  CRESST  limits
//#define  NEUTRINO              // Neutrino telescope
//#define DECAY                  //  particle widths and branching
```

EXAMPLE (Inert Doublet Model)

[pukhov@localhost IDM]$ ./main data1.par

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

=== MASSES OF HIGGS AND ODD PARTICLES: ===
Higgs masses and widths
    h   125.00 3.97E-03

Masses of odd sector Particles:
~X   : MHX   = 600.000 || ~H3   : MH3   = 601.000 || ~H+   : MHC   = 604.000

LILITH(DB19.06): -2*log(L): 48.17; -2*log(L_reference): 0.00; ndf: 59; **p-value: 8.42E-01**

==== Calculation of relic density =====
Xf=2.62e+01 **Omega=1.12e-01**
# Channels which contribute to 1/(omega) more than 1%.
# Relative contributions in % are displayed
  21% ~X ~X ->W+ W-
  14% ~X ~X ->Z Z
  11% ~H3 ~H3 ->W+ W-
   9% ~H+ ~H- ->W+ W-
   7% ~H3 ~H3 ->Z Z
   6% ~H+ ~X ->A W+
   5% ~H3 ~H+ ->A W+
   4% ~H+ ~H- ->A A

EXAMPLE (continue IDM data1.par)

```
==== Indirect detection =======
   Channel          vcs[cm^3/s]
==================================
 annihilation cross section 6.18E-26 cm^3/s
 contribution of processes
  ~X,~X -> W+ W-        6.01E-01
  ~X,~X -> Z Z          3.99E-01

Photon flux  for angle of sight f=0.10[rad]
and spherical region described by cone with angle 0.10[rad]
 Photon flux = 9.36E-16[cm^2 s GeV]^{-1} for E=300.0[GeV]
 Positron flux  =  1.04E-13[cm^2 sr s GeV]^{-1} for E=300.0[GeV]
 Antiproton flux  =  5.88E-13[cm^2 sr s GeV]^{-1} for E=300.0[GeV]

==== Calculation of CDM-nucleons amplitudes  =====
CDM[antiCDM]-nucleon micrOMEGAs amplitudes:
proton:  SI  1.497E-11 [1.497E-11]  SD  0.000E+00 [0.000E+00]
neutron: SI  1.512E-11 [1.512E-11]  SD  0.000E+00 [0.000E+00]
CDM[antiCDM]-nucleon cross sections[pb]:
 proton   SI 9.767E-14  SD 0.000E+00
 neutron SI 9.962E-14  SD 0.000E+00
Not excluded by DD experiments  at 90% level

===== Direct detection exclusion:======
Not excluded by DD experiments  at 90% level
```

Free parameters of the model.

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

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

Constrained parameter of the model.

Constrained parameters are stored in file
*MODEL***/work/models/func1.mdl**

For example

```
Inert Doublet
 Constraints
 Name  |> Expression
CW     |sqrt(1-SW^2)
MW     |MZ*CW        % mass of W
Mb     |MbEff(Q)
Mc     |McEff(Q)
mu2    |MHX^2-laL*(2*MW/EE*SW)^2
la3    |2*(MHC^2-mu2)/(2*MW/EE*SW)^2
la5    |(MHX^2-MH3^2)/(2*MW/EE*SW)^2
```

Model Files: Particles of the model

List fo particles presented in file MODEL/work/models/prtcls1.mdl

Full Name	P	aP	number	spin2	mass	width	color	aux	> LaTeX(A)
photon	A	A	22	2	0	0	1	G	A
Z boson	Z	Z	23	2	MZ	!wZ	1	G	Z
gluon	G	G	21	2	0	0	8	G	G
W boson	W+	W-	24	2	MW	!wW	1	G	W^+
neutrino	n1	N1	12	1	0	0	1	L	\nu^e
electron	e1	E1	11	1	0	0	1		e
mu-neutrino	n2	N2	14	1	0	0	1	L	\nu^\mu
muon	e2	E2	13	1	Mm	0	1		\mu
tau-neutrino	n3	N3	16	1	0	0	1	L	\nu^\tau
tau-lepton	e3	E3	15	1	Mt	0	1		\tau
u-quark	u	U	2	1	0	0	3		u
d-quark	d	D	1	1	0	0	3		d
c-quark	c	C	4	1	Mc	0	3		c
s-quark	s	S	3	1	Ms	0	3		s
t-quark	t	T	6	1	Mtop	wtop	3		t
b-quark	b	B	5	1	Mb	0	3		b
Higgs	h	h	25	0	Mh	!wh	1		h
odd Higgs	~H3	~H3	36	0	MH3	!wH3	1		(H3)
Charged Higgs	~H+	~H-	37	0	MHC	!wHC	1		(H+)
second Higgs	~X	~X	35	0	MHX	!wHX	1		(X)

Names of particles of odd sector are started with tilde ~ or ~~ (second DM)

Model Files: Feynman rules

Stored in file MODEL/work/models/lgrng1.mdl

```
Inert Dublet
 Lagrangian
P1 |P2 |P3 |P4 |>   Factor          <|> dLagrangian/ dA(p1) dA(p2)dA(p3)
A  |W+ |W- |   |-EE                  |m3.p2*m1.m2-m1.p2*m2.m3- …....
A  |~H+|~H-|   |EE                   |m1.p3-m1.p2
B  |b  |A  |   |EE/3                 |G(m3)
B  |b  |G  |   |GG                   |G(m3)
B  |b  |Z  |   |-EE/(12*CW*SW)       |4*SW^2*G(m3)-3*G(m3)*(1-G5)
B  |b  |h  |   |-EE*Mb/(2*MW*SW)     |1
B  |t  |W- |   |-EE*Sqrt2/(4*SW)     |G(m3)*(1-G5)
W+ |W- |~X |~X |EE^2/(2*SW^2)        |m1.m2
h  |~X |~X |   |-2*MW*SW/EE          |la3+la4+la5
Z  |Z  |~X |~X |EE^2/(2*CW2*SW^2)    |m1.m2
   ….............…
Here p – particle momentum
     m – Lorentz index
     G(m), G(p), G5  - Dirac gamma matrices
```

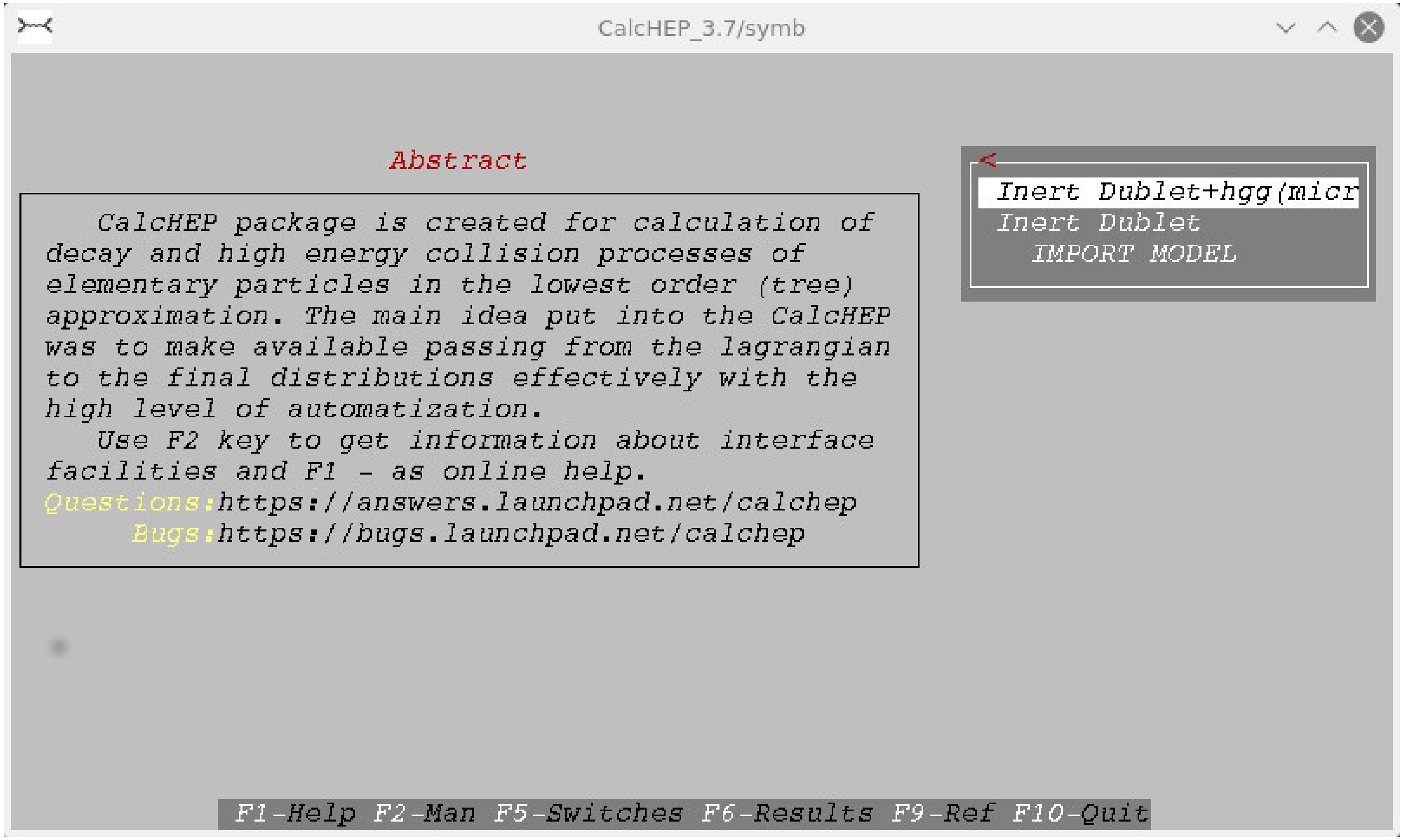
CalcHEP Session

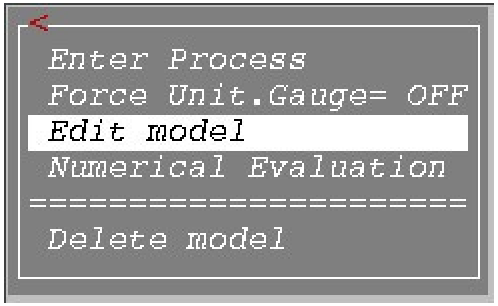
CalcHEP is package developed by A. Belyaev , N. Christesen, A.Pukhov intended for calculation of cross sections and particle widths. See source code, manual and lectures at

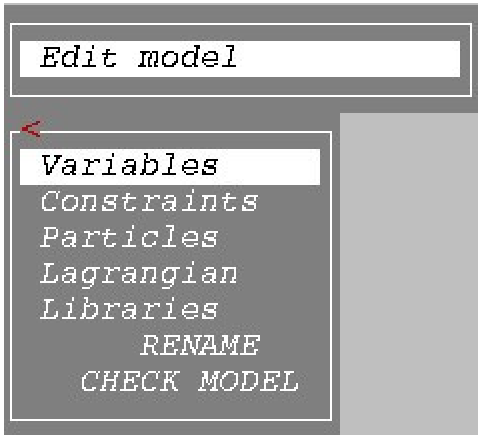
http://theory.sinp.msu.ru/~pukhov/calchep.html

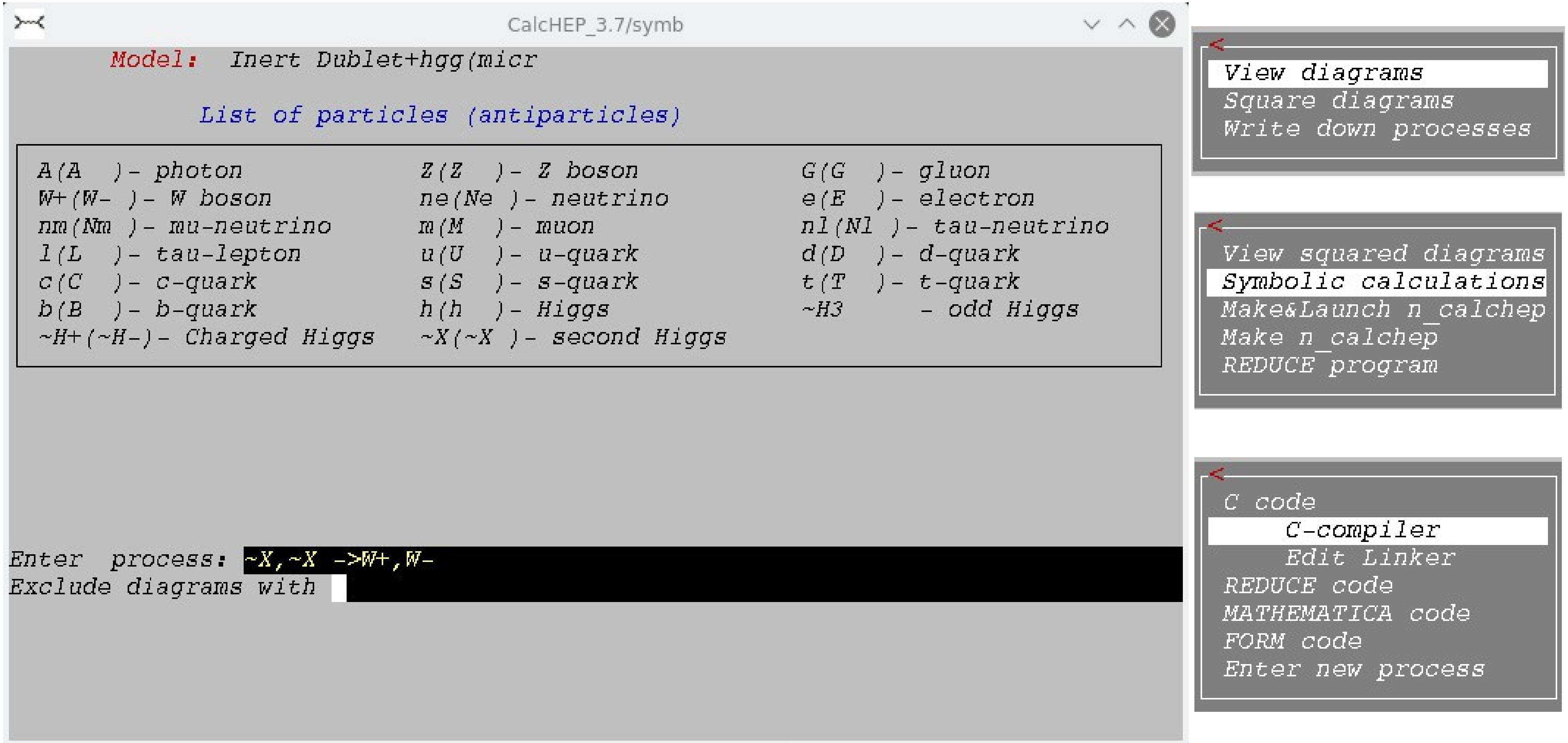
You can go to work/ (for instance, IDM/work) and launch

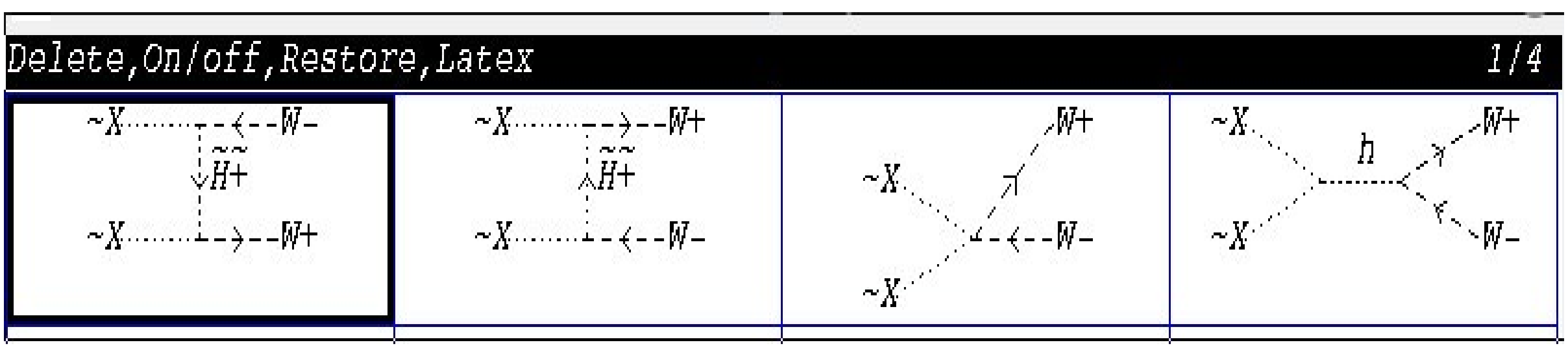
./calchep

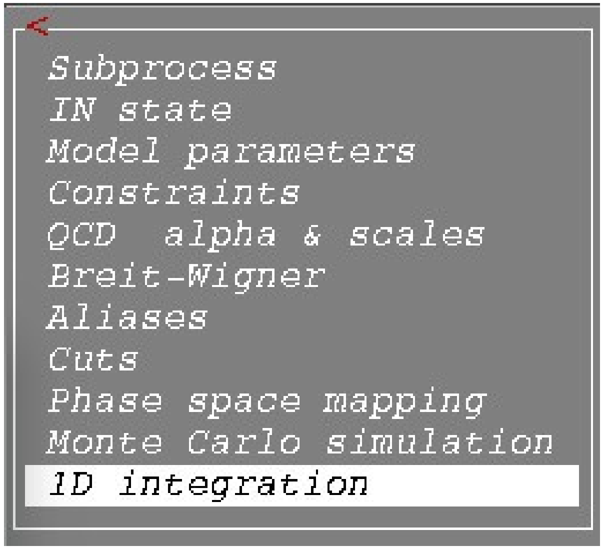


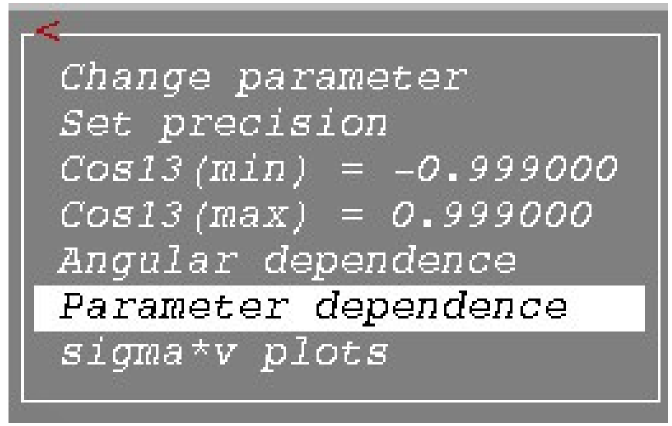


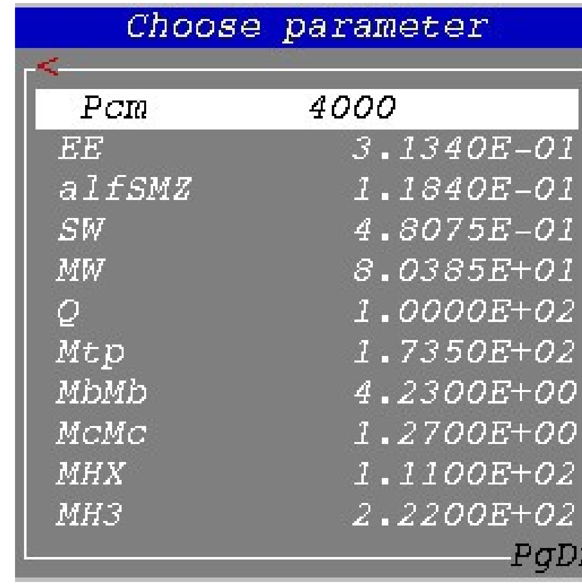


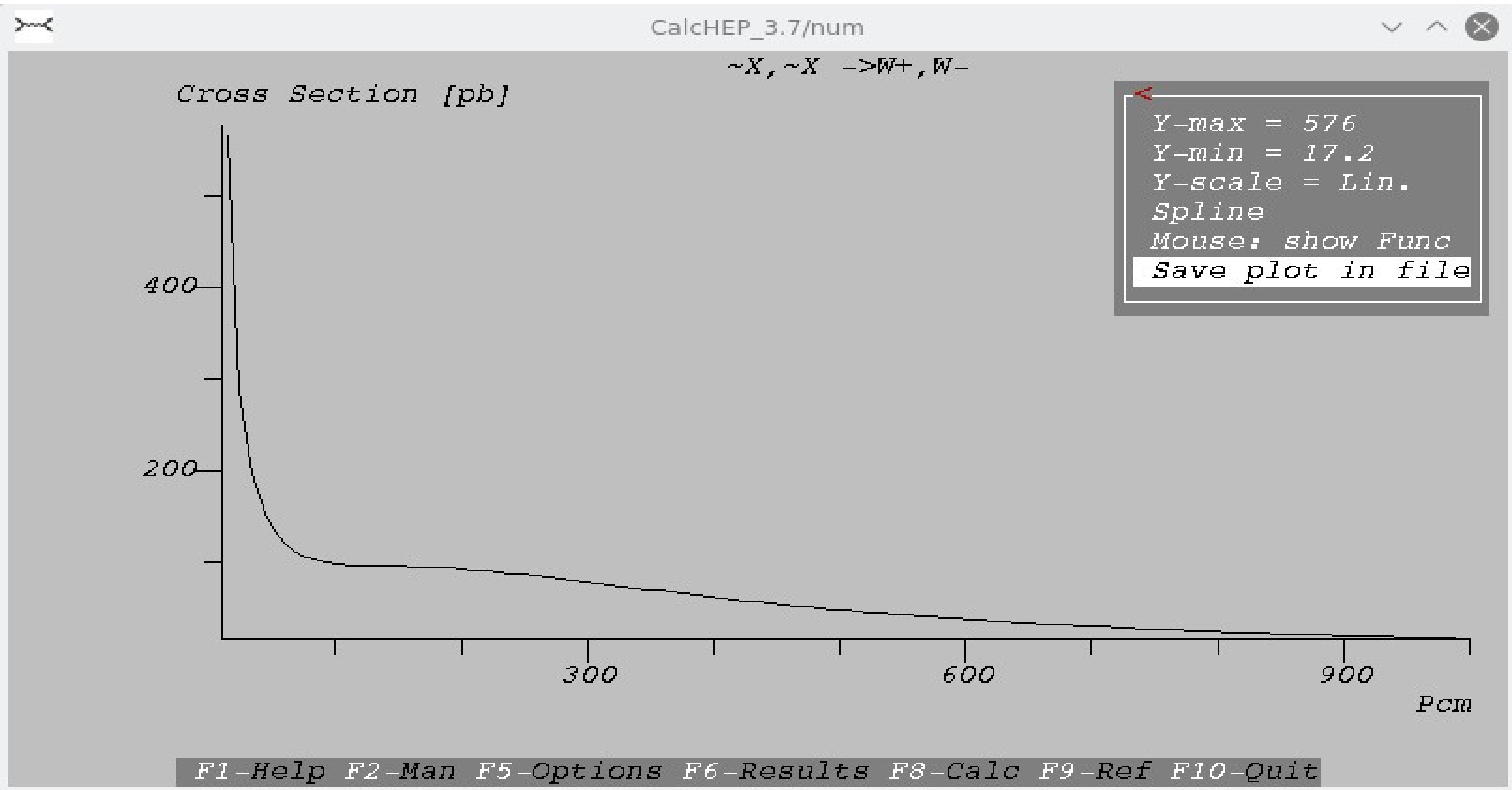

CalcHEP_3.7/symb
Model: Inert Dublet+hgg(micr
List of particles (antiparticles)
A(A)- photon
Z(Z)- Z boson
G(G)- gluon
W+(W-)- W boson
ne(Ne)- neutrino
e(E)- electron
nm(Nm)- mu-neutrino
m(M)- muon
nl(Nl)- tau-neutrino
l(L)- tau-lepton
u(U)- u-quark
d(D)- d-quark
c(C)- c-quark
s(S)- s-quark
t(T)- t-quark
b(B)- b-quark
h(h)- Higgs
~H3 - odd Higgs
~H+(~H-)- Charged Higgs
~X(~X)- second Higgs
Enter process: ~X,~X ->W+,W-
Exclude diagrams with
View diagrams
Square diagrams
Write down processes
View squared diagrams
Symbolic calculations
Make&Launch n_calchep
Make n_calchep
REDUCE program
C code
C-compiler
Edit Linker
REDUCE code
MATHEMATICA code
FORM code
Enter new process

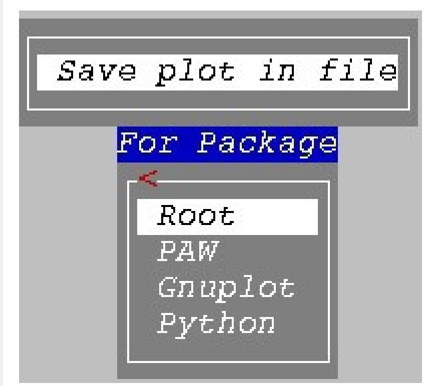

Delete,On/off,Restore,Latex
1/4
~X
W-
~H+
~X
W+
W+
W-
h


Subprocess
IN state
Model parameters
Constraints
QCD alpha & scales
Breit-Wigner
Aliases
Cuts
Phase space mapping
Monte Carlo simulation
1D integration


Change parameter
Set precision
Cos13(min) = -0.999000
Cos13(max) = 0.999000
Angular dependence
Parameter dependence
sigma*v plots


Choose parameter
Pcm 4000
EE 3.1340E-01
alfSMZ 1.1840E-01
SW 4.8075E-01
MW 8.0385E+01
Q 1.0000E+02
Mtp 1.7350E+02
MbMb 4.2300E+00
McMc 1.2700E+00
MHX 1.1100E+02
MH3 2.2200E+02
PgDn


CalcHEP_3.7/num
~X,~X ->W+,W-
Cross Section [pb]
400
200
300
600
900
Pcm
Y-max = 576
Y-min = 17.2
Y-scale = Lin.
Spline
Mouse: show Func
Save plot in file
F1-Help F2-Man F5-Options F6-Results F8-Calc F9-Ref F10-Quit


Save plot in file
For Package
Root
PAW
Gnuplot
Python

CalcHEP-micrOMEGAs interface

CalcHEP generates file VandP.c (Variable and Particles) which is linked to ./main of micrOMEGAs.

micrOMEGAs command:

assignValW(char *name, double value) - *assigns new value to parameter.*

For example: assignValW("MHX",600);

In order to download set of parameters micrOMEGAs has the function

readVar(fileName);

Structure of file records has to be

name value [# comment]

For instance, in case of IDM

```
laL      0.001   # coupling
MHX      600     # inert sector Higgs
 Mh      125    # SM Higgs mass
la2      0.01   # coupling
MHC      604    # mass of charged Higgs
MH3      601    # mass of CP odd Higgs
```

CalcHEP-micrOMEGAs interface

sortOddParticles(name);

Calculate all constraint parameters. In case of success

a) returns 0;

b) detects DM particle (lightest one whose name starts with **~**).

c) Sets name= name of DM,

If some constrained parameter can not be calculated, then

a) returns number of parameter

b) Set name=name of parameter which leads to the problem

When constraints are calculated one can check constrained parameters:

```
findValW( parameter_name);   //  findVAlW("CW");
```

Particle masses:

```
pMass(particle_name);             // pMass("h");
```

Particle width and decay branching:

```
txtList hb;
pWidth("h",&hb);   // pWidth("h",NULL)  if you don't need branching
printTxtList(hb);
```

Generation of matrix elements

When micrOMEGAs needs matrix element for some process, it sends corresponding request to CalcHEP. CalcHEP generates diagrams, squares them, calculates symbolically, writes down C-code, compiles code to shared library and stores library in **work/so_generated** sub-directory.

So, when you call ./main first time, micrOMEGAs compiles libraries of matrix elements:

==== Calculation of relic density =====

```
PROCESS: ~X,~X->AllEven,1*x{A,Z,G,W+,W-,ne,Ne,e,E,nm,Nm,m,M,nl,Nl,l,L,u,U,d,D,c,C,s,S,t,T,b,B,h
PROCESS: ~H3,~X->AllEven,1*x{A,Z,G,W+,W-,ne,Ne,e,E,nm,Nm,m,M,nl,Nl,l,L,u,U,d,D,c,C,s,S,t,T,b,B,h
PROCESS: ~H3,~H3->AllEven,1*x{A,Z,G,W+,W-,ne,Ne,e,E,nm,Nm,m,M,nl,Nl,l,L,u,U,d,D,c,C,s,S,t,T,b,B,h
PROCESS: ~H3,~H+->AllEven,1*x{A,Z,G,W+,W-,ne,Ne,e,E,nm,Nm,m,M,nl,Nl,l,L,u,U,d,D,c,C,s,S,t,T,b,B,h
PROCESS: ~H+,~X->AllEven,1*x{A,Z,G,W+,W-,ne,Ne,e,E,nm,Nm,m,M,nl,Nl,l,L,u,U,d,D,c,C,s,S,t,T,b,B,h
PROCESS: ~H+,~H+->AllEven,1*x{A,Z,G,W+,W-,ne,Ne,e,E,nm,Nm,m,M,nl,Nl,l,L,u,U,d,D,c,C,s,S,t,T,b,B,h
PROCESS: ~H+,~H-->AllEven,1*x{A,Z,G,W+,W-,ne,Ne,e,E,nm,Nm,m,M,nl,Nl,l,L,u,U,d,D,c,C,s,S,t,T,b,B,h
```

When you call ./main second time, micrOMEGAs looks for compiled matrix element in

work/so_generated

MicrOMEGAs compares time of creation of shared library and time of creation of models files. If one changes model files, then library will be rebuilt.

CalcHEP-micrOMEGAs interface

Example: calculation of cross section for 2→2 scattering

numout *cc ;   // numout – is a type for matrix element in micrOMEGAs.

cc = newProcess(char*Process);   // call CalcHEP to calculate symbolically and   compile matrix element for given process. For instance

cc = newProcess("e,E→m,M");

or

cc =newProcess("e,E->2*x");

Then cross sections of 2->2 processes can be   calculated by

cs= cs22(cc,L,Pcm,cos_min,cos_max,&err);

Pcm – momentum in Center of Mass reference frame

cos_min, cos_max - cuts for cosine of scattering angle in the same frame

L=1 in case you have generated codes only for one process. For general case L numerates subprocesses.