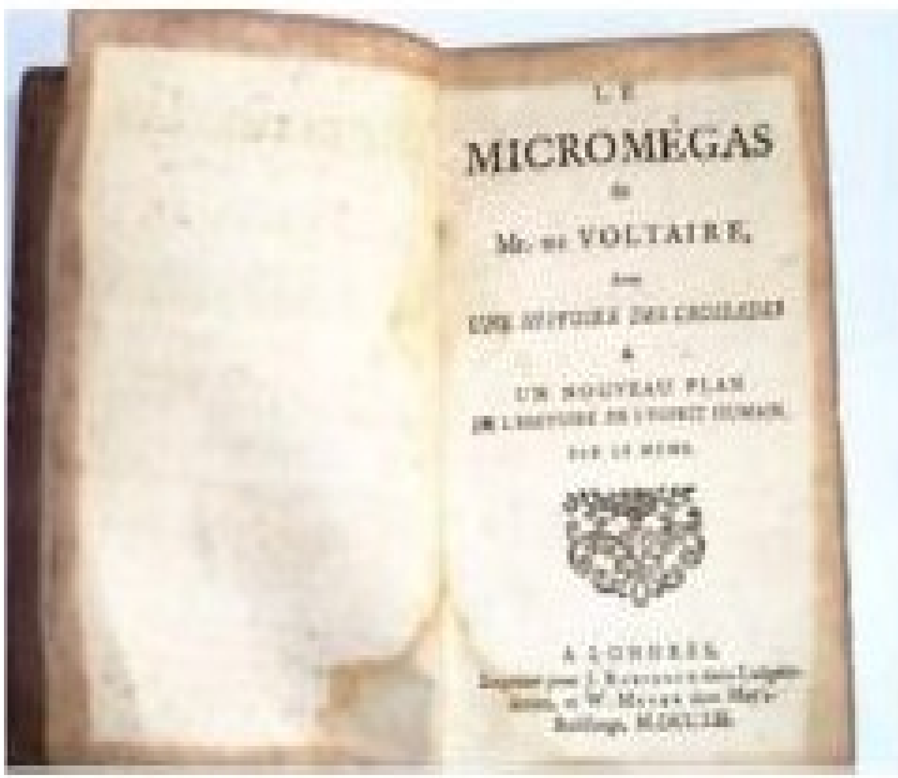
MicrOMEGAs - a tool for dark matter studies in a generic model of particle physics.

Version 3

G. Belanger, F. Boudjema, A. Pukhov, A. Semenov

arXiv:1305.0237 [hep-ph]



Outline

- DM observables calculated by micrOMEGAs:
  - Relic density
  - Direct detection
  - Indirect detection *(Green function method)*
  - Sun/Earth captured DM neutrino signal
- Dark matter models

  - MSSM, NMSSM,CPVMSS *(SUSY)*

  - IDM, Z3M, LHM,RHNM, ...

  - any user model
- Particle decays and cross sections
  - Higgs decays with $\gamma\gamma$, gg and virtial Z/W channels
- Easy interface with other packages:

  - SuSpect, SoftSUSY, SPHENO,.., NMSSMTools, CPsuperH (spectra)

  - HIGGSBOUNGS, SUPERISO, (observables)

Guiding principles of micrOMEGAs

- Human make mistakes - computer not
  - Automation
- Several groups are developing specialized codes
  - Interface routines
- Users might want to improve one aspect
  - Modularity
- We do not know what DM is made of
  - Possibility to include different DM candidates
- Models are often complex with huge parameter space
  - Speed of execution
- Ready made, stand-alone package for the non-expert
  - User friendly interface and manual

Matrix elements in micrOMEGAS

MicrOMEGAs uses **CalcHEP** program

arXiv 1207.6082(hep_ph)

for generation of matrix elements. Because **CalcHEP** is designed to work with generic model, **micrOMEGAs** is able to calculate DM related observables for generic model as well.

Model of particle interaction in CalcHEP is presented by 5 tables.

1) Variables

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
```

3) Constrained parameters of the model.

```
Inert Doublet
 Constraints
 Name    |> Expression
CW       |sqrt(1-SW^2)
MW       |MZ*CW
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
%Local!|
```

4) External functions and and their prototypes.

```
Libraries
 % - comment
extern   type func(type X)  % C-prototype
```

Lines of other type are passed to linker

Particle list

Inert Doublet Model

Particles

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

4) List of Feynman rules

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- ....
B	b	A		EE/3	G(m3)
B	b	G		GG	G(m3)
B	b	Z		EE/(12*CW*SW)	3*G(m3)*(1-G5)-4*SW^2*G(m3)
W+	~H-	~H3		-EE/(2*SW)	m1.p2-m1.p3
W+	~H-	~X		i*EE/(2*SW)	m1.p2-m1.p3
W-	~H+	~H3		-EE/(2*SW)	m1.p3-m1.p2
W-	~H+	~X		-i*EE/(2*SW)	m1.p3-m1.p2
Z	~H+	~H-		EE/(2*CW*SW)	B00003*m1.p3+B00005*m1.p2
Z	~H3	~X		i*EE/(2*CW*SW)	m1.p2-m1.p3
~H3	~H3	~X	~X	-2*la2	1
~X	~X	~X	~X	-6*la2	1

LanHEP package is able to generate model files with Feynman rules based on Lagrangin.

Semenov, A.
LanHEP - a package for automatic generation of Feynman rules from the Lagrangian.
arrXiv: 1005.1909 [hep-ph]

Matrix elements codes are not generated in advance. When some matrix element needs, it is

1) generated by means of CalcHEP,
2) compiled as a shared library,
3) linked to the main code,
4) included in the list of attached matrix elements,
5) stored on the disk.

Last two options need for subsequent call of the same matrix element. Such scheme was initially realized for co-annihilation precesses, but now is used for all matrix elements in micrOMEGAs.

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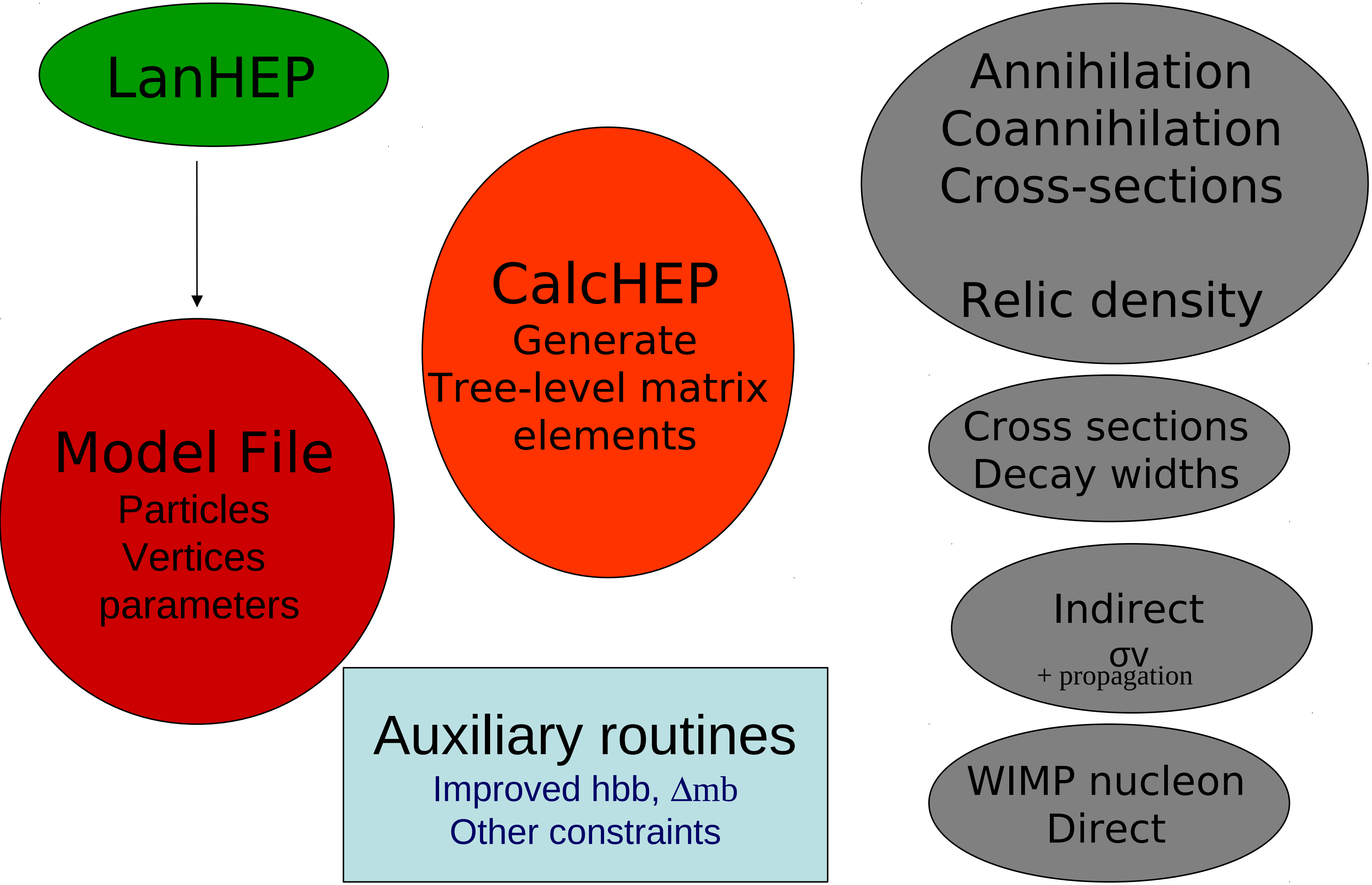
micrOMEGAs


LanHEP
Model File
Particles
Vertices
parameters
CalcHEP
Generate
Tree-level matrix
elements
Auxiliary routines
Improved hbb, Δmb
Other constraints
Annihilation
Coannihilation
Cross-sections
Relic density
Cross sections
Decay widths
Indirect
σv
+ propagation
WIMP nucleon
Direct

MicrOMEGAs_3 :new features

- Neutrino signal of DM captured by Sun/Earth
- Generalization of relic density computation
  - 3-body final state with virtual W/Z
  - Z_3 discrete symmetry
  - Asymmetric dark matter
  - g_eff(T), h_eff(T) input (SM termodynamics)

Particle decays

-Virtual W/Z channels (automatically)

-Loop-induced Higgs decay (semi-automatically)

Loop induces 2ɣ and ɣZ signals of DM annihilation

- for SUSY-like models (semi-automatically)

SLHA interface with BSM related packages

DM capture in Sun

- DM particles captured by Sun/Earth, concentrate in center and annihilate into SM
- Lead to neutrino flux, can be observed at Earth (SuperKamiokande, IceCube)
- Shape of neutrino flux depends on dominant DM annihilation channel
- Signal determined by cross section for DM scattering on nuclei --related to DD
- Capture rate

$$C_\chi = \frac{\rho_\chi}{m_\chi} \int_o^\infty du\, f_1(u) \int 4\pi r^2 dr \sum_A \sigma_{\chi A} n_A(r) \frac{\beta_A}{\alpha_A} \left(e^{-\alpha_A u^2} - e^{-\alpha_A (u^2 + v_{esc}^2(r))/\beta_A} \right)$$

$$\alpha_A = \frac{1}{3} m_\chi m_A R_A^2, \quad \beta_A = \frac{(m_\chi + m_A)^2}{4 m_\chi m_A}$$

- Annihilation

$$A_\chi = \langle \sigma v \rangle \frac{V_2}{V_1^2}$$

- Number of DM particles

$$\dot{N}_\chi = C_\chi - A_{\chi\chi} N_\chi^2 - A_{\chi\bar{\chi}} N_\chi N_{\bar{\chi}} - E N_\chi \,,$$
$$\dot{N}_{\bar{\chi}} = C_{\bar{\chi}} - A_{\chi\bar{\chi}} N_\chi N_{\bar{\chi}} - A_{\chi\bar{\chi}} N_{\bar{\chi}}^2 - E N_{\bar{\chi}} \,,$$

- When capture/annihilation is large, no evaporation, self-conj. particle, equilibrium is reached and annih. rate determined by capture rate

$$\Gamma_\chi = A_{\chi\chi} N_\chi^2 = C_\chi / 2.$$

- In general solve equation for number density numerically and obtain ν flux at Earth

$$\frac{d\phi_\nu}{dE_\nu} = \frac{1}{4\pi d^2} \left(\Gamma_{\chi\chi} Br_{\nu\nu} \frac{dN_{\nu\nu}}{dE} + \Gamma_{\chi\bar{\chi}} \sum_f Br_{f\bar{f}} \frac{dN_f}{dE} \right)$$

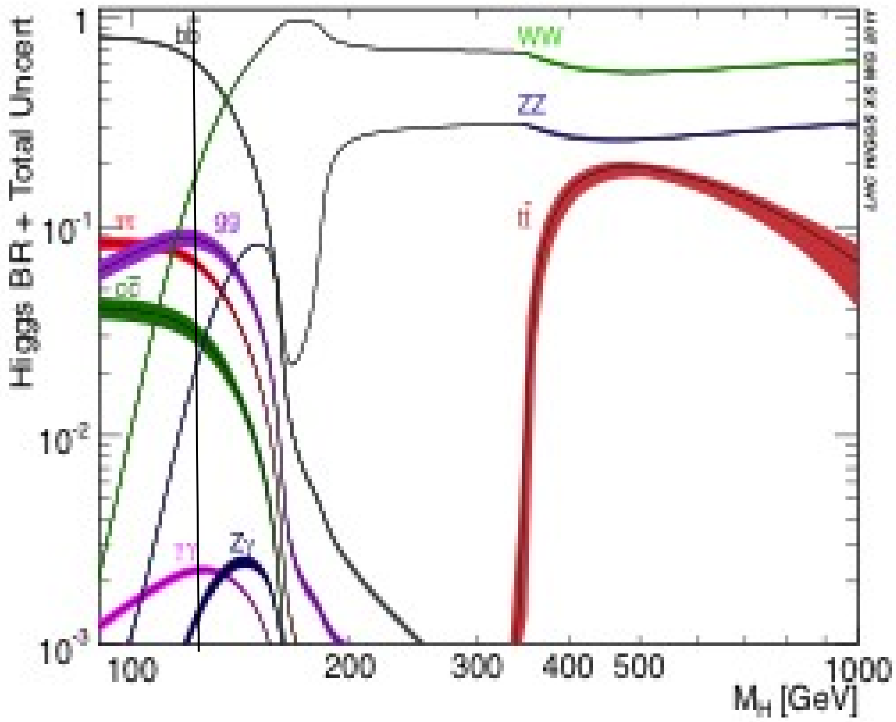
- neutrino spectrum originating from different SM annihilation channels and including oscillation available in
  - M. Cirelli, hep-ph/0506298

Neutrino-muon conversions in rocks is calculated according to Erkoca, Reno, Sarcevic 2009

- Upward and contained and muon fluxes are computed

Higgs decays

- Higgs at 126 GeV at LHC
- Decay modes : bb,WW*,ZZ*,gg,γγ
- Include
  - 3 body decays
  - loop-induced decays
- Experimental results give signal strength



$$R_{gg}^{h_i}(X) \equiv \frac{\Gamma(h_i \to gg)\ \mathrm{BR}(h_i \to X)}{\Gamma(h_{\rm SM} \to gg)\ \mathrm{BR}(h_{\rm SM} \to X)}, \quad R_{\rm VBF}^{h_i}(X) \equiv \frac{\Gamma(h_i \to WW)\ \mathrm{BR}(h_i \to X)}{\Gamma(h_{\rm SM} \to WW)\ \mathrm{BR}(h_{\rm SM} \to X)}$$

Loop induced Higgs decays

- Introduce effective operators
  - $\lambda h\, F_{\mu\nu} F^{\mu\nu}$ (CP-even) $\lambda' h\, F_{\mu\nu} F^{\mu\nu}$ (CP-odd)

$$\mathcal{L} = g_{h\psi\psi}\bar{\psi}\psi h + i g'_{h\psi\psi}\bar{\psi}\gamma_5\psi h + g_{h\phi\phi}M_\phi h\phi\phi + g_{hVV}M_V hV_\mu V^\mu$$

$$\begin{aligned}\lambda &= \frac{\alpha}{8\pi}\left[g_{h\psi\psi}f^c_\psi q^2_\psi \frac{1}{M_\psi}A_{1/2}\left(\frac{M_h^2}{4M_\psi^2}\right) - g_{hVV}f^c_V q^2_V \frac{1}{2M_V}A_1\left(\frac{M_h^2}{4M_V^2}\right)\right.\\ &\left. + \; g_{h\phi\phi}f^c_\phi q^2_\phi \frac{1}{2M_\phi}A_0\left(\frac{M_h^2}{4M_\phi^2}\right)\right]\end{aligned}$$

- Add QCD corrections
  - e.g. for gluons

$$\lambda = -R\left[A^{LO}_{htt}C_t + (A^{LO}_{hbb} + A^{LO}_{hcc})C_q + \sum_{\tilde{q}} A^{LO}_{h\tilde{q}\tilde{q}}C_{\tilde{q}}\right]$$

micrOMEGAS packages contains Passarino-Veltman functions needed for H->gg, H->ɣɣ and tabulated functions for QCD corrections for H->ɣɣ amplitudes.

At the level of LanHEP package it was implemented an option to extract couplings of Higgs->X,X interaction and convert them to Hgg, Hɣɣ vertexes off effective Lagrangian.

A good agreement with HDECAY for MSSM Higgses was obtained, although some special SUSY effects can not be included in this way.

Files with BSM/SM coupling rates is **HIGGBOUNDS** format is generated.

Generalization of relic density calculation

Three-body processes

- Annihilation into 3-body final state can be as large. Example is IDM where annihilation DM,DM-> fermions is suppressed and processes with vitrual W are important before WW threshold (Yaguna, arXiv: 1003.2730)
- About 5% correction in MSSM (close to threshold)
- Problems:

I) As we know from Higgs decay calculation that 4-body kinematics needs. But it is very slow.

a) calculate Dm,Dm-> W+,e,ν

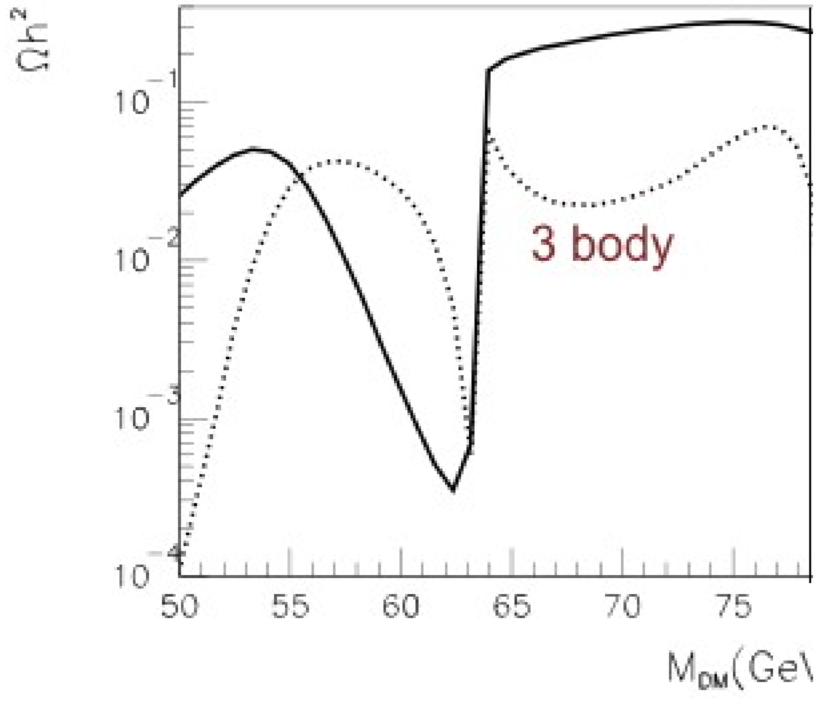
b) assume Breit-Wigner structure of 4-body reaction

and calculate for it K-factor 3-body/4-body

II) Dm,Dm-> W+,e,ν contains not resonance diagrams, but resonance ones are not gauge invariant.

Select diagrams with at least one virtual gauge boson

Example : MSSM



- bino/higgsino LSP, μ=150GeV, M_2=2M_1

Semi-annihilation

- Discrete remnant of some broken gauge group, in general does not have to be Z_2 - consider Z_N
- Impact for dark matter :
  - New processes
    - semi-annihilation : processes involving different number of "odd particles" xx --> x* SM
    - T. Hambye, 0811.0172, T. Hambye, M. Tytgat, 0907.1007
  - More than one DM candidate
    - Assisted freeze-out/DM conversion : interaction between particles from different dark sectors
      - » $x_1 x_1 \leftrightarrow x_2 x_2$

The Z_3 case

- Number density (x : dark sector X: SM)

$$\frac{dn}{dt} = -v\sigma^{xx^* \to XX}\left(n^2 - \overline{n}^2\right) - \frac{1}{2}v\sigma^{xx \to x^* X}\left(n^2 - n\,\overline{n}\right) - 3Hn.$$

$$\sigma_v \equiv v\sigma^{xx^* \to XX} + \frac{1}{2}v\sigma^{xx \to x^* X} \quad \text{and} \quad \alpha = \frac{1}{2}\frac{\sigma_v^{xx \to x^* X}}{\sigma_v}$$

$$3H\frac{dY}{ds} = \sigma_v\left(Y^2 - \alpha Y\overline{Y} - (1-\alpha)\overline{Y}^2\right).$$

- Modified equation solved numerically. At low temperatures standard freeze-out pictures is expected ($Y=Y_{eq}+\Delta Y$)

$$3H\frac{d\overline{Y}}{ds} = \sigma_v \overline{Y}\Delta Y\,(2-\alpha)$$

Asymmetric DM

- The case where DM is not self-conjugate (e.g. Dirac fermion, complex scalar)
- $Y^+(Y^-)$: abundance of DM particle(anti-)

$$\frac{dY^\pm}{ds} = \frac{2 < \sigma v >}{3H}\left(Y^+Y^- - Y^+_{eq}Y^-_{eq}\right)$$

- $\Delta Y = Y^+ - Y^-$ is constant
- Define $Y = 2(Y^+Y^-)^{1/2}$

$$\frac{dY}{ds} = \frac{< \sigma v >}{3H}\left(Y^2 - Y^2_{eq}\right)\sqrt{1 + \left(\frac{\Delta Y}{Y}\right)^2}$$

- Equation is solved numerically. No freeze-out for large ΔY

- Relic density

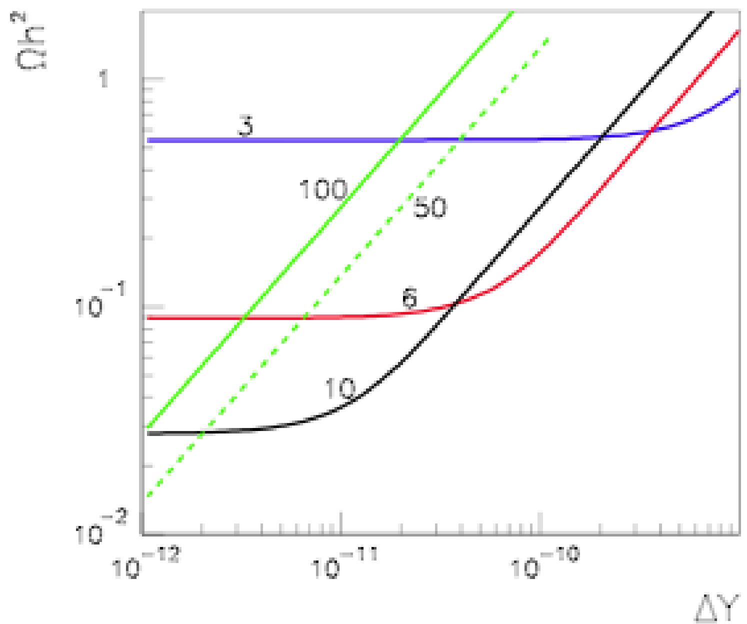
$$\Omega h^2 = \frac{8\pi}{3H_{100}^2}\frac{m_\chi}{M_{\rm Planck}}\frac{\sqrt{Y_0^2+\Delta Y^2}}{s_0}$$

- For each specie

$$\Omega_\pm h^2 = \frac{\Omega h^2}{1+e^{\mp\delta_{DM}}}$$

- DM asymmetry always increase relic abundance
- Example : neutrino DM
- deltaY global parameter - taken into account for DD (always compute DM-nucleon and antiDM-nucleon) and indirect detection

$$Q = \frac{1}{2}\langle\sigma v\rangle\frac{\rho_\chi\rho_{\bar\chi}}{m_\chi^2}\frac{dN_a}{dE}$$



Monochromatic gamma-rays

- Monochromatic gamma rays ($\gamma\gamma$,γZ) are loop-induced (suppressed) BUT lead to very distinctive signal
  - C. Weniger, 1204.2797, T.Bringmann et al, 1203.1312 (signal in Fermi-LAT?)

  In generic models only Higgs contribution are known.

NEW

- Available in micrOMEGAs for SUSY models (MSSM,NMSSM,CPVMSSM) and Z3M
  - Computed with SloopS, a code for computation of one-loop processes in the SM,MSSM and some extensions
    - F. Boudjema, A. Semenov, D. Temes, hep-ph/0507127
    - G. Chalons, A. Semenov, arXiv:1110.2064

Can be extended for any model.

Conclusion

- To understand the nature of dark matter clearly need information and cross checks from cosmology, direct and indirect detection as well as from collider physics

- micrOMEGAs is tool to perform these analyses in a generic model