micrOMEGAs

A Tool for Dark Matter and New Physics

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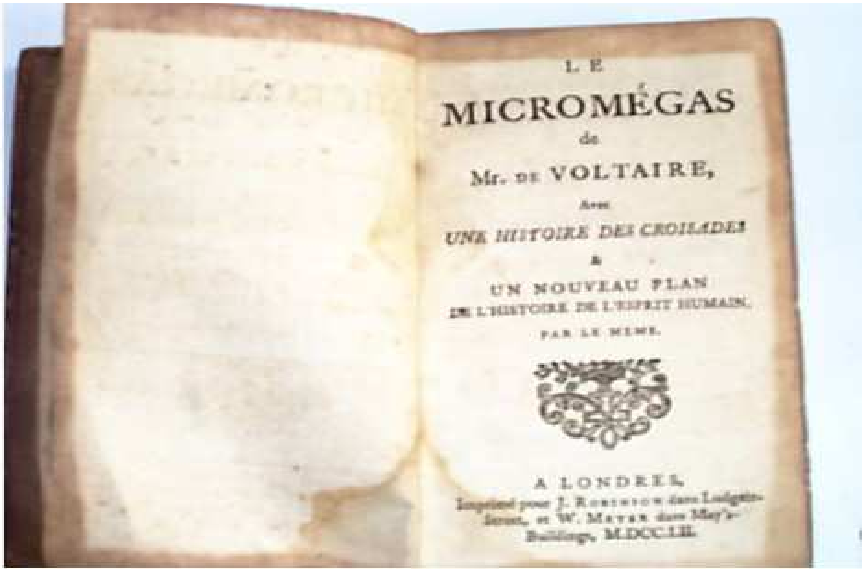
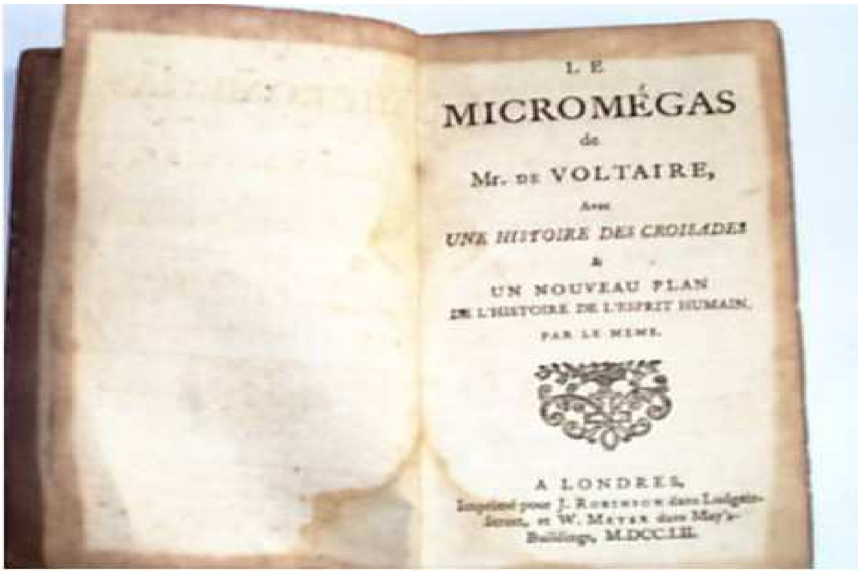
micrOMEGAs

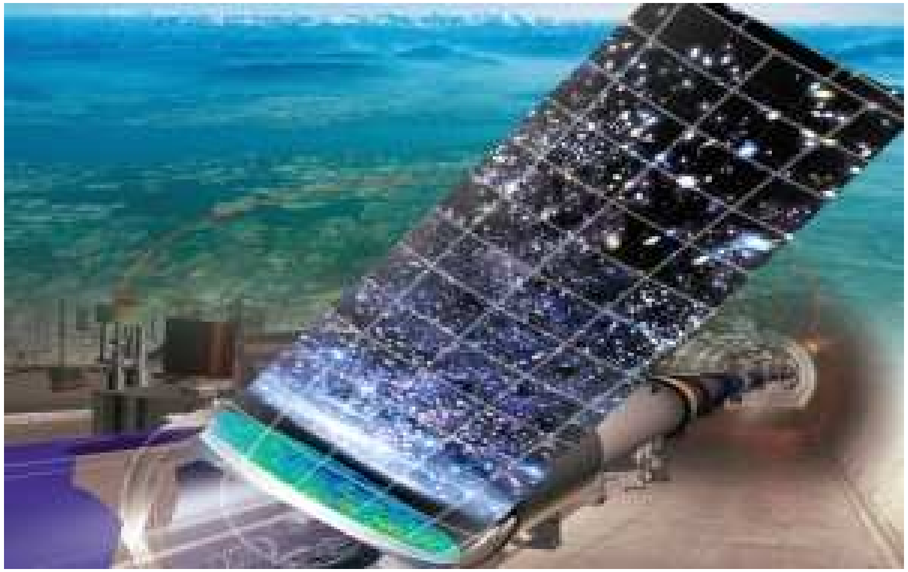

LE
MICROMÉGAS
de
Mr. DE VOLTAIRE,
Avec
UNE HISTOIRE DES CROISADES
&
UN NOUVEAU PLAN
DE L'HISTOIRE DE L'ESPRIT HUMAIN.
PAR LE MEME.
A LONDRES,
M.DCC.LII.

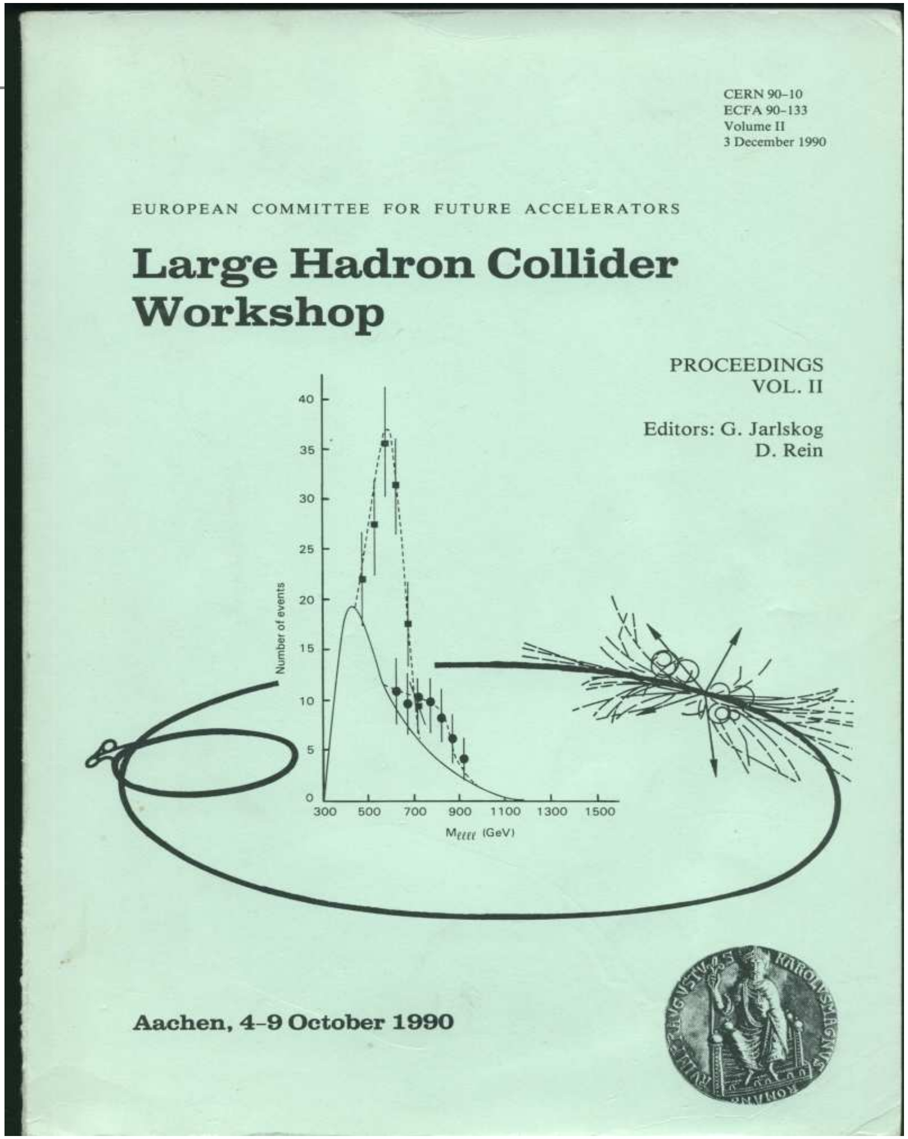


“ O atomes intelligents,
dans qui l’Etre éternel
s’est plu à manifester
son adresse et sa puissance,
vous devez sans doute
goûter des joies
bien pures sur
votre globe car,
ayant si peu de matière...,”

Voltaire, Micromegas,
chapitre septième,
conversation avec les hommes

LHC Dark Matter Connection





no mention of a connection, despite a SUSY WG

There is a mention of LSP to be stable/neutral because of cosmo reason, but no attempt at identifying it or weighing the universe at the LHC

LHC: Symmetry breaking and Higgs

New Paradigm, Dark Matter is New Physics. Dark Matter is being looked for everywhere

New Paradigm, Particle Physics to match the precision of recent cosmological measurements

Need powerful, modular and versatile tools

micrOMEGAs: Tools for DM/ Collider Physics/ Flavour for a general NP

Models of New Physics: Symmetry breaking and DM

- The SM Higgs naturalness problem has been behind the construction of many models of New Physics: at LHC not enough to see the Higgs need to address electroweak symmetry breaking
- DM is New Physics, most probable that the New Physics of EWSB provides DM candidate, especially that
- All models of NP can be made to have quite easily and naturally a conserved quantum number, Z_2 parity such that all the NP particles have $Z_2 = -1$ (odd) and the SM part. have $Z2$ even (Z_3 can work also)
- Then the lightest New Physics particle is stable. If it is electrically neutral then can be a candidate for DM
- This conserved quantum number is not imposed just to have a DM candidate it has been imposed for the model to survive

Symmetry breaking and DM

- Survival

  evade proton decay

  indirect precision measurements (LEP legacy)

- Examples:

  R-parity and LSP in SUSY (majorana fermion)

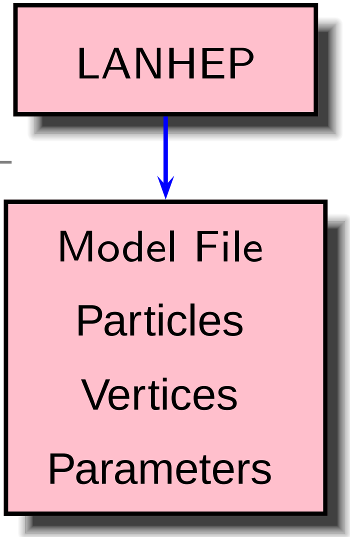
  KK parity and the and LKP in UED (gauge boson)

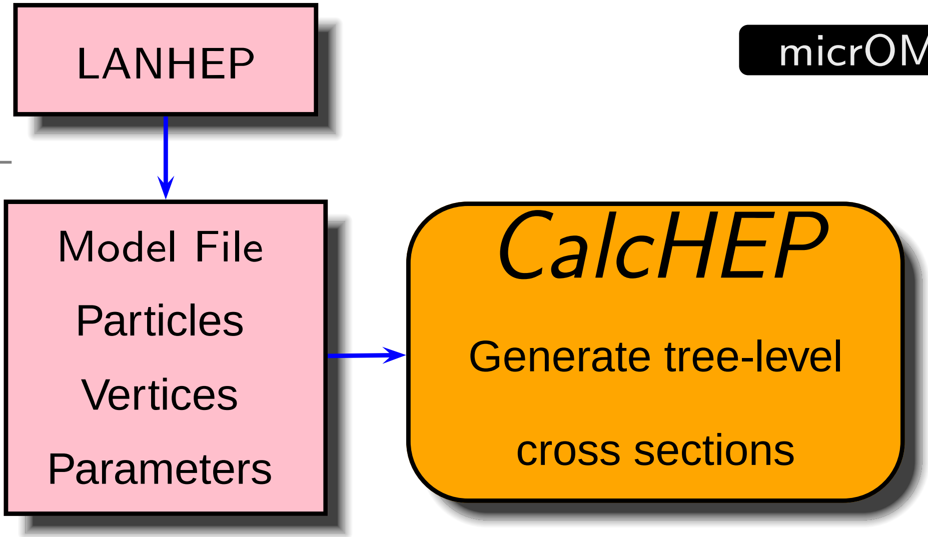
  T-parity in Little Higgs with the LTP (gauge boson)

  LZP (warped GUTs) (actually it's a Z_3 here) (Dirac fermion)

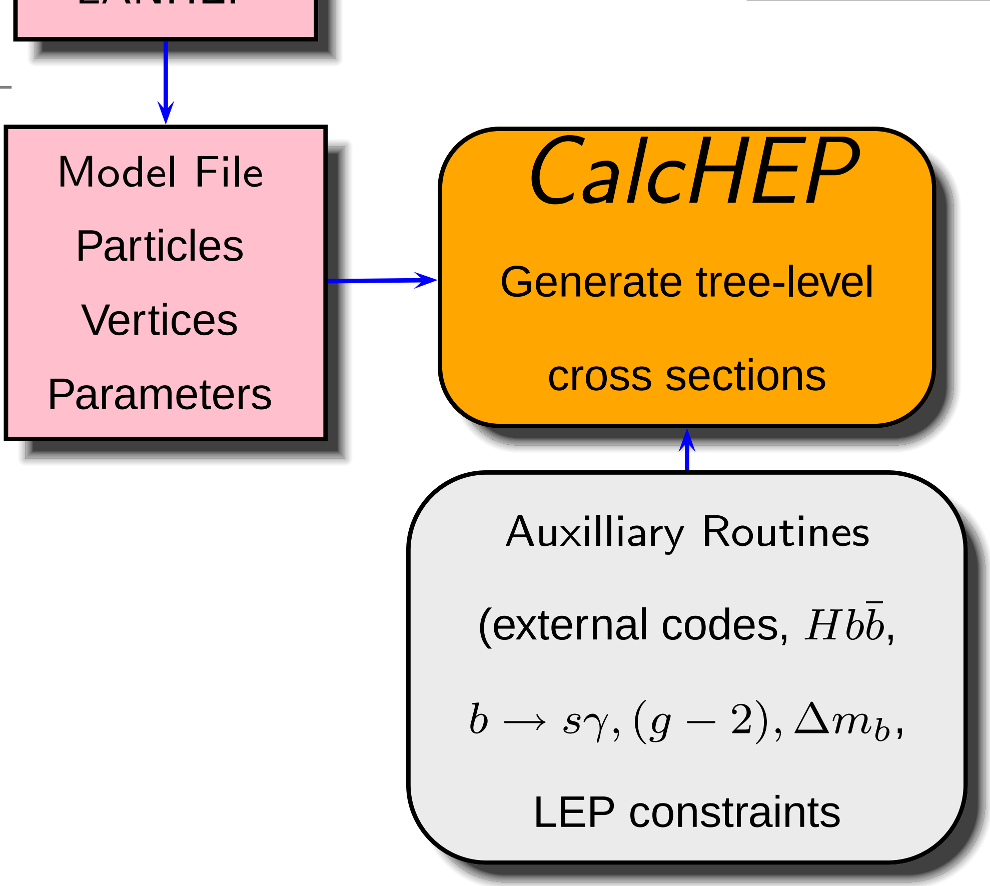
  even modern technicolour has a DM candidate

LANHEP

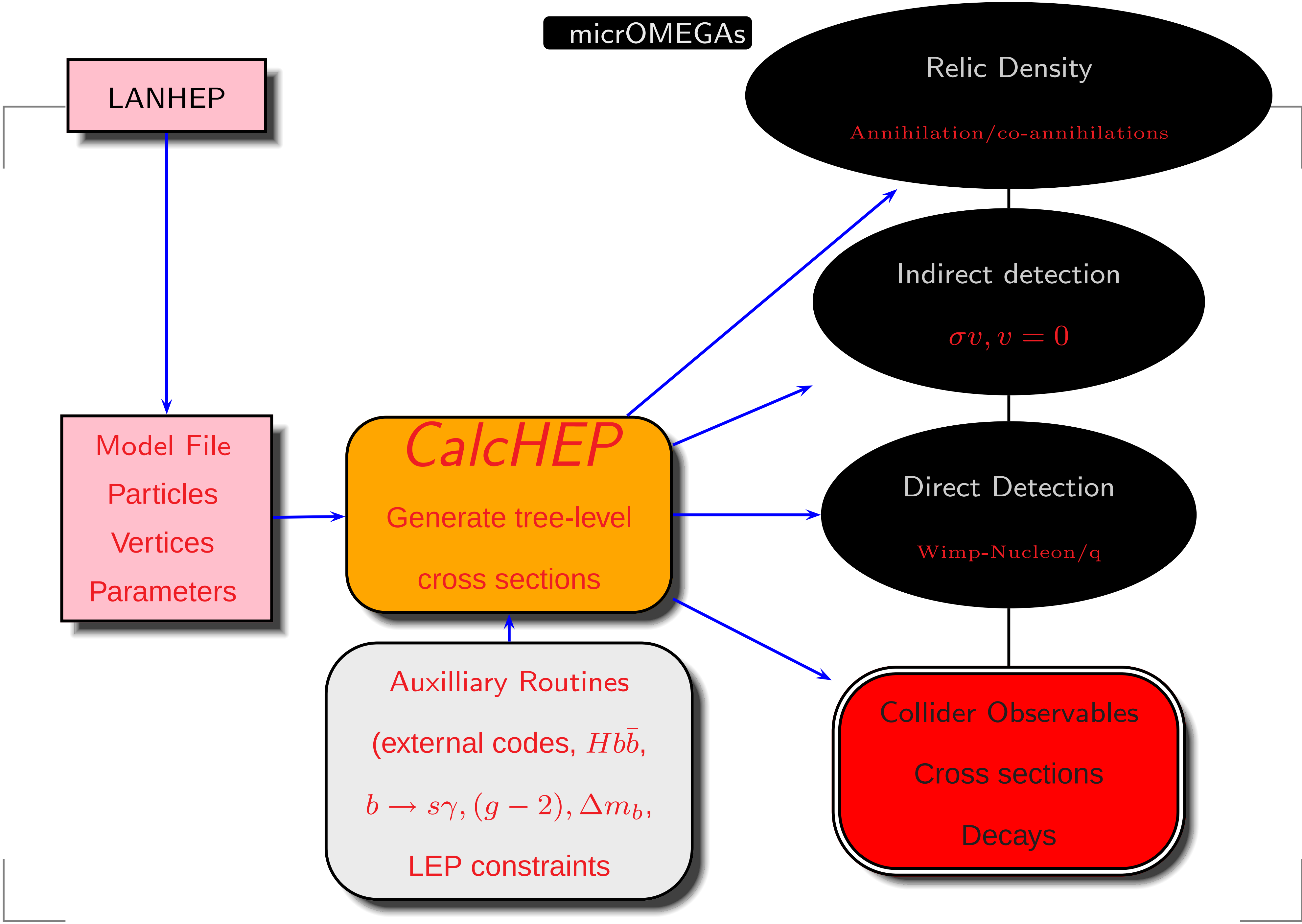

LANHEP
Model File
Particles
Vertices
Parameters


LANHEP
Model File
Particles
Vertices
Parameters
CalcHEP
Generate tree-level
cross sections

micrOMEGAs



LANHEP
Model File
Particles
Vertices
Parameters
CalcHEP
Generate tree-level
cross sections
Auxilliary Routines
(external codes, $Hb\bar{b}$,
$b \to s\gamma, (g-2), \Delta m_b$,
LEP constraints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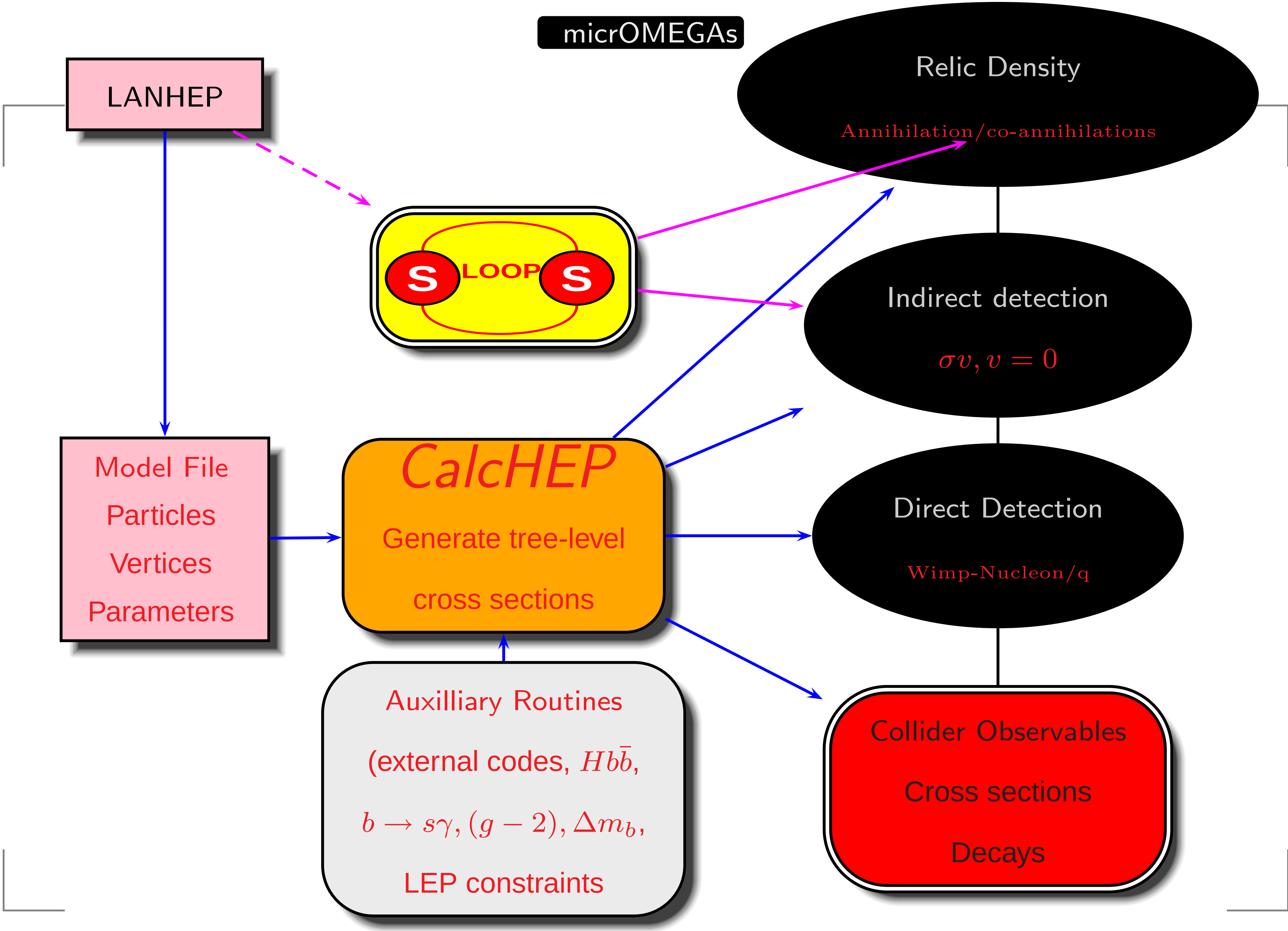
LEP constraints
Relic Density
Annihilation/co-annihilations
Indirect detection
$\sigma v, v=0$
Direct Detection
Wimp-Nucleon/q
Collider Observables
Cross sections
Decays


micrOMEGAs
LANHEP
S
LOOP
S
Relic Density
Annihilation/co-annihilations
Indirect detection
$\sigma v, v = 0$
Model File
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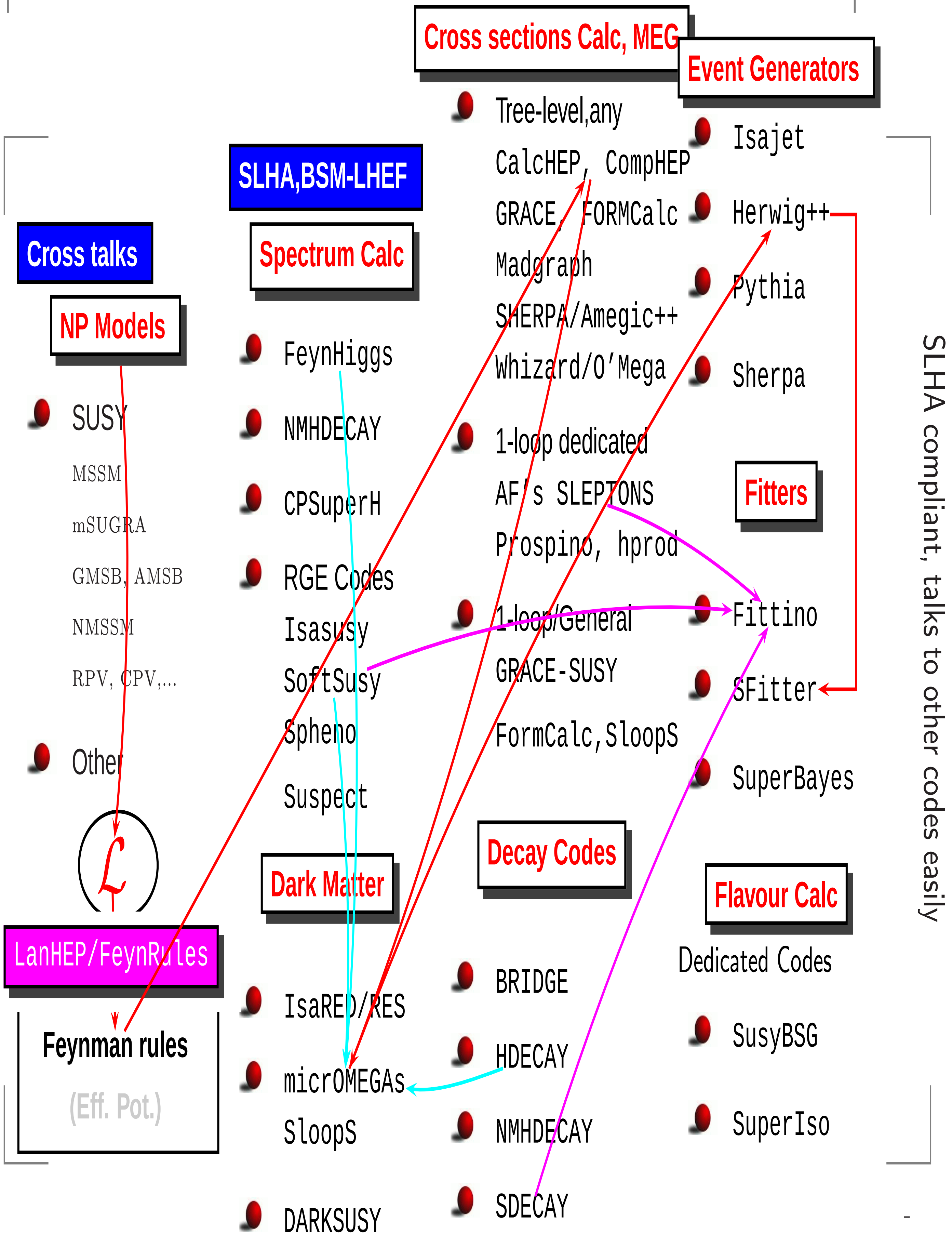
LEP constraints
Collider Observables
Cross sections
Decays

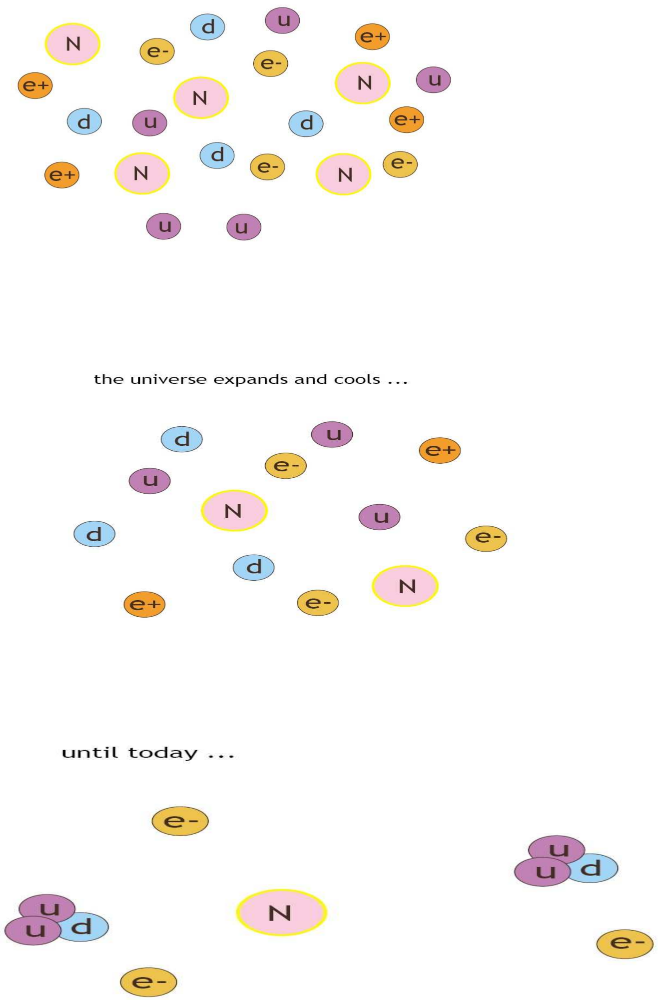
micrOMEGAs

- given any set of parameters it can identify LSP, NLSP, generate and calculate Ωh^2
- Model defined in Lanhep (more later)
- Fed into CalcHEP ....tree-level, some 3000 processes could be needed.
- Higgs sector (SUSY): improved Higgs masses/mixings (read from FeynHiggs, for example) but interpreted in terms of an effective scalar potential (GI), following FB and A. Semenov (PRD 02)
- Effective Lagrangian also includes important RC (Higgs couplings, Δm_b effects,..)
- Interfaced with Isajet, Suspect, SoftSUSY parameters at high scale run down to the ew scale
- $(g-2)_\mu$, $b \to s\gamma$, $B_s \to \mu^-\mu^+$,..
- NMSSM (with C. Hugonie), CP violation (with S. Kraml), UED, Dirac, host of others
- "open source": procedure to define your own model
- powerful generalised direct detection module
- indirect detection cross sections, interface with propagation, polarisation completed
- SLHA compliant, MCMC interface for parameter scans


Cross sections Calc, MEG
Event Generators
Tree-level,any
CalcHEP, CompHEP
GRACE, FORMCalc
Madgraph
SHERPA/Amegic++
Whizard/O'Mega
1-loop dedicated
AF's SLEPTONS
Prospino, hprod
1-loop/General
GRACE-SUSY
FormCalc,SloopS
Isajet
Herwig++
Pythia
Sherpa
Fitters
Fittino
SFitter
SuperBayes
SLHA,BSM-LHEF
Spectrum Calc
FeynHiggs
NMHDECAY
CPSuperH
RGE Codes
Isasusy
SoftSusy
Spheno
Suspect
Cross talks
NP Models
SUSY
MSSM
mSUGRA
GMSB, AMSB
NMSSM
RPV, CPV,...
Other
$\mathcal{L}$
LanHEP/FeynRules
Feynman rules
(Eff. Pot.)
Dark Matter
IsaRED/RES
micrOMEGAs
SloopS
DARKSUSY
Decay Codes
BRIDGE
HDECAY
NMHDECAY
SDECAY
Flavour Calc
Dedicated Codes
SusyBSG
SuperIso
SLHA compliant, talks to other codes easily

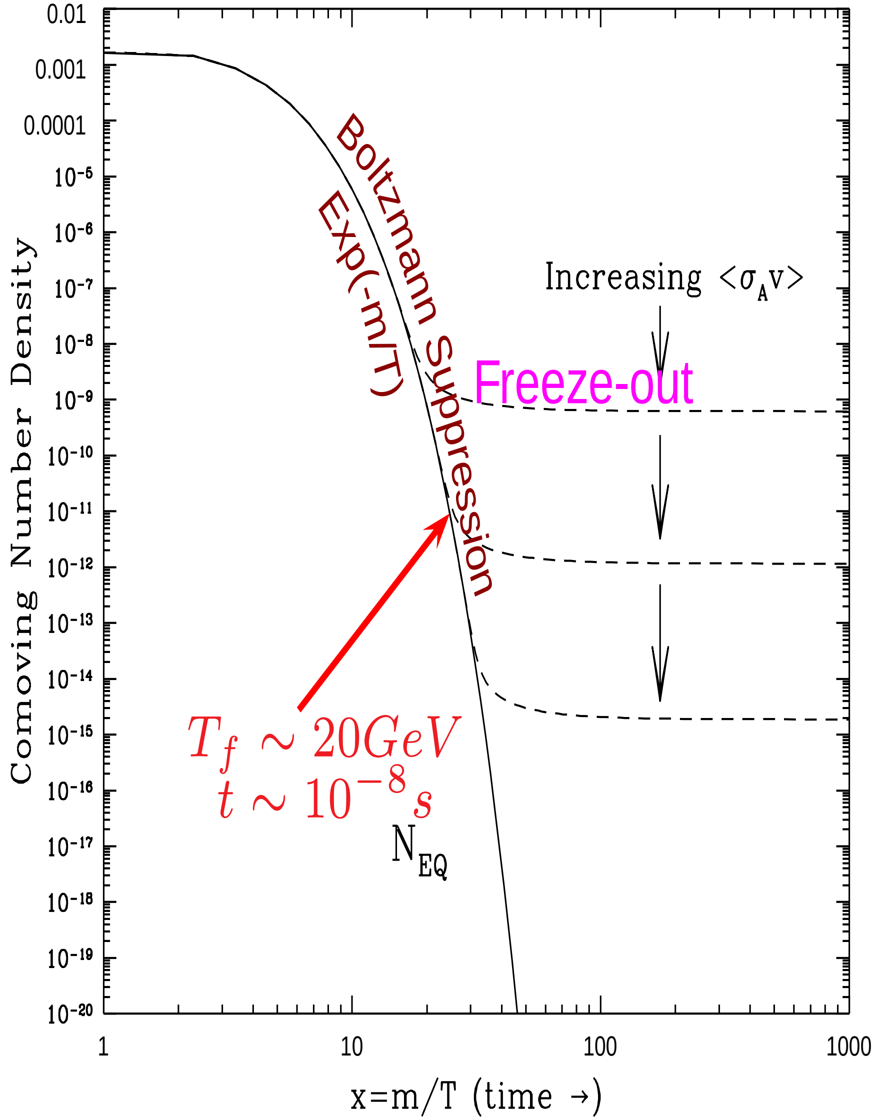
Relic Density

formation of DM: Very basics of decoupling



- At first all particles in thermal equilibrium, frequent collisions and particles are trapped in the cosmic soup
- universe cools and expands: interaction rate too small or not efficient to maintain Equil.
- (stable) particles can not find each other: freeze out and get free and leave the soup, their number density is locked giving the observed relic density
- from then on total number $(n \times a^3) = cste$
- Condition for equilibrium: mean free path smaller than distance traveled: $l_{\mathrm{m.f.p}} < vt \quad l_{\mathrm{m.f.p}} = 1/n\sigma$ $t \sim 1/H$ or Equilbrium: $\Gamma = n\sigma v > H$

freeze ou/decoupling occurs at $T = T_D = T_F : \Gamma = H$ and $\Omega_{\tilde{\chi}_1^0} h^2 \propto 1/\sigma_{\tilde{\chi}_1^0}$



based on $\mathcal{L}[f] = \mathcal{C}[f]$

dilution due to expansion

$$dn/dt = -3Hn - <\sigma v> (n^2 - n_{eq}^2)$$

$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to X$

$X \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$

- at early times $\Gamma \gg H \to n \sim n_{eq}$
- $T \sim m_X$ not enough energy to give $X \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ n drops and so does Γ

$T_f \simeq m/25$

$$\boxed{\Omega_{\tilde{\chi}_1^0} h^2 \propto 1/\sigma_{\tilde{\chi}_1^0}}$$

Thermal average

must calculate all annihilation, co-annihilation processes. Each annihilation can consist of tens of cross sections...

$$\chi_i^0 \chi_j^0 \to X_{SM} Y_{SM}, \chi_1^0 \tilde{f}_1 \to X_{SM} Y_{SM}, \ldots \qquad v \times \sigma v$$

$$< \sigma v >= \frac{\sum\limits_{i,j} g_i g_j \int\limits_{(m_i+m_j)^2} ds \sqrt{s} K_1(\sqrt{s}/T)\, p_{ij}^2 \sigma_{ij}(s)}{2T\left(\sum\limits_i g_i m_i^2 K_2(m_i/T)\right)^2},$$

p_{ij} is the momentum of the incoming particles in their center-of-mass frame.

Origin of Boltzman factor $exp(-\delta M/T)$

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p_{ij} is the momentum of the incoming particles in their center-of-mass frame.

Origin of Boltzman factor $exp(-\delta M/T)$

$$B_f = \frac{K_1((m_i+m_j)/T_f)}{K_1(2m_{\tilde{\chi}_1^0}/T_f)} \approx e^{-X_f \frac{(m_i+m_j-2m_{\tilde{\chi}_1^0})}{m_{\tilde{\chi}_1^0}}} \qquad if\ B_f < B_\epsilon \text{ do not compute}$$

In the code $B_\epsilon = 10^{-6}$ by default. Most often $B_\epsilon = 10^{-2}$ enough for 1% accuracy, only a few processes computed.

Thermal average

must calculate all annihilation, co-annihilation processes. Each annihilation can consist of tens of cross sections...

$$\chi_i^0\chi_j^0 \to X_{SM}Y_{SM}, \chi_1^0\tilde{f}_1 \to X_{SM}Y_{SM}, \ldots \qquad v \times \sigma v$$

$$<\sigma v>= \frac{\sum_{i,j} g_i g_j \int_{(m_i+m_j)^2} ds\sqrt{s}\, K_1(\sqrt{s}/T)\, p_{ij}^2\sigma_{ij}(s)}{2T\left(\sum_i g_i m_i^2 K_2(m_i/T)\right)^2},$$

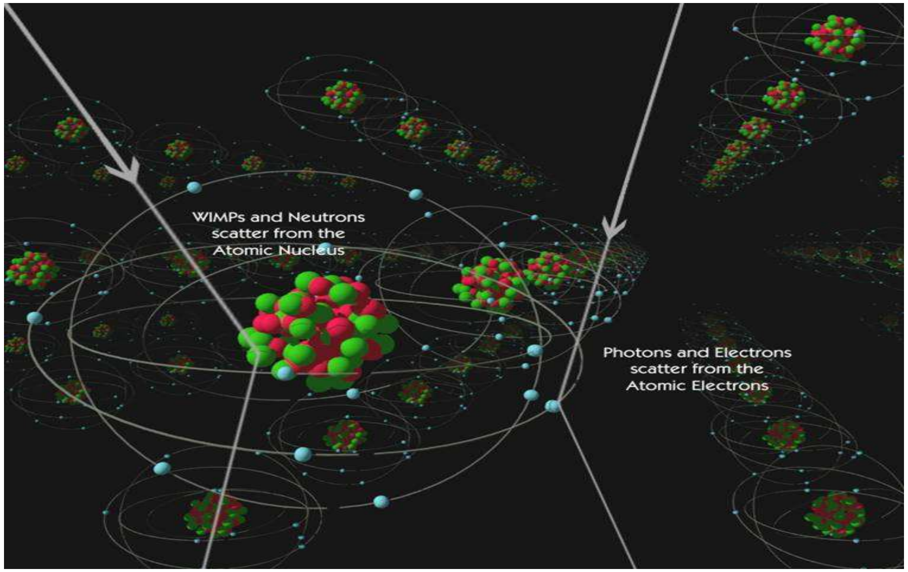
p_{ij} is the momentum of the incoming particles in their center-of-mass frame.

Origin of Boltzman factor $exp(-\delta M/T)$

In micrOMEGAs $<\sigma v>(T)$ is obtained from direct integration, through adaptive Simpson with two options (fast, default) and accurate (checks for accuracy). Adaptive: looks for poles and thresholds.

in DarkSUSY: tabulation

Direct detection

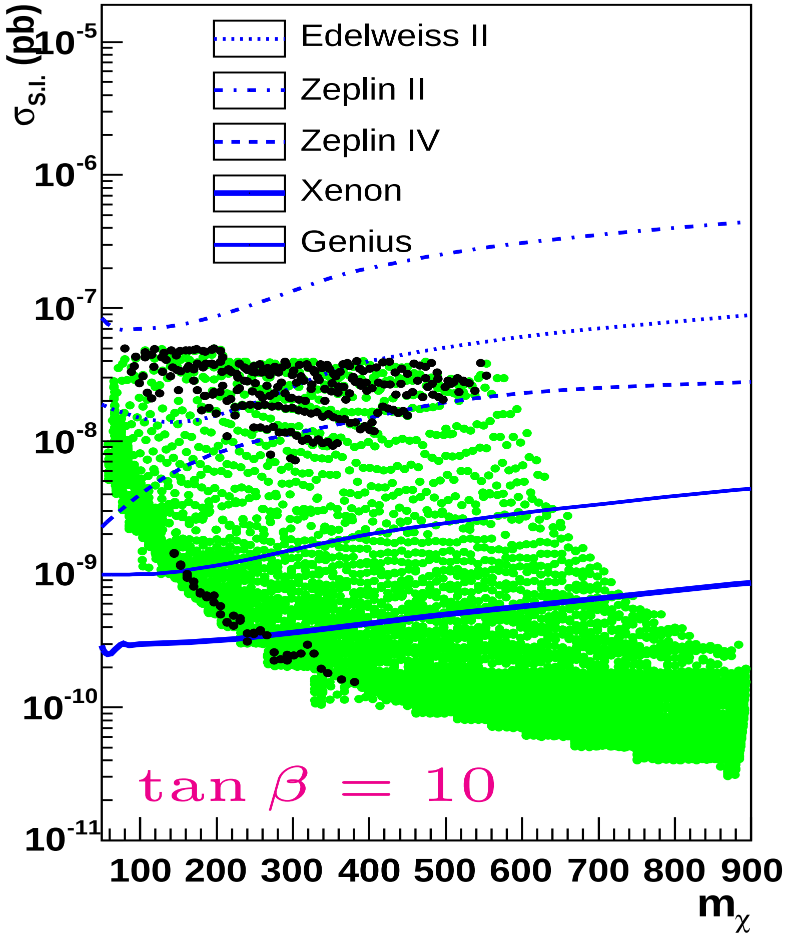


$\chi\mathcal{N} \to \chi\mathcal{N}$ **to** $\chi N \to \chi N$ $(N = n, p)$

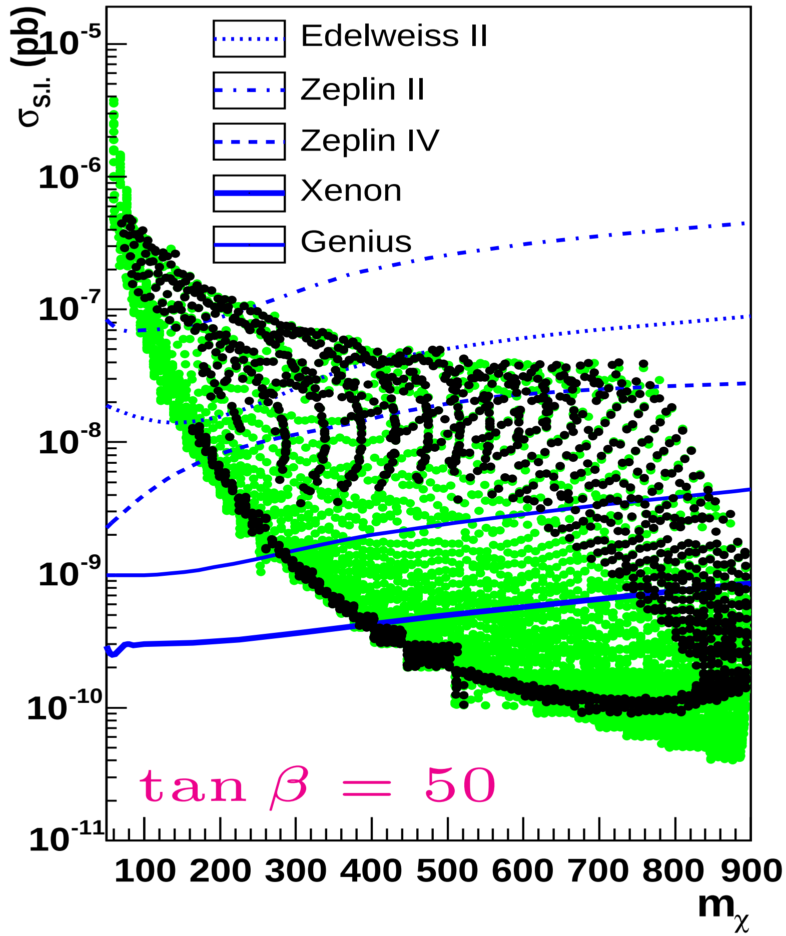
to $\chi q \to \chi q$

ingredients/Modules: dark matter density and modulation, velocity distribution quark content in nucleon, Nuclear form factors,.....

• within WMAP

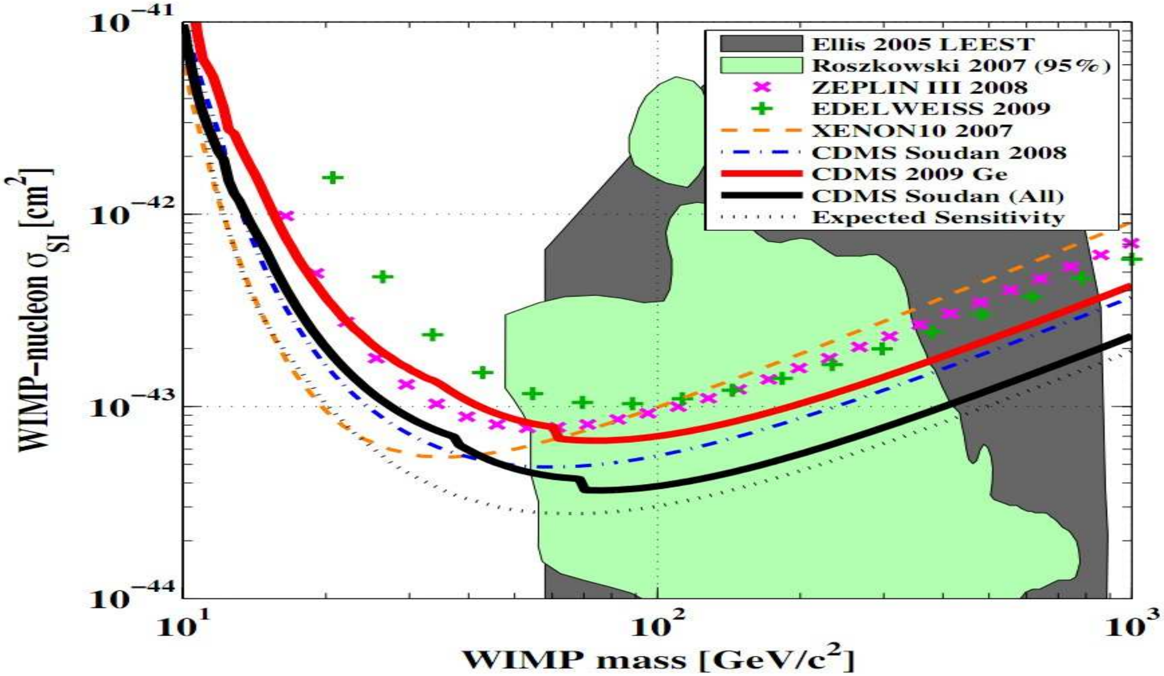


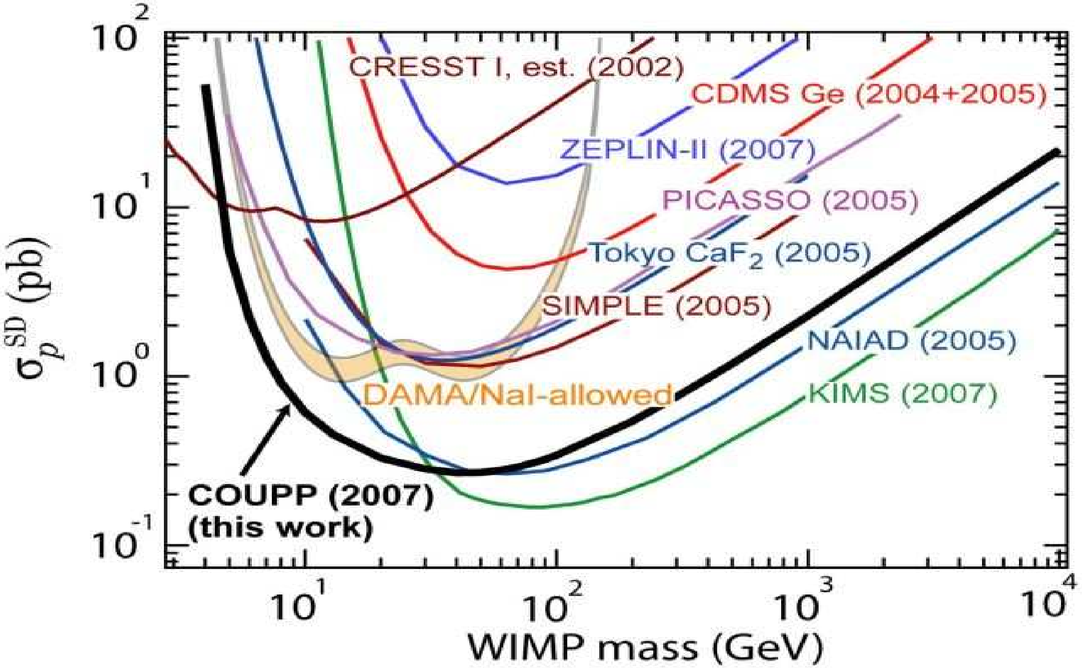
Edelweiss II
Zeplin II
Zeplin IV
Xenon
Genius
$\sigma_{S.I.}$ (pb)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
100 200 300 400 500 600 700 800 900
m_χ
$\tan\beta = 10$



Edelweiss II
Zeplin II
Zeplin IV
Xenon
Genius
$\sigma_{S.I.}$ (pb)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
100 200 300 400 500 600 700 800 900
m_χ
$\tan\beta = 50$

Limits are improving fast, signals??





Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}|>v_{\min}} d^3v\, v\, f(\vec{v}, \vec{v_e}) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}|>v_{\min}} d^3v \, v \, f(\vec{v}, \vec{v_e}) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

- N_T is the number of target nuclei per unit mass
- E_R= recoil energy
- $\vec{v}$ is the dark matter velocity in the frame of the Earth, $\vec{v_e}$ is the velocity of the Earth with respect to the galactic halo, and $f(\vec{v}, \vec{v_e})$ is the distribution function of dark matter particle velocities.
  In micrOMEGAs a truncated Maxwellian distribution is implemented by default, with free parameters to allow for study/deviations from the isothermal model.
- $\sigma_{W\mathcal{N}}$ Wimp-Nucleus cross section. Involves: BSM physics, nuclear physics, SM particle physics

Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}|>v_{\min}} d^3v\, v\, f(\vec{v},\vec{v_e}) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

$$\frac{d\sigma_{W\mathcal{N}}}{dE_R} = \frac{m_{\mathcal{N}}}{2v^2\mu_{\mathcal{N}}^2} \left(\sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2\right)$$

Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}|>v_{\min}} d^3v \, v \, f(\vec{v}, \vec{v_e}) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

$$\frac{d\sigma_{W\mathcal{N}}}{dE_R} = \frac{m_{\mathcal{N}}}{2v^2\mu_{\mathcal{N}}^2} \left(\sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2 \right)$$

$F_{SI,SD}$ = Nuclear Form Factors

$\mu_{\mathcal{N}}^2$ reduced $\mathcal{N} - \chi$ mass

Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}|>v_{\min}} d^3v\, v\, f(\vec{v}, \vec{v_e}) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

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For SI further factorisation

$$\sigma_0^{SI} = \frac{4\mu_N^2}{\pi} \left[\lambda_p Z + \lambda_n (A - Z)\right]^2,$$

(For SD no factorisation but spin structure functions (more involved)).

Nuclear Physics: Fourier transform of the nucleus distribution function, use Fermi distribution (which leads to so called Woods-Saxon FF)

$$F_{SI} = F_\mathcal{N}(q) = \int e^{-iqx} \rho_\mathcal{N}(x) d^3x, \quad \rho_\mathcal{N}(r) = \frac{c_{norm}}{1 + exp((r - R_\mathcal{N})/a)}$$

Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}|>v_{\min}} d^3v\, v\, f(\vec{v}, \vec{v_e}) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

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$\lambda_{p,n}$ **coupling of DM but also quark content in nucleon**

Take for exemple the case of a Majorana Wimp **Majorana:** $\chi = \overline{\chi}$

$$
\begin{aligned}
\mathcal{L}_F &= \lambda_N \overline{\psi}_\chi \psi_\chi \overline{\psi}_N \psi_N \\
&+ i\kappa_1 \overline{\psi}_\chi \psi_\chi \overline{\psi}_N \gamma_5 \psi_N + i\kappa_2 \overline{\psi}_\chi \gamma_5 \psi_\chi \overline{\psi}_N \psi_N \\
&+ \kappa_3 \overline{\psi}_\chi \gamma_5 \psi_\chi \overline{\psi}_N \gamma_5 \psi_N + \kappa_4 \overline{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \overline{\psi}_N \gamma^\mu \psi_N \\
&+ \xi_N \overline{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \overline{\psi}_N \gamma^\mu \gamma_5 \psi_N
\end{aligned}
$$

Majorana $q^2 \rightarrow 0$

$$\begin{aligned} \mathcal{L}_F &= \lambda_N \overline{\psi}_\chi \psi_\chi \overline{\psi}_N \psi_N \quad \Rightarrow \mathrm{scalar} \quad \mathrm{spin-independent} \quad \mathrm{SI} \\ &+ \xi_N \overline{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \overline{\psi}_N \gamma^\mu \gamma_5 \psi_N \quad \Rightarrow \mathrm{spin-dependent} \quad \mathrm{SD} \end{aligned}$$

Majorana $q^2 \to 0$

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Generalisation to other DM particles, Spin-0, 1/2, 1 for $q^2 \to 0$
not necessarily of Majorana type : $\chi \neq \overline{\chi}$
Classify as two types of operators
1) $_e$=even under $\chi \leftrightarrow \overline{\chi}$ interchange
2) $_o$=odd under $\chi \leftrightarrow \overline{\chi}$ interchange, vanish for self-conjugate (Majorana) DM

Majorana $q^2 \to 0$

$$\begin{aligned}
\mathcal{L}_F &= \lambda_N \overline{\psi}_\chi \psi_\chi \overline{\psi}_N \psi_N \qquad \Rightarrow \text{scalar} \quad \text{spin} - \text{independent} \quad \text{SI} \\
&+ \quad \xi_N \overline{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \overline{\psi}_N \gamma^\mu \gamma_5 \psi_N \qquad \Rightarrow \text{spin} - \text{dependent} \quad \text{SD}
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{s=1/2} &= \lambda_{N,e} \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N + \lambda_{N,o} \bar{\psi}_\chi \gamma_\mu \psi_\chi \bar{\psi}_N \gamma^\mu \psi_N \\
&+ \quad \xi_{N,e} \bar{\psi}_\chi \gamma_5 \gamma_\mu \psi_\chi \bar{\psi}_N \gamma_5 \gamma^\mu \psi_N - \frac{1}{2} \xi_{N,o} \bar{\psi}_\chi \sigma_{\mu\nu} \psi_\chi \bar{\psi}_N \sigma^{\mu\nu} \psi_N
\end{aligned}$$

Majorana $q^2 \to 0$

$$
\begin{aligned}
\mathcal{L}_F &= \lambda_N \overline{\psi}_\chi \psi_\chi \overline{\psi}_N \psi_N \quad \Rightarrow \mathrm{scalar} \quad \mathrm{spin-independent} \quad \mathrm{SI} \\
&+ \quad \xi_N \overline{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \overline{\psi}_N \gamma^\mu \gamma_5 \psi_N \quad \Rightarrow \mathrm{spin-dependent} \quad \mathrm{SD} \\
\mathcal{L}_{s=1/2} &= \lambda_{N,e} \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N + \lambda_{N,o} \bar{\psi}_\chi \gamma_\mu \psi_\chi \bar{\psi}_N \gamma^\mu \psi_N \\
&+ \quad \xi_{N,e} \bar{\psi}_\chi \gamma_5 \gamma_\mu \psi_\chi \bar{\psi}_N \gamma_5 \gamma^\mu \psi_N - \frac{1}{2} \xi_{N,o} \bar{\psi}_\chi \sigma_{\mu\nu} \psi_\chi \bar{\psi}_N \sigma^{\mu\nu} \psi_N \\
\mathcal{L}_{s=0} &= 2\lambda_{N,e} M_\chi \phi_\chi \phi_\chi^* \bar{\psi}_N \psi_N + i\lambda_{N,o} (\partial_\mu \phi_\chi \phi_\chi^* - \phi_\chi \partial_\mu \phi_\chi^*) \bar{\psi}_N \gamma_\mu \psi_N
\end{aligned}
$$

Majorana $q^2 \to 0$

$$
\begin{aligned}
\mathcal{L}_F &= \lambda_N \overline{\psi}_\chi \psi_\chi \overline{\psi}_N \psi_N \quad \Rightarrow \text{scalar} \quad \text{spin} - \text{independent} \quad \text{SI} \\
&+ \xi_N \overline{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \overline{\psi}_N \gamma^\mu \gamma_5 \psi_N \quad \Rightarrow \text{spin} - \text{dependent} \quad \text{SD}
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{s=1/2} &= \lambda_{N,e} \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N + \lambda_{N,o} \bar{\psi}_\chi \gamma_\mu \psi_\chi \bar{\psi}_N \gamma^\mu \psi_N \\
&+ \xi_{N,e} \bar{\psi}_\chi \gamma_5 \gamma_\mu \psi_\chi \bar{\psi}_N \gamma_5 \gamma^\mu \psi_N - \frac{1}{2} \xi_{N,o} \bar{\psi}_\chi \sigma_{\mu\nu} \psi_\chi \bar{\psi}_N \sigma^{\mu\nu} \psi_N \\
\mathcal{L}_{s=0} &= 2\lambda_{N,e} M_\chi \phi_\chi \phi_\chi^* \bar{\psi}_N \psi_N + i\lambda_{N,o} (\partial_\mu \phi_\chi \phi_\chi^* - \phi_\chi \partial_\mu \phi_\chi^*) \bar{\psi}_N \gamma_\mu \psi_N \\
\mathcal{L}_{s=1} &= 2\lambda_{N,e} M_\chi A_{\chi\mu} A_\chi^\mu \overline{\psi}_N \psi_N + \lambda_{N,o} i (A_\chi^{*\alpha} \partial_\mu A_{\chi,\alpha} - A_\chi{}^\alpha \partial_\mu A^*_{\chi\alpha}) \overline{\psi}_N \gamma_\mu \psi_N \\
&+ \sqrt{6} \xi_{N,e} (\partial_\alpha A^*_{\chi\beta} A_{\chi\gamma} - A^*_{\chi\beta} \partial_\alpha A_{\chi\gamma}) \epsilon^{\alpha\beta\gamma\mu} \overline{\psi}_N \gamma_5 \gamma_\mu \psi_N \\
&+ i \frac{\sqrt{3}}{2} \xi_{N,o} (A_{\chi\mu} A^*_{\chi\nu} - A^*_{\chi\mu} A_{\chi\nu}) \overline{\psi}_N \sigma^{\mu\nu} \psi_N
\end{aligned}
$$

Majorana $q^2 \to 0$

$$\begin{aligned}
\mathcal{L}_F &= \lambda_N \overline{\psi}_\chi \psi_\chi \overline{\psi}_N \psi_N \quad \Rightarrow \text{scalar} \quad \text{spin}-\text{independent} \quad \text{SI} \\
&+ \xi_N \overline{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \overline{\psi}_N \gamma^\mu \gamma_5 \psi_N \quad \Rightarrow \text{spin}-\text{dependent} \quad \text{SD}
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{s=1/2} &= \lambda_{N,e} \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N + \lambda_{N,o} \bar{\psi}_\chi \gamma_\mu \psi_\chi \bar{\psi}_N \gamma^\mu \psi_N \\
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\mathcal{L}_{s=1} &= 2\lambda_{N,e} M_\chi A_{\chi\mu} A_\chi^\mu \overline{\psi}_N \psi_N + \lambda_{N,o} i (A_\chi^{*\alpha} \partial_\mu A_{\chi,\alpha} - A_\chi{}^\alpha \partial_\mu A_{\chi\alpha}^*) \overline{\psi}_N \gamma_\mu \psi_N \\
&+ \sqrt{6} \xi_{N,e} (\partial_\alpha A_{\chi\beta}^* A_{\chi\gamma} - A_{\chi\beta}^* \partial_\alpha A_{\chi\gamma}) \epsilon^{\alpha\beta\gamma\mu} \overline{\psi}_N \gamma_5 \gamma_\mu \psi_N \\
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\end{aligned}$$

$$\begin{aligned}
\lambda_N &= \frac{\lambda_{N,e} \pm \lambda_{N,o}}{2} \quad \text{and} \quad \xi_N = \frac{\xi_{N,e} \pm \xi_{N,o}}{2} \\
+ &\mapsto \text{WIMP} \quad \text{and} \quad - \mapsto \text{anti}-\text{WIMP}
\end{aligned}$$

Wimp-quark effective Lagrangian, $\psi_N \to \psi_q$

	WIMP Spin	Even Operators $\hat{\mathcal{O}}_{q,e}$ $\hat{\mathcal{O}}'_{q,e}$	Odd Operators $\hat{\mathcal{O}}_{q,o}$ $\hat{\mathcal{O}}'_{q,o}$
		$\hat{\mathcal{O}}_{q,e}$	$\hat{\mathcal{O}}_{q,o}$
SI	0	$2M_\chi \phi_\chi \phi^*_\chi \overline{\psi}_q \psi_q$	$i(\partial_\mu \phi_\chi \phi^*_\chi - \phi_\chi \partial_\mu \phi^*_\chi)\overline{\psi}_q \gamma^\mu \psi_q$
	1/2	$\overline{\psi_\chi} \psi_\chi \overline{\psi}_q \psi_q$	$\overline{\psi}_\chi \gamma_\mu \psi_\chi \overline{\psi}_q \gamma^\mu \psi_q$
	1	$2M_\chi A^*_{\chi\mu} A^\mu_\chi \overline{\psi}_q \psi_q$	+$i(A^{*\alpha}_\chi \partial_\mu A_{\chi,\alpha} - A_\chi{}^\alpha \partial_\mu A^*_{\chi\alpha})\overline{\psi}_q \gamma_\mu \psi_q$
		$\hat{\mathcal{O}}'_{q,e}$	$\hat{\mathcal{O}}'_{q,o}$
SD	1/2	$\overline{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \overline{\psi}_q \gamma_\mu \gamma_5 \psi_q$	$-\frac{1}{2}\overline{\psi}_\chi \sigma_{\mu\nu} \psi_\chi \overline{\psi}_q \sigma^{\mu\nu} \psi_q$
	1	$\sqrt{6}(\partial_\alpha A^*_{\chi\beta} A_{\chi\nu} - A^*_{\chi\beta} \partial_\alpha A_{\chi\nu})$ $\epsilon^{\alpha\beta\nu\mu} \overline{\psi}_q \gamma_5 \gamma_\mu \psi_q$	$i\frac{\sqrt{3}}{2}(A_{\chi\mu} A^*_{\chi\nu} - A^*_{\chi\mu} A_{\chi\nu})\overline{\psi}_q \sigma^{\mu\nu} \psi_q$

$$\hat{\mathcal{L}}_{eff}(x) = \sum_{q,s} \lambda_{q,s} \hat{\mathcal{O}}_{q,s}(x) + \xi_{q,s} \hat{\mathcal{O}}'_{q,s}(x)$$

In model files of `micrOMEGAs` (`CalcHEP`) these operators are added

- In the usual approach these low energy operators and their coefficients are extracted by computing WIMP-quark *amplitudes* from Feynman diagrams and using Fierz transformations,..

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- with the S-matrix, $\hat{S} = 1 - i\mathcal{L}$ obtained from the complete Lagrangian at the quark level

$$\lambda_{q,e} + \lambda_{q,o} = \frac{-i\langle q(p_1), \chi(p_2)|\hat{S}\hat{\mathcal{O}}_{q,e}|q(p_1), \chi(p_2)\rangle}{\langle q(p_1), \chi(p_2)|\hat{\mathcal{O}}_{q,e}\hat{\mathcal{O}}_{q,e}|q(p_1), \chi(p_2)\rangle}$$

$$\lambda_{q,e} - \lambda_{q,o} = \frac{-i\langle \bar{q}(p_1), \chi(p_2)|\hat{S}\mathcal{O}_{q,e}|\bar{q}(p_1), \chi(p_2)\rangle}{\langle \bar{q}(p_1), \chi(p_2)|\hat{\mathcal{O}}_{q,e}\hat{\mathcal{O}}_{q,e}|\bar{q}(p_1), \chi(p_2)\rangle}$$

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\lambda_{q,e} + \lambda_{q,o} &= \frac{-i\langle q(p_1), \chi(p_2)|\hat{S}\hat{\mathcal{O}}_{q,e}|q(p_1), \chi(p_2)\rangle}{\langle q(p_1), \chi(p_2)|\hat{\mathcal{O}}_{q,e}\hat{\mathcal{O}}_{q,e}|q(p_1), \chi(p_2)\rangle} \\
\lambda_{q,e} - \lambda_{q,o} &= \frac{-i\langle \bar{q}(p_1), \chi(p_2)|\hat{S}\mathcal{O}_{q,e}|\bar{q}(p_1), \chi(p_2)\rangle}{\langle \bar{q}(p_1), \chi(p_2)|\hat{\mathcal{O}}_{q,e}\hat{\mathcal{O}}_{q,e}|\bar{q}(p_1), \chi(p_2)\rangle}
\end{aligned}$$

- warning: couplings proportional to light quark masses must be kept

χq to χN: Sandwich within nucleon, Nucleon form factors

$\langle N|\overline{\psi}_q\psi_q|N\rangle$, $\langle N|\overline{\psi}_q\gamma_\mu\psi_q|N\rangle$, $\langle N|\overline{\psi}_q\gamma_\mu\gamma_5\psi_q|N\rangle$, $\langle N|\overline{\psi}_q\sigma_{\mu\nu}\psi_q|N\rangle$

These are extracted from experiments (*e.g* $\sigma_{\pi N}$), lattice computations, plus a fair deal of theory (trace anomaly, chiral perturbation,...)

Large source of uncertainty, apart from vector (which counts number of quarks minus anti-quarks, valence quarks)

χq to χN: Sandwich within nucleon, Nucleon form factors

Scalar, light quarks

$$\langle N|m_q\overline{\psi}_q\psi_q|N\rangle = f_q^N M_N \Rrightarrow \lambda_N = \sum_{q=1,6} f_q^N \lambda_q \quad M_N : \text{Nucleon mass}$$

$$f_q^{p,n} \quad = \quad \sigma_{\pi N} G_q^{n,p}(m_u/m_d, m_s/m_d, B_u/B_d, y), \quad B_q = \langle N|\bar{q}q|N\rangle, \quad y = 1 - \sigma_0/\sigma_{\pi N}$$

Large uncertainty in $\sigma_{\pi N}$ translates into very large range for $0.08 < f_s^{p,n} < 0.46$ and hence expect variations in detection range within an order of magnitude

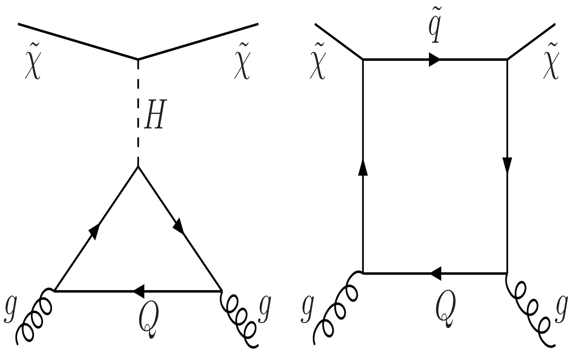
Lattice calculations are providing new estimates that will reduce uncertainty. Tensor coefficients are for example extracted from lattice calculations.

χq to χN: Sandwich within nucleon, Nucleon form factors

SI, heavy quarks, Gluons and QCD

$$\begin{aligned}\langle N|m_Q\bar{\psi}_Q\psi_Q|N\rangle &= -\frac{\Delta\beta^{h.Q}}{2\alpha_s^2(1+\gamma)}\langle N|\alpha_s G_{\mu\nu}G^{\mu\nu}|N\rangle \\ &= -\frac{1}{12\pi}(1+\frac{11\alpha_s(m_Q)}{4\pi})\langle N|\alpha_s G_{\mu\nu}G^{\mu\nu}|N\rangle\end{aligned}$$

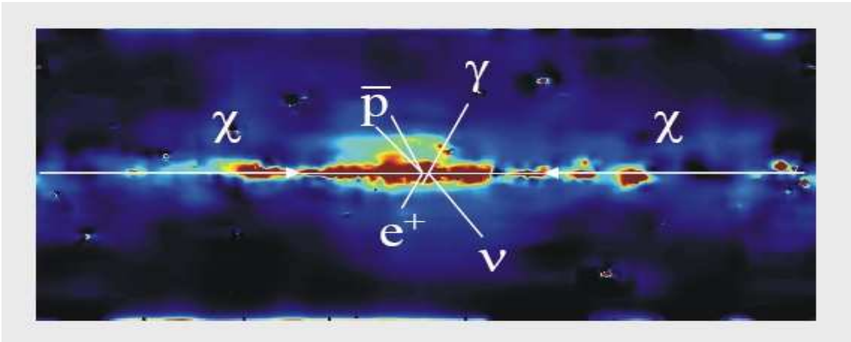
Good description of the dominant triangle, Box diagram model dependent, sub-dominant, evaluated for the MSSM only



Diagrams that contribute to WIMP-gluon interaction via quark loops in the MSSM

Other QCD and SQCD corrections for MSSM

Indirect Detection

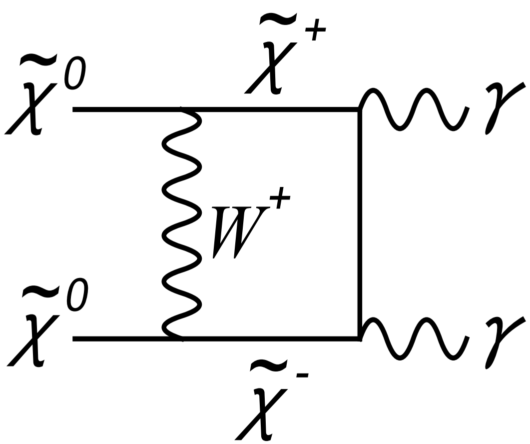


Annihilation into photons

$$\frac{d\Phi_\gamma}{d\Omega dE_\gamma} = \sum_i \underbrace{\frac{dN^i_\gamma}{dE_\gamma}\sigma_i v \frac{1}{4\pi m^2_\chi}}_{\text{Particle physics}} \underbrace{\int (\rho + \delta\rho)^2 dl}_{\text{Astro}}$$

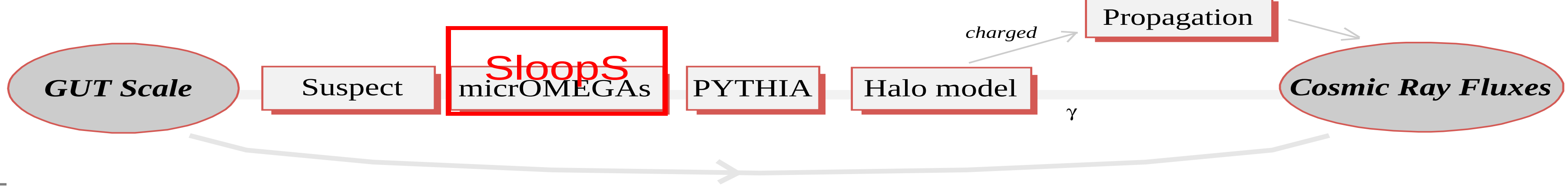
$\gamma' s$: Point to the source, independent of propagation model(s)

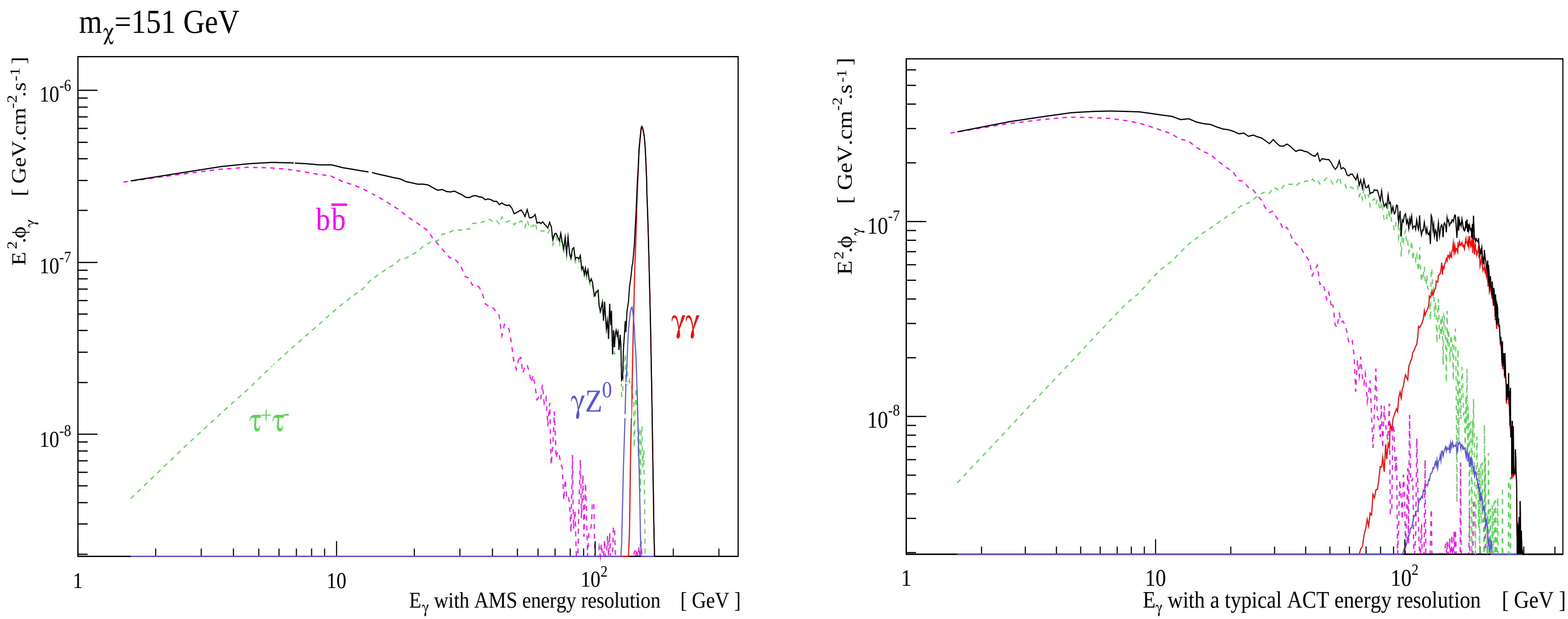
- continuum spectrum from $\tilde{\chi}^0_1\tilde{\chi}^0_1 \rightarrow f\bar{f},\ldots,$ hadronisation/fragmentation ($\rightarrow \pi^0 \rightarrow \gamma$) done through isajet/herwig
- Loop induced mono energetic photons, $\gamma\gamma$, $Z\gamma$ final states



ACT: HESS, Magic, VERITAS, Cangoroo, ...

Space-based: AMS, Fermi-LAT, Egret,...





SIMULATION: (with/from P. Brun)

Parameterising the halo profile:

$(\alpha, \beta, \gamma) = (1, 3, 1)$, $a = 25$kpc. (core radius), $r_0 = 8kpc$ (distance to galactic centre),

$\rho_0 = 0.3\, GeV/cm^3$ (DM density), opening angle cone 1^o

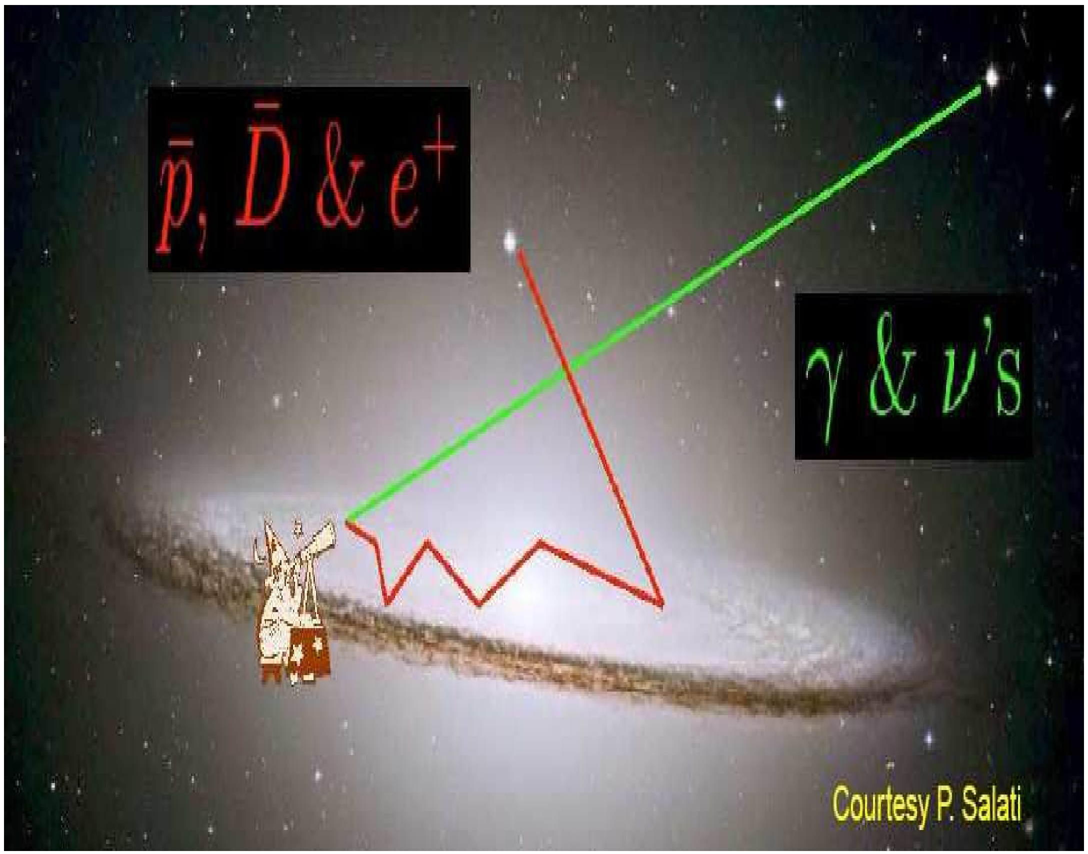
SUSY parameterisation

$m_0 = 113$GeV, $m_{1/2} = 375$ GeV, $A = 0$, $\tan\beta = 20$, $\mu > 0$

γ lines could be distinguished from diffuse background

Annihilation into $e^+, \bar{p}, \bar{D}$

$$\frac{d\Phi_{\bar{f}}}{d\Omega dE_{\bar{f}}} = \sum_i \underbrace{\frac{dN^i_{\bar{f}}}{dE_{\bar{f}}} \sigma_i v \frac{1}{4\pi m_\chi^2}}_{\text{Particle physics}} \underbrace{\int (\rho + \delta\rho)^2 P_{prop}}_{\text{Astro}}$$



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charged particles: Model of propagation and background

- Halo Profile modeling, clumps, cusps,..boost factors,...

- Annihilation cross sections for all 2-body tree-level processes for all models.

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- Annihilation cross sections including radiative emission of a photon for all models.

Features in the Indirect Detection Module of micrOMEGas

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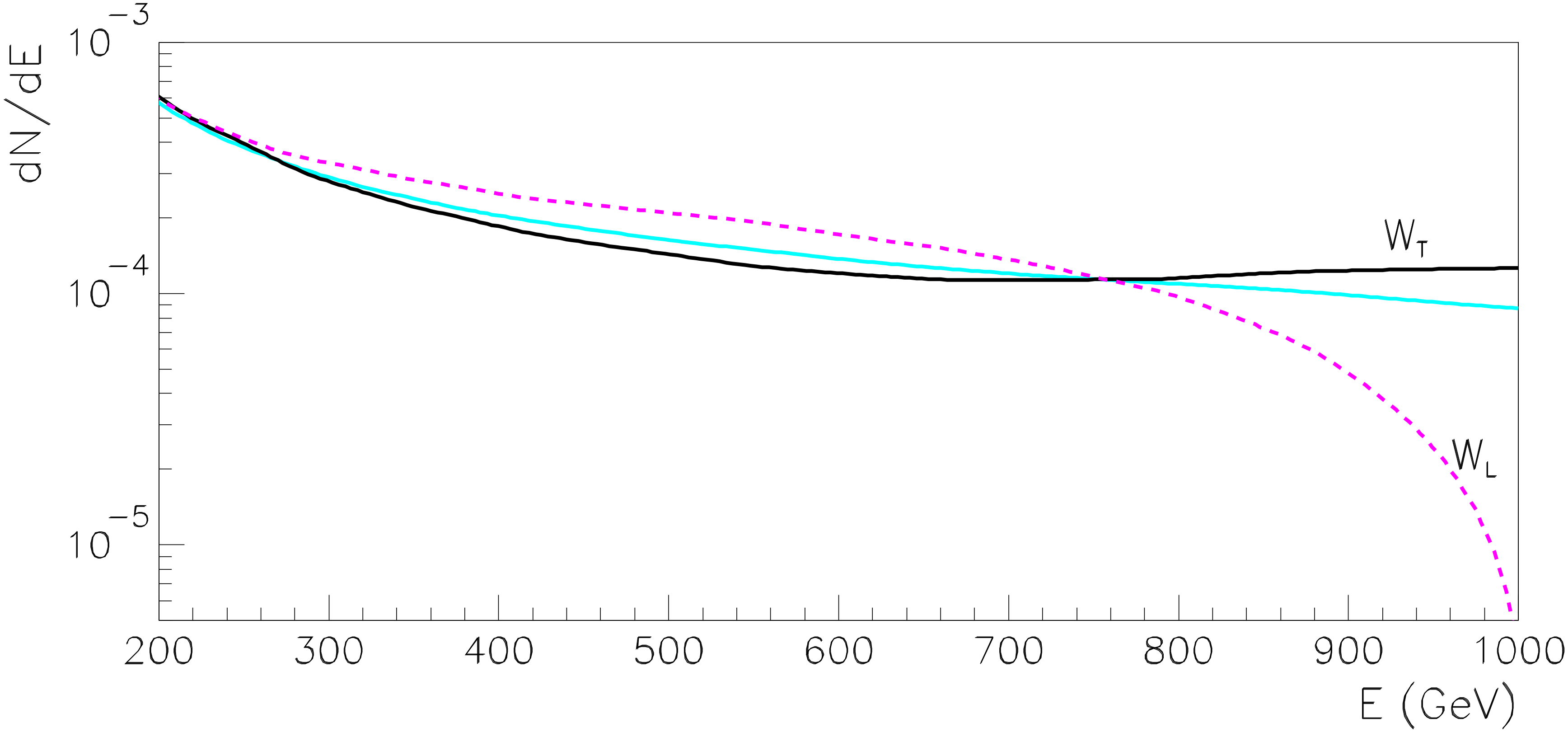
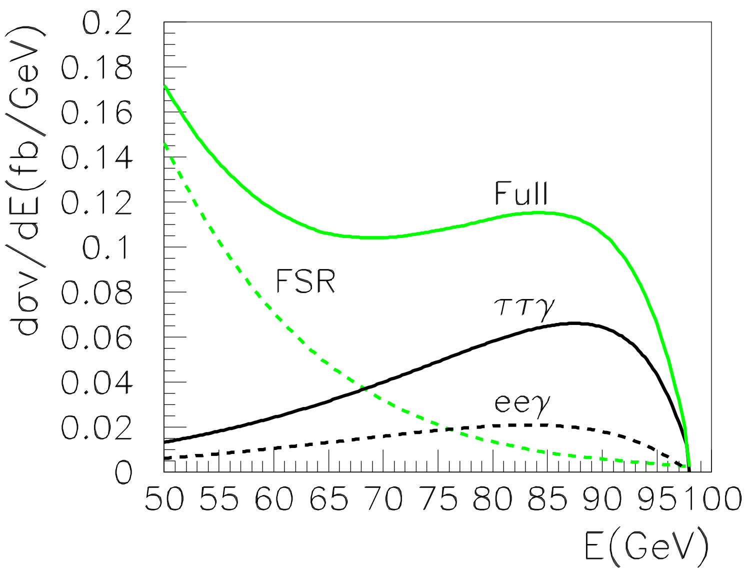
- Model independent predictions of the indirect detection signal
- The neutrino spectrum originating from dark matter annihilation is also computed, however the neutrino signal is usually dominated by neutrinos coming from DM capture in the Sun or the Earth. The inclusion of this signature is left for a further upgrade.

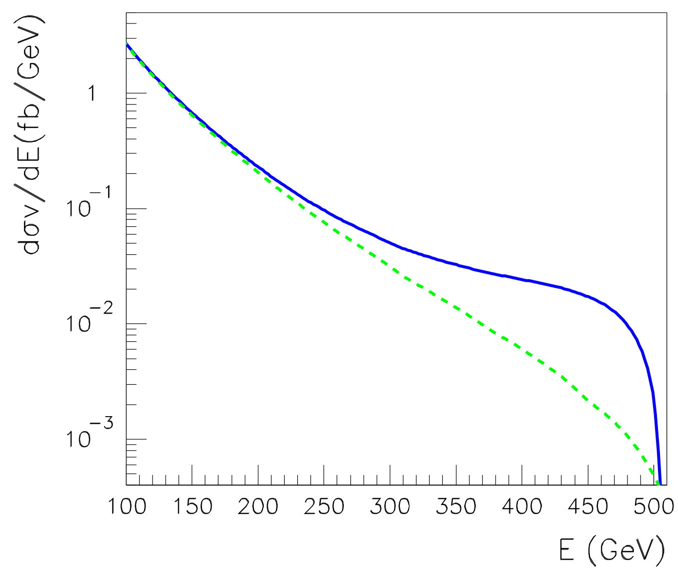
Effect of the polarisation



dN/dE_{e^+} for positrons from $\chi\chi \to W^+W^-$. $M_\chi = 1$ TeV.

Effects of non factorisable (non collinear, hard) photons

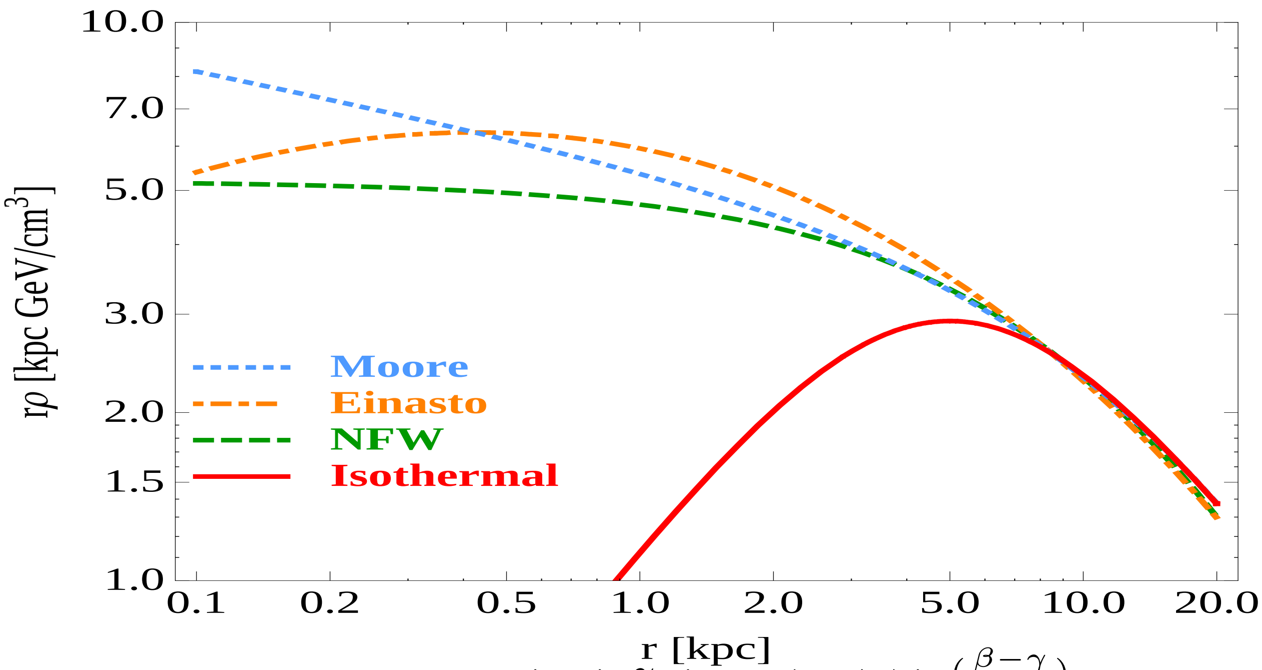




Photon spectrum within a CMSSM point including the aditional photon contribution from $2 \to 3$ $\tau\tau\gamma$, $e^+e^-\gamma$, and FSR photons from PYTHIA (FSR)

In a model for WW production, including full $WW\gamma$ as compared to PYTHIA FSR

Dark Matter Halo Profiles in micrOMEGAs



$$\rho(r) = \rho_o \left(\frac{r_o}{r}\right)^{\gamma} \left(\frac{1+(r_o/a)}{1+(r_o/a)}\right)^{\left(\frac{\beta-\gamma}{\alpha}\right)}$$

$$(\alpha, \beta, \gamma, a(kpc)) = (2, 2, 0, 4) \quad \text{Isothermal}$$

$$(\alpha, \beta, \gamma, a(kpc)) = (1, 3, 1, 20) \quad \text{NFW cusped}$$

$$(\alpha, \beta, \gamma, a(kpc)) = (1.5, 3, 1.5, 28) \quad \text{Moore, cusped}$$

$$\rho_o \sim 0.3GeV/cm^3 \ \text{ at } r_o = 8.5kpc \tag{1}$$

Other profiles (provided they are spherically symmetric are possible. For example Einasto

To avoid central divergence, we set $r > r_{min} = 10^{-3}$pc

$$\frac{\partial \psi_a}{\partial t} - \nabla \cdot (K(E)\nabla\psi_a) - \frac{\partial}{\partial E}(b(E)\psi_a) + \frac{\partial}{\partial z}(V_C\psi_a) = Q_a(\mathbf{x}, E) + \tilde{\Gamma}_{ann}, \quad \psi_a = dn/dE$$

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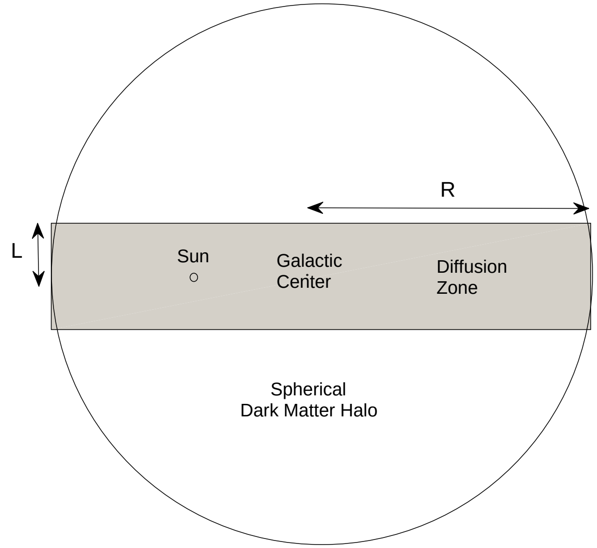
- $K(E) = K_0\beta(E)(E/E_0)^\delta$ diffusion term, stochastic galactic magnetic fields
- B energy losses due to synchroton rad., CMB , ICS, negligible for $\bar{p}$
- V_C convection galactic wind wipes away charged particles from disk (not for e+)
- $\Gamma_{ann.}$ for $\bar{p}$ disappearance through nuclear reactions (H, H_e)
- from Sun to earth “rescaling", due to solar wind and energy loss. (use Fisk pot.)

$$\frac{\partial \psi_a}{\partial t} - \nabla \cdot (K(E)\nabla\psi_a) - \frac{\partial}{\partial E}(b(E)\psi_a) + \frac{\partial}{\partial z}(V_C\psi_a) = Q_a(\mathbf{x}, E) + \tilde{\Gamma}_{ann}, \quad \psi_a = dn/dE$$

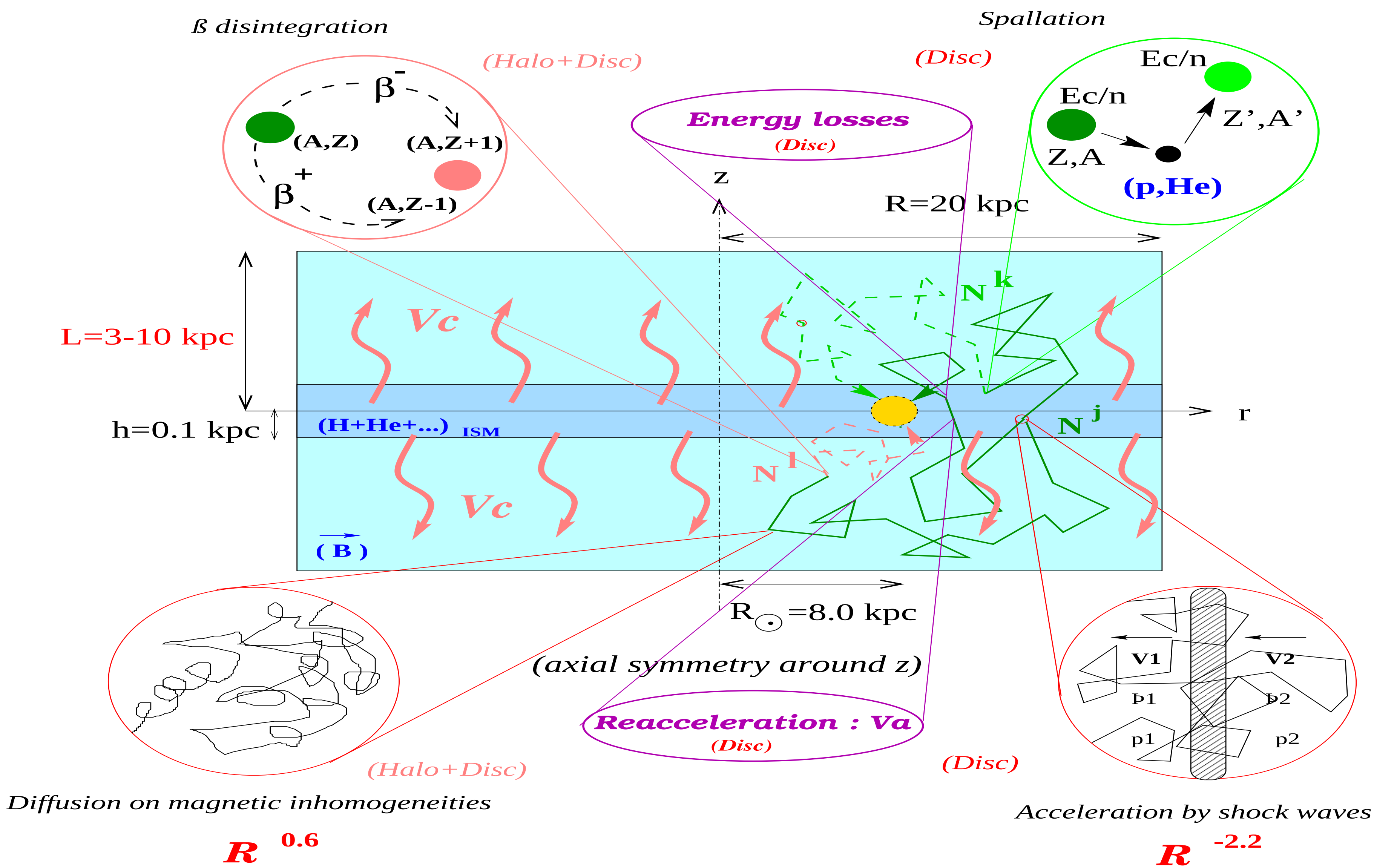
Model	δ	K_0 $\mathrm{kpc}^2/\mathrm{Myr}$	L kpc	V_C km/s
MIN	0.85	0.0016	1	13.5
MED	0.7	0.0112	4	12
MAX	0.46	0.0765	15	5

Two-zone diffusion model. Typical diffusion parameters that are compatible with the B/C analysis (Maurin et al. 2001) $E_0 = 1$GeV.

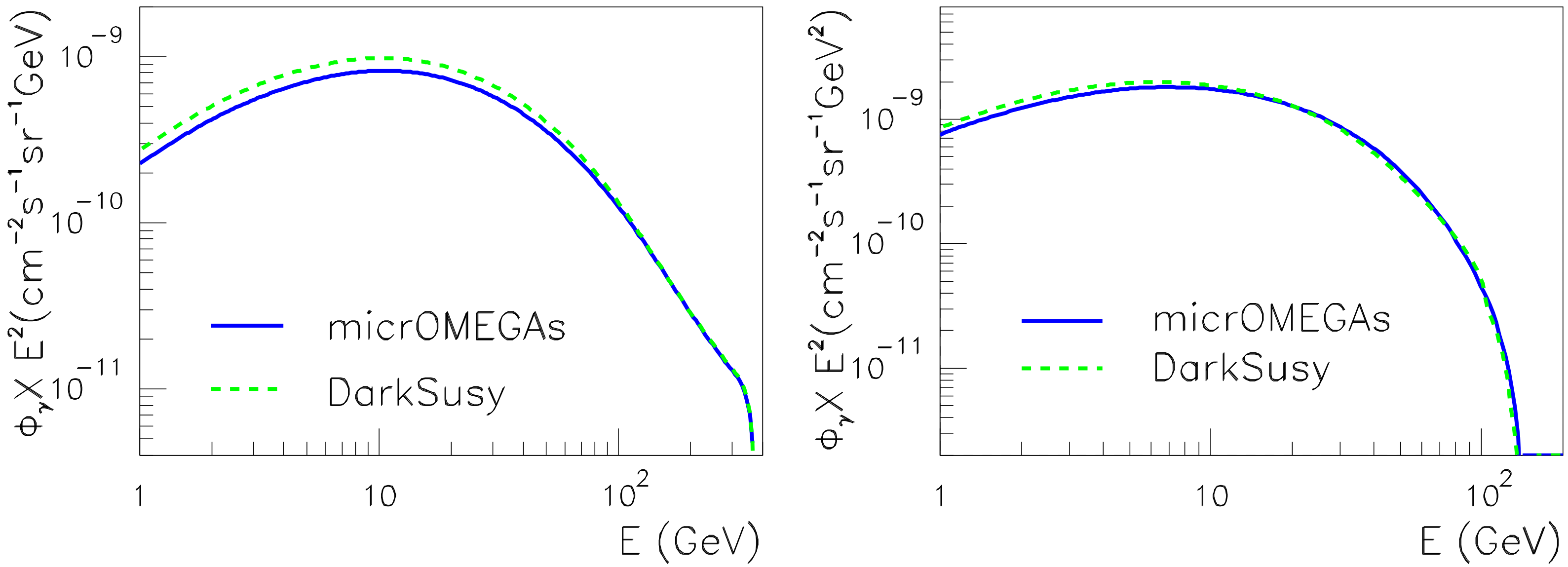


$\frac{\partial \psi_a}{\partial t} = 0$, steady state, takes e^+ 10^8y to reach the edge.

Equations solved semi-analytically


ß disintegration
(Halo+Disc)
β-
(A,Z)
(A,Z+1)
β+
(A,Z-1)
Energy losses
(Disc)
Spallation
(Disc)
Ec/n
Ec/n
Z',A'
Z,A
(p,He)
z
R=20 kpc
L=3-10 kpc
Vc
N k
h=0.1 kpc
(H+He+...) ISM
r
N j
N l
Vc
(B)
R⊙ =8.0 kpc
(axial symmetry around z)
Reacceleration : Va
(Disc)
(Halo+Disc)
(Disc)
V1
V2
p1
p2
p1
p2
Diffusion on magnetic inhomogeneities
R 0.6
Acceleration by shock waves
R -2.2

Results and Comparison, microMEGAs vs DARKSUSY, γ

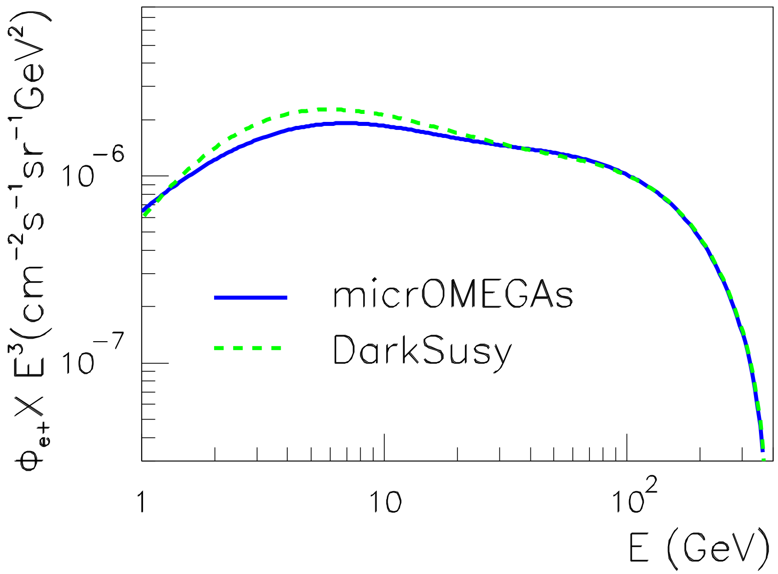


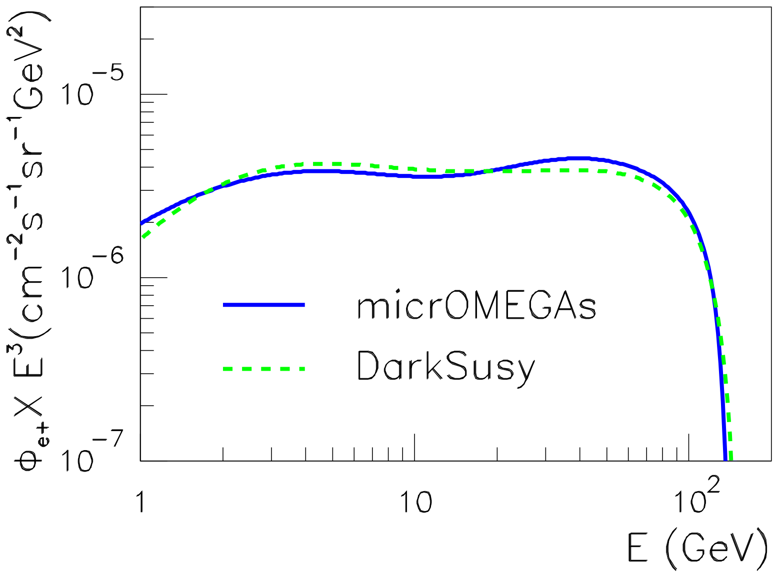
comparisons for γ signal from two CMSSM models, with NFW profile, signal from the GC in a cone of 1^o opening angle (corresponding to a solid angle of $\Delta\Omega = 10^{-3}$ sr)

slight difference due to σv

For γ line, good agreement from $\gamma\gamma$ but not $Z\gamma$, DS misses contributions

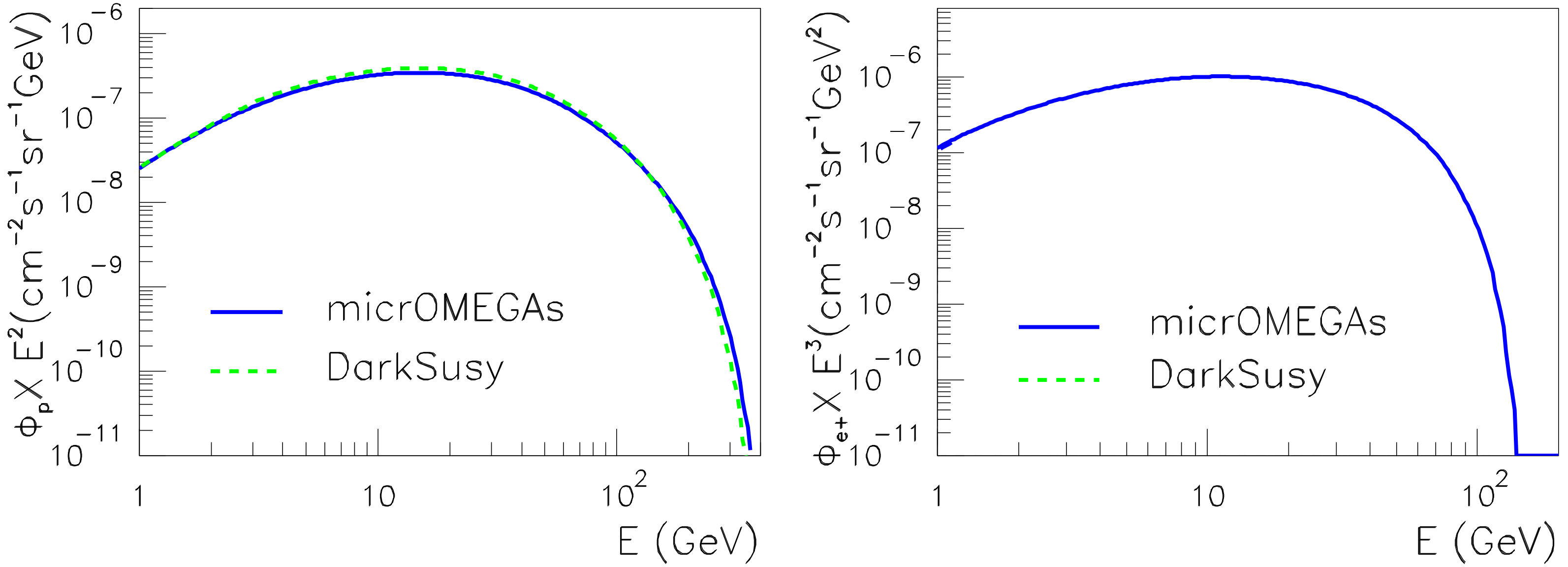
Results and Comparison, microMEGAs vs DARKSUSY, e^+





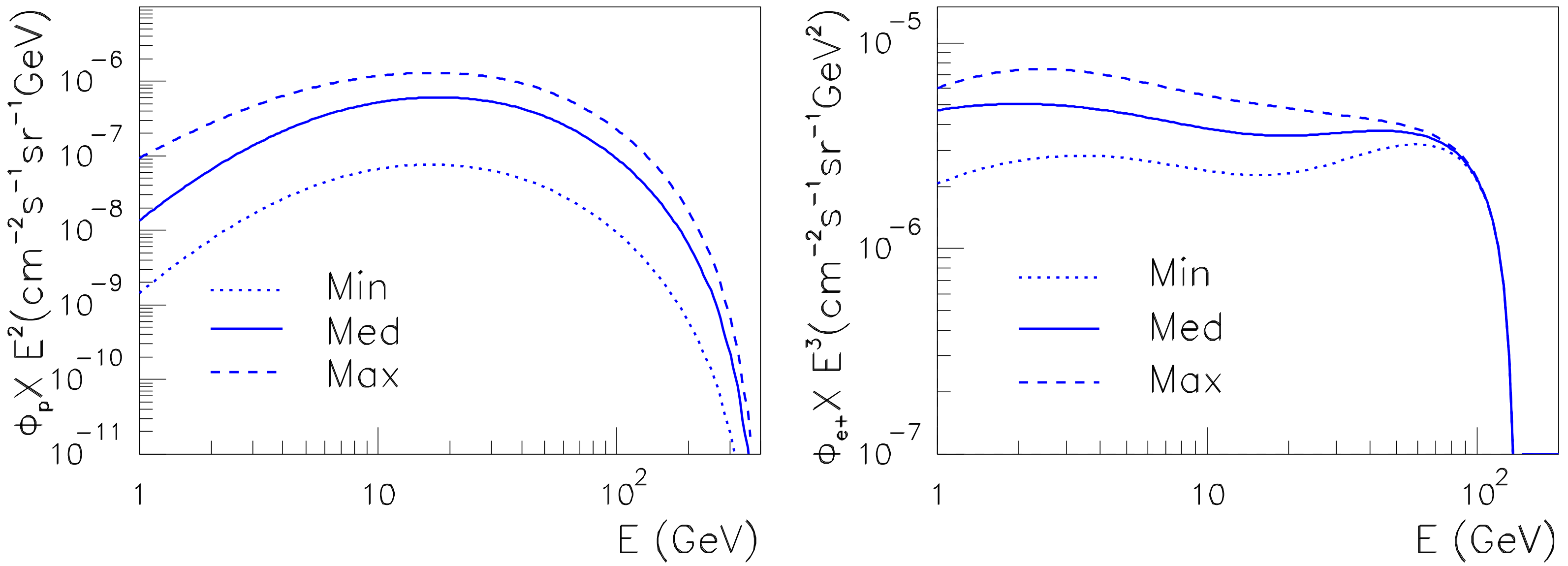
In the same SUSY models, default prop. parameters of microMEGAs tuned.

Results and Comparison, microMEGAs vs DARKSUSY, $\bar{p}$



In the same SUSY models, default prop. parameters of microMEGAs tuned.

Uncertainties due to propagation microMEGAs



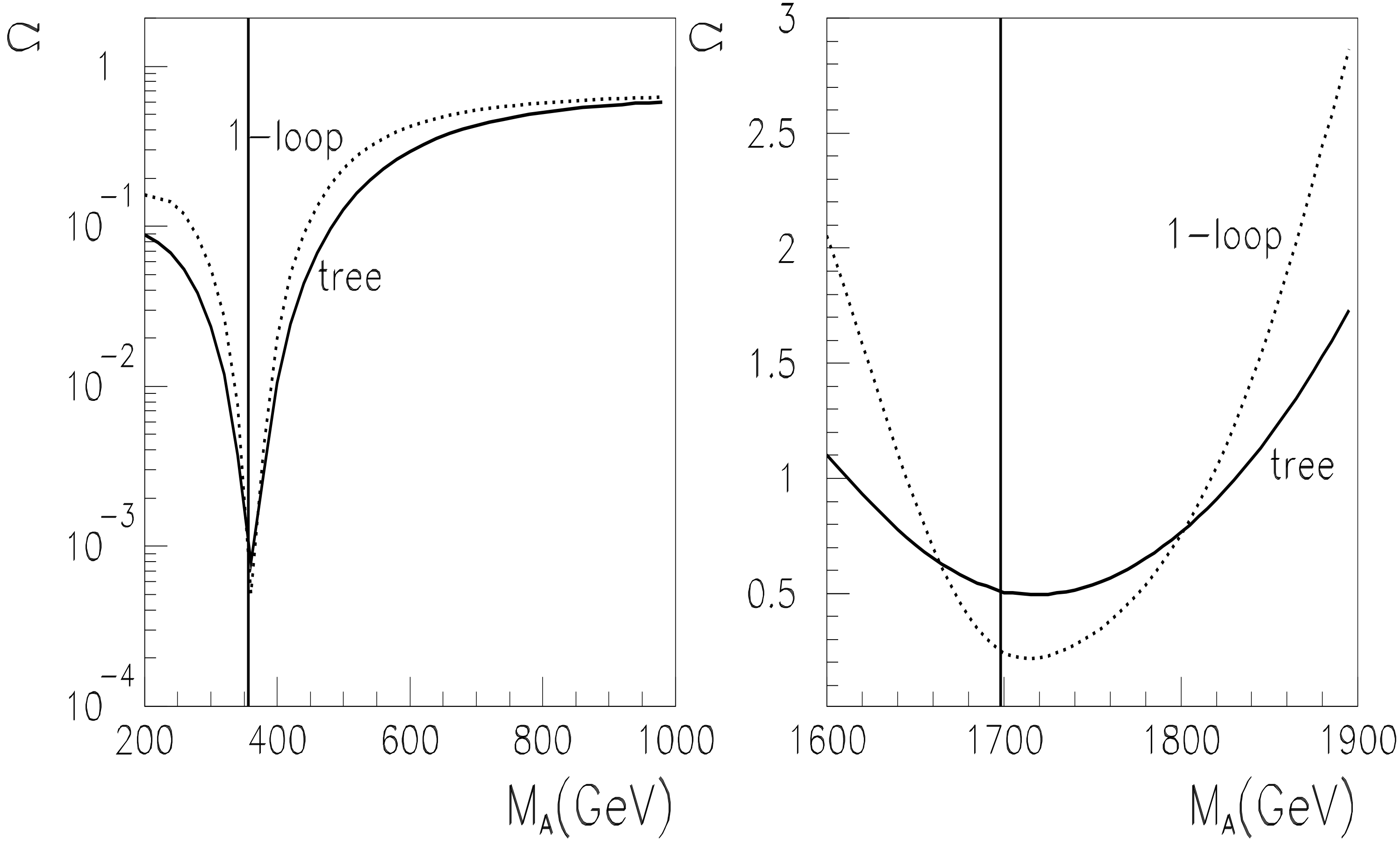
Present measurement at 2σ $\boxed{0.0975 < \omega = \Omega_{\rm DM} h^2 < 0.1223}$ **(6%)**

future (SNAP+Planck) $\rightarrow < 1\%$

Need more Precise Predictions

γ ray-line is a one-loop calc.

2. Need to go beyond tree-level: Need percent level



SLOOPS N. Baro, FB, G. Chalons, S. Hao, A. Semenov, (D. Temes)

- Need for an automatic tool for susy calculations
- handles large numbers of diagrams both for tree-level
- and loop level
- able to compute loop diagrams at $v = 0$: dark matter, LSP, move at galactic velocities, $v = 10^{-3}$
- ability to check results: UV and IR finiteness but also gauge parameter independence for example
- ability to include different models easily and switch between different renormalisation schemes
- Used for SM one-loop multi-leg: new powerful loop libraries (with Ninh Le Duc, Sun Hao)

Non-linear gauge implementation

$$\mathcal{L}_{GF} = -\frac{1}{\xi_W}|(\partial_\mu - ie\tilde{\alpha}A_\mu - igc_W\tilde{\beta}Z_\mu)W^{\mu\,+} + \xi_W\frac{g}{2}(v + \tilde{\delta}_h h + \tilde{\delta}_H H + i\tilde{\kappa}\chi_3)\chi^+|^2$$
$$-\frac{1}{2\xi_Z}(\partial.Z + \xi_Z\frac{g}{2c_W}(v + \tilde{\epsilon}_h h + \tilde{\epsilon}_H H)\chi_3)^2 - \frac{1}{2\xi_\gamma}(\partial.A)^2$$

- quite a handful of gauge parameters, but with $\xi_i = 1$, no "unphysical threshold"
- more important: no need for higher (than the minimal set)for higher rank tensors and tedious algebraic manipulations

Strategy: Exploiting and interfacing modules from different codes

Lagrangian of the model defined in LanHEP

- particle content
- interaction terms
- shifts in fields and parameters
- ghost terms constructed by BRST

$\downarrow$ $\downarrow$

Generic Model
-kinematical structures

Classes Model
-Feynman rules, including CT

$\Downarrow$

Evaluation via FeynArts-FormCalc

LoopTools modified!!
tensor reduction inappropriate for small relative velocities
(Zero Gram determinants)

$\Uparrow$

Renormalisation scheme

- definition of renorm. const. in the classes model

Non-Linear gauge-fixing constraints, gauge parameter dependence checks

```
vector
    A/A: (photon, gauge),
    Z/Z:('Z boson', mass MZ = 91.1875, gauge),
    'W+'/'W-': ('W boson', mass MW = MZ*CW, gauge).
scalar  H/H:(Higgs, mass MH = 115).



transform A->A*(1+dZAA/2)+dZAZ*Z/2, Z->Z*(1+dZZZ/2)+dZZA*A/2,
    'W+'->'W+'*(1+dZW/2),'W-'->'W-'*(1+dZW/2).
transform H->H*(1+dZH/2), 'Z.f'->'Z.f'*(1+dZZf/2),
    'W+.f'->'W+.f'*(1+dZWf/2),'W-.f'->'W-.f'*(1+dZWf/2).

let pp = { -i*'W+.f',  (vev(2*MW/EE*SW)+H+i*'Z.f')/Sqrt2 },
PP=anti(pp).



lterm -2*lambda*(pp*anti(pp)-v**2/2)**2
     where
    lambda=(EE*MH/MW/SW)**2/16, v=2*MW*SW/EE .

let Dpp^mu^a = (deriv^mu+i*g1/2*B0^mu)*pp^a +
     i*g/2*taupm^a^b^c*WW^mu^c*pp^b.
let DPP^mu^a = (deriv^mu-i*g1/2*B0^mu)*PP^a
    -i*g/2*taupm^a^b^c*{'W-'^mu,W3^mu,'W+'^mu}^c*PP^b.
lterm DPP*Dpp.
```

Gauge fixing and BRS transformation

```
let G_Z = deriv*Z+(MW/CW+EE/SW/CW/2*nle*H)*'Z.f'.

lterm -G_A**2/2 - G_Wp*G_Wm - G_Z**2/2.

lterm -'Z.C'*brst(G_Z).
```

From the Lagrangian to the Feynman Rules

```
vector
    A/A: (photon, gauge),
    Z/Z:('Z boson', mass MZ = 91.1875, gauge),
    'W+'/'W-': ('W boson', mass MW = MZ*CW, gauge).
scalar  H/H:(Higgs, mass MH = 115).



transform A->A*(1+dZAA/2)+dZAZ*Z/2, Z->Z*(1+dZZZ/2)+dZZA*A/2,
    'W+'->'W+'*(1+dZW/2),'W-'->'W-'*(1+dZW/2).
transform H->H*(1+dZH/2), 'Z.f'->'Z.f'*(1+dZZf/2),
    'W+.f'->'W+.f'*(1+dZWf/2),'W-.f'->'W-.f'*(1+dZWf/2).

let pp = { -i*'W+.f',  (vev(2*MW/EE*SW)+H+i*'Z.f')/Sqrt2 },
PP=anti(pp).



lterm -2*lambda*(pp*anti(pp)-v**2/2)**2
     where
    lambda=(EE*MH/MW/SW)**2/16, v=2*MW*SW/EE .

let Dpp^mu^a = (deriv^mu+i*g1/2*B0^mu)*pp^a +
     i*g/2*taupm^a^b^c*WW^mu^c*pp^b.
let DPP^mu^a = (deriv^mu-i*g1/2*B0^mu)*PP^a
    -i*g/2*taupm^a^b^c*{'W-'^mu,W3^mu,'W+'^mu}^c*PP^b.
lterm DPP*Dpp.
```

Gauge fixing and BRS transformation

```
let G_Z = deriv*Z+(MW/CW+EE/SW/CW/2*nle*H)*'Z.f'.

lterm -G_A**2/2 - G_Wp*G_Wm - G_Z**2/2.

lterm -'Z.C'*brst(G_Z).
```

with Counterterms !!

```
M$CouplingMatrices = {

  (*------    H  H  ------*)
   C[ S[3], S[3] ] == - I *
{
 { 0 , dZH },
 { 0 , MH^2 dZH + dMHsq }
},
  (*------    W+.f  W-.f  ------*)
   C[ S[2], -S[2] ] == - I *
{
 { 0 , dZWf },
 { 0, 0 }
}, (*------    A  Z  ------*)
   C[ V[1], V[2] ] == 1/2 I / CW^2 MW^2 *
{
 { 0, 0 },
 { 0 , dZZA },
 { 0, 0 }
},

(*------    H  H  H  ------*)
   C[ S[3], S[3], S[3] ] == -3/4 I EE / MW / SW *
{
 { 2 MH^2 , 3 MH^2 dZH -2 MH^2 / SW dSW - MH^2 / MW^2 dMWsq +
},
  (*------    H  W+.f  W-.f  ------*)
   C[ S[3], S[2], -S[2] ] == -1/4 I EE / MW / SW *
{
 { 2 MH^2 , MH^2 dZH + 2 MH^2 dZWf -2 MH^2 / SW dSW - MH^2 /
},

  (*------    W-.C  A.c  W+  ------*)
   C[ -U[3], U[1], V[3] ] == - I EE *
{
 { 1 },
 { - nla }
},
```

From the Lagrangian to the Feynman Rules

```
vector
    A/A: (photon, gauge),
    Z/Z:('Z boson', mass MZ = 91.1875, gauge),
    'W+'/'W-': ('W boson', mass MW = MZ*CW, gauge).
scalar  H/H:(Higgs, mass MH = 115).



transform A->A*(1+dZAA/2)+dZAZ*Z/2, Z->Z*(1+dZZZ/2)+dZZA*A/2,
    'W+'->'W+'*(1+dZW/2),'W-'->'W-'*(1+dZW/2).
transform H->H*(1+dZH/2), 'Z.f'->'Z.f'*(1+dZZf/2),
    'W+.f'->'W+.f'*(1+dZWf/2),'W-.f'->'W-.f'*(1+dZWf/2).

let pp = { -i*'W+.f',  (vev(2*MW/EE*SW)+H+i*'Z.f')/Sqrt2 },
PP=anti(pp).



lterm -2*lambda*(pp*anti(pp)-v**2/2)**2
     where
    lambda=(EE*MH/MW/SW)**2/16, v=2*MW*SW/EE .

let Dpp^mu^a = (deriv^mu+i*g1/2*B0^mu)*pp^a +
     i*g/2*taupm^a^b^c*WW^mu^c*pp^b.
let DPP^mu^a = (deriv^mu-i*g1/2*B0^mu)*PP^a
    -i*g/2*taupm^a^b^c*{'W-'^mu,W3^mu,'W+'^mu}^c*PP^b.
lterm DPP*Dpp.
```

Gauge fixing and BRS transformation

```
let G_Z = deriv*Z+(MW/CW+EE/SW/CW/2*nle*H)*'Z.f'.

lterm -G_A**2/2 - G_Wp*G_Wm - G_Z**2/2.

lterm -'Z.C'*brst(G_Z).
```

```
RenConst[ dMHsq ] := ReTilde[SelfEnergy[prt["H"] -> prt["H"], MH]]
RenConst[ dZH ] := -ReTilde[DSelfEnergy[prt["H"] -> prt["H"], MH]]
RenConst[ dZZf ] := -ReTilde[DSelfEnergy[prt["Z.f"] -> prt["Z.f"],
MZ]] RenConst[ dZWf ] := -ReTilde[DSelfEnergy[prt["W+.f"] ->
prt["W+.f"], MW]]
```

Output of Feynman Rules with Counterterms !!

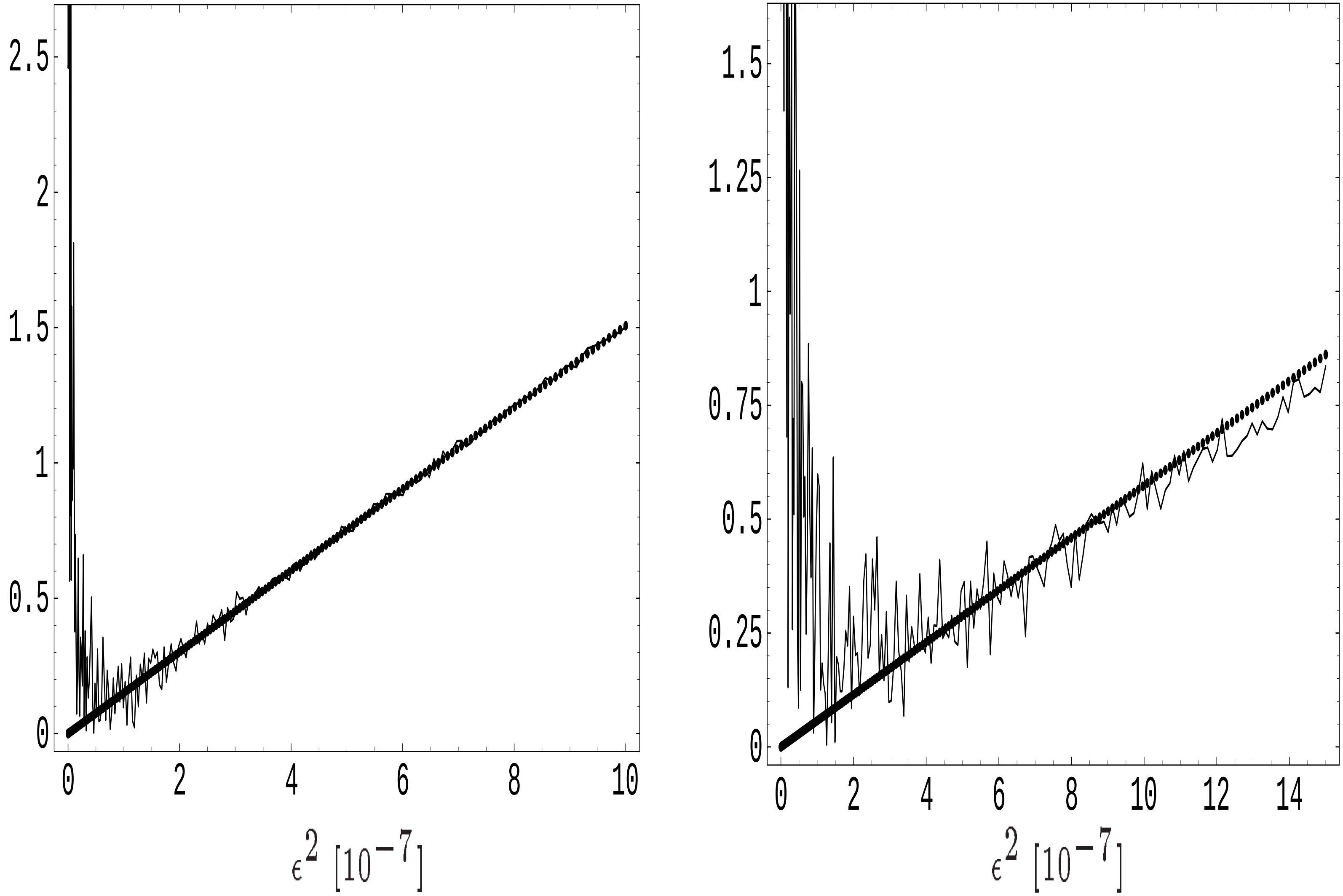
```
M$CouplingMatrices = {

  (*------    H   H   ------*)
   C[ S[3], S[3] ] == - I *
{
 { 0 , dZH },
 { 0 , MH^2 dZH + dMHsq }
},
  (*------    W+.f  W-.f   ------*)
   C[ S[2], -S[2] ] == - I *
{
 { 0 , dZWf },
 { 0, 0 }
}, (*------    A   Z   ------*)
   C[ V[1], V[2] ] == 1/2 I / CW^2 MW^2 *
{
 { 0, 0 },
 { 0 , dZZA },
 { 0, 0 }
},

(*------    H   H   H   ------*)
   C[ S[3], S[3], S[3] ] == -3/4 I EE / MW / SW *
{
 { 2 MH^2 , 3 MH^2 dZH -2 MH^2 / SW dSW - MH^2 / MW^2 dMWsq +
},
  (*------    H   W+.f  W-.f   ------*)
   C[ S[3], S[2], -S[2] ] == -1/4 I EE / MW / SW *
{
 { 2 MH^2 , MH^2 dZH + 2 MH^2 dZWf -2 MH^2 / SW dSW - MH^2 /
},

  (*------    W-.C  A.c  W+   ------*)
   C[ -U[3], U[1], V[3] ] == - I EE *
{
 { 1 },
 { - nla }
},
```

Gram determinant for small velocity



TREE LEVEL CALCULATIONS

Comparison with public codes: Grace and CompHEP

Cross-section [pb]	SloopS	CompHEP	Grace
$h^0 h^0 \to h^0 h^0$	3.932×10^{-2}	3.932×10^{-2}	3.929×10^{-2}
$W^+ W^- \to \tilde{t}_1 \bar{\tilde{t}}_1$	7.082×10^{-1}	7.082×10^{-1}	7.083×10^{-1}
$e^+ e^- \to \tilde{\tau}_1 \bar{\tilde{\tau}}_2$	2.854×10^{-3}	2.854×10^{-3}	2.854×10^{-3}
$H^+ H^- \to W^+ W^-$	6.643×10^{-1}	6.643×10^{-1}	6.644×10^{-1}
Decay [GeV]			
$A^0 \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$	1.137×10^{0}	1.137×10^{0}	1.137×10^{0}
$\tilde{\chi}_1^+ \to t \bar{\tilde{b}}_1$	5.428×10^{0}	5.428×10^{0}	5.428×10^{0}
$H^0 \to \tilde{\tau}_1 \bar{\tilde{\tau}}_1$	7.579×10^{-3}	7.579×10^{-3}	7.579×10^{-3}
$H^+ \to \tilde{\chi}_1^+ \tilde{\chi}_1^0$	1.113×10^{-1}	1.113×10^{-1}	1.113×10^{-1}

... ... # 200 processes checked

All annihilations and co-annihilations, Baro+FB (2008)

A FEW EXAMPLES

BINO-LIKE NEUTRALINO

$\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow l^+l^-$

M_1	M_2	μ	M_3	$M_{\tilde{f}_{L,R}}$	A_f	M_{A^0}	t_β
90	200	-600	1000	250/110 800/800	0	500	5

COANNIHILATION WITH A STAU

$\tilde{\chi}_1^0\tilde{\tau}_1^+ \rightarrow \tau^+\gamma$
$\tilde{\chi}_1^0\tilde{\tau}_1^+ \rightarrow \tau^+Z^0$
$\tilde{\tau}_1^+\tilde{\tau}_1^+ \rightarrow \tau^+\tau^+$

M_1	M_2	μ	M_3	$M_{\tilde{f}_{L,R}}$	A_f	M_{A^0}	t_β
166	300	400	1000	290-276/190-166 800/800	0	1000	10

MIXED-LIKE NEUTRALINO

$\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow W^+W^-$
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow Z^0Z^0$

M_1	M_2	μ	M_3	$M_{\tilde{f}_{L,R}}$	A_f	M_{A^0}	t_β
110	150	-163	1000	1000	0	1000	5

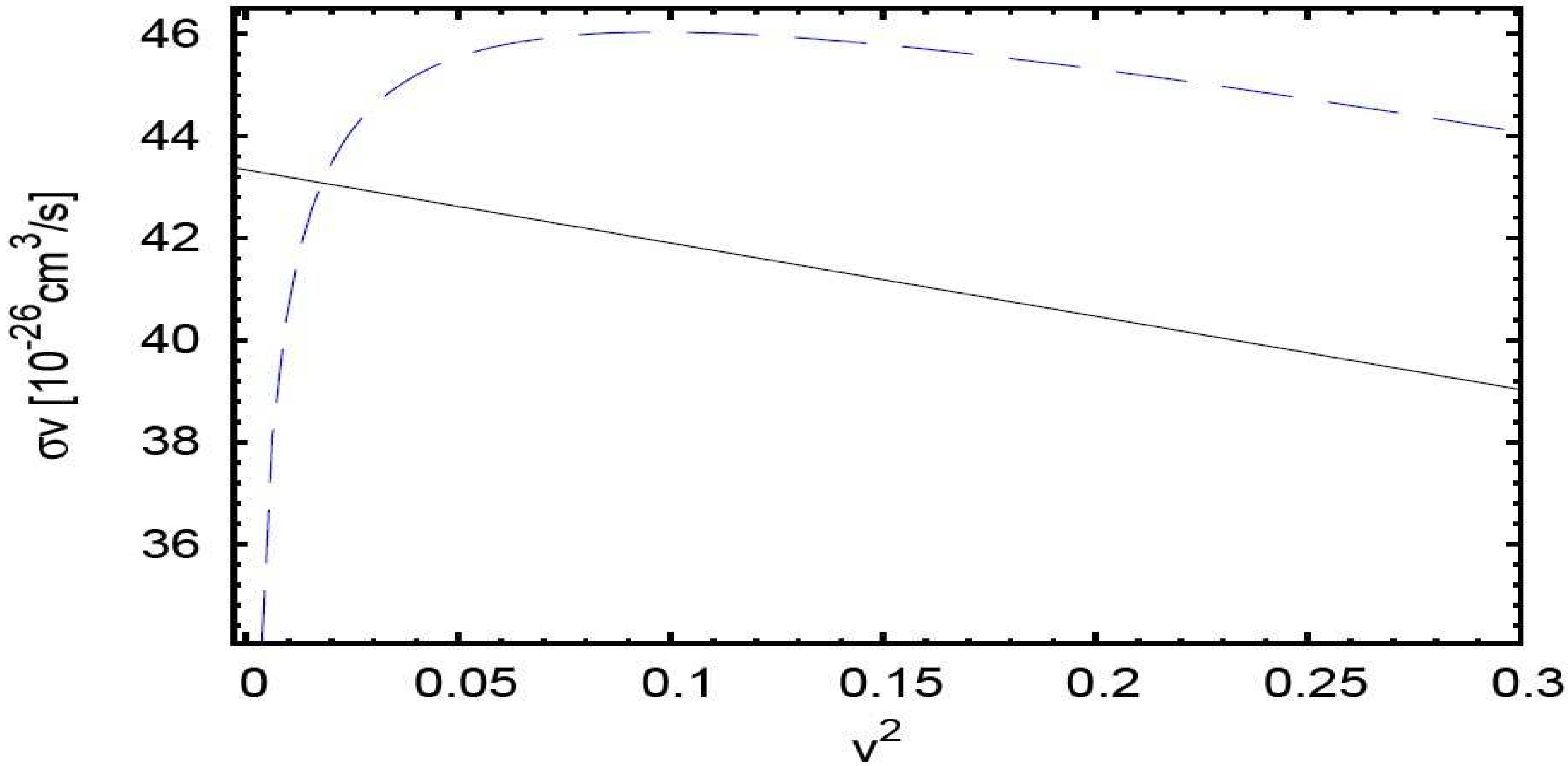
QCD CORRECTION

$\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow b\bar{b}$

M_1	M_2	μ	M_3	$M_{\tilde{f}_{L,R}}$	A_f	M_{A^0}	t_β
250	150	-180	400	250/200	0	300	5

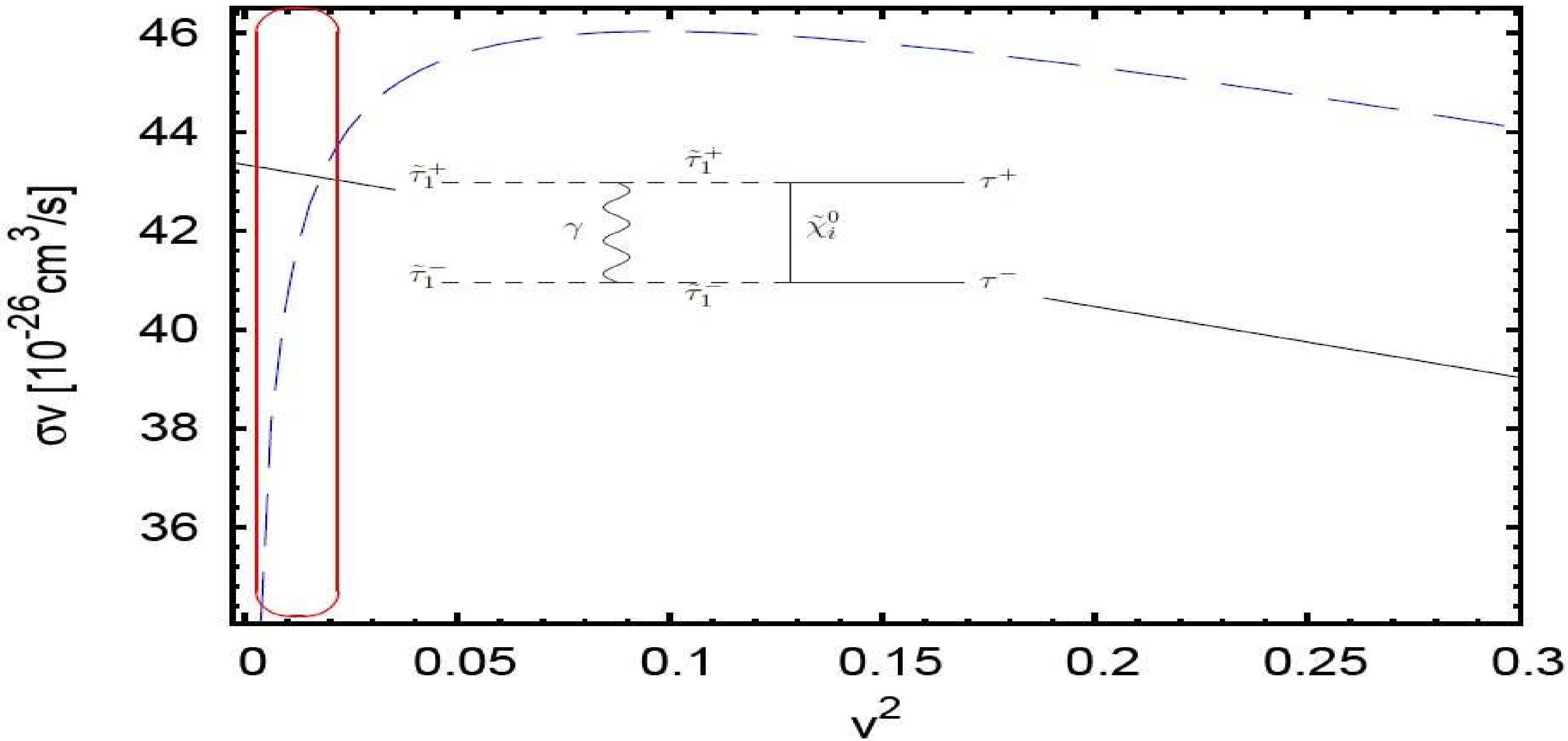
COANNIHILATION CASE

$\tilde{\tau}_1^+ \tilde{\tau}_1^+ \rightarrow \tau^+ \tau^+$ (23%)

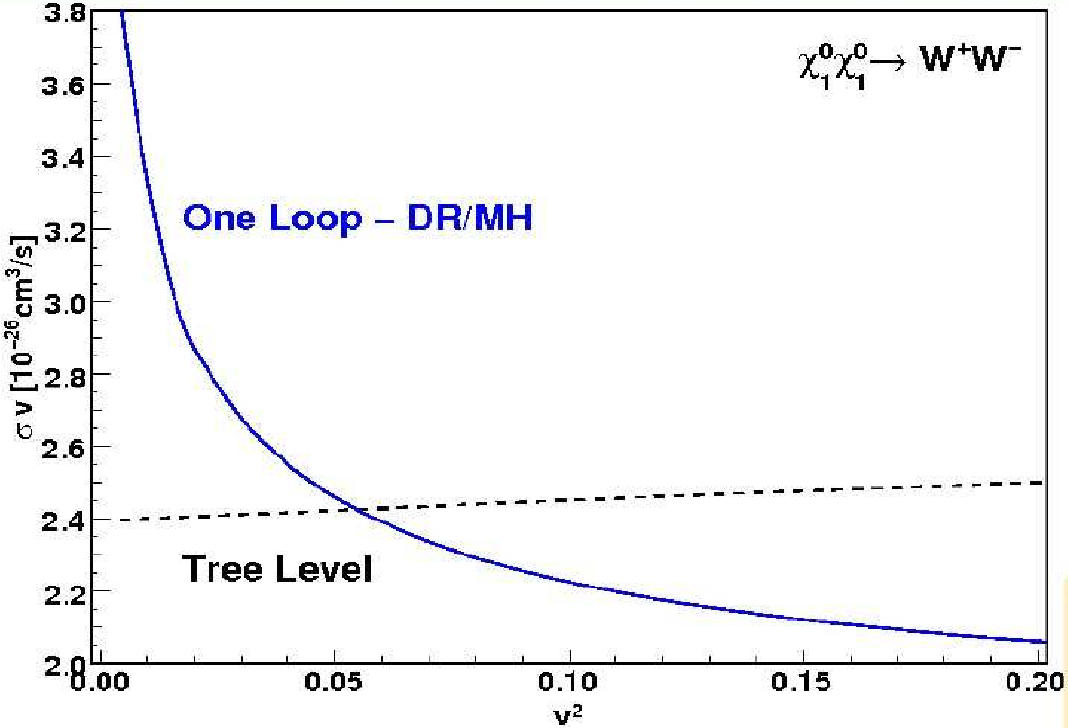


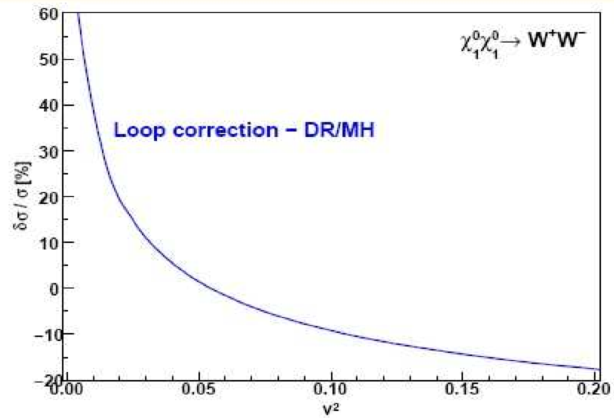
COANNIHILATION CASE - COULOMB EFFECT

$\tilde{\tau}_1^+ \tilde{\tau}_1^+ \to \tau^+ \tau^+$ (23%)



HEAVY WINO-LIKE CASE

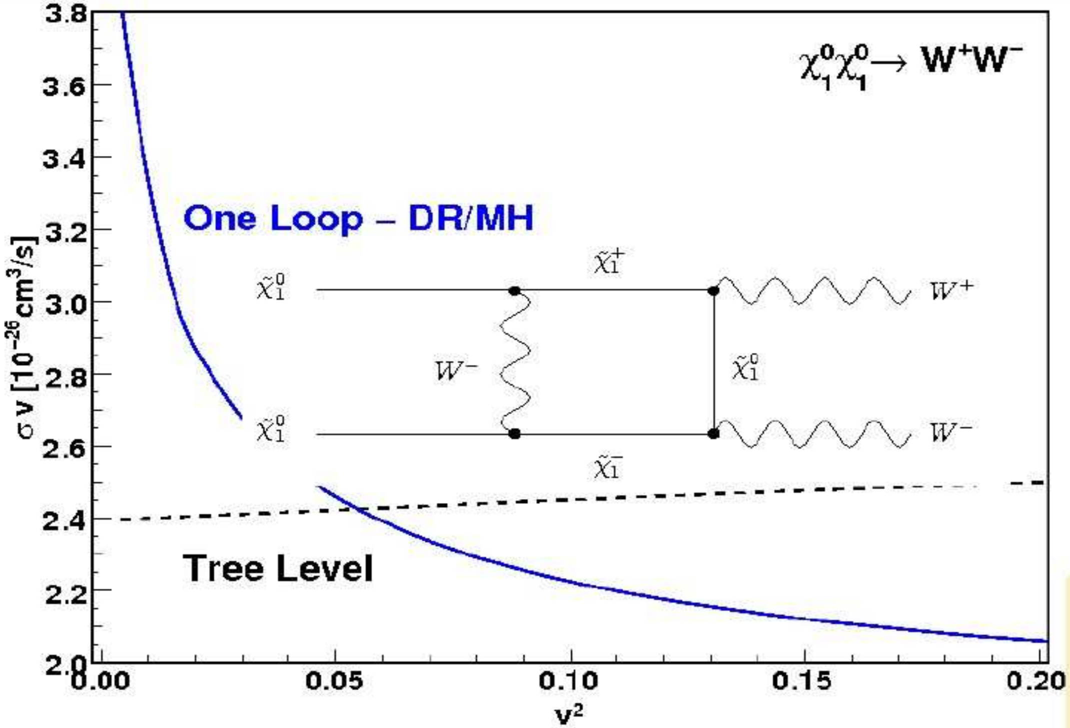


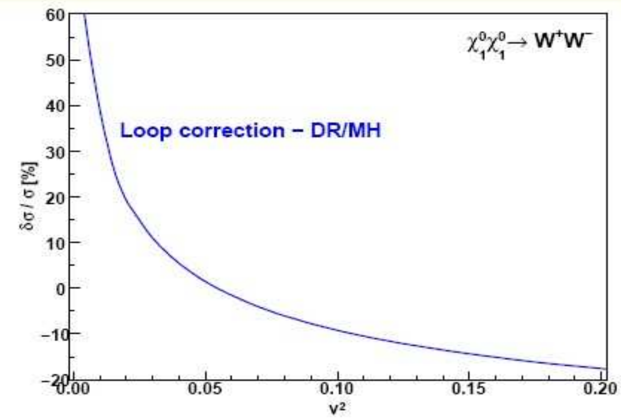


M_1	M_2	μ	M_3	$M_{\tilde{f}_{L,R}}$	A_f	M_{A^0}	t_β
3500	1800	4500	5000	5000	0	5000	15

- No t_β scheme dependence
- Large corrections
- Sommerfeld effect
  $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_1^+}$ with TeV masses
  same effect for $\tilde{\chi}_1^+\tilde{\chi}_1^+ \to W^+W^+$
  $\tilde{\chi}_1^+\tilde{\chi}_1^- \to W^+W^-$

HEAVY WINO-LIKE CASE





- No t_β scheme dependence
- Large corrections
- Sommerfeld effect
  $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_1^+}$ with TeV masses
  same effect for $\tilde{\chi}_1^+ \tilde{\chi}_1^+ \to W^+ W^+$
  $\tilde{\chi}_1^+ \tilde{\chi}_1^- \to W^+ W^-$

M_1	M_2	μ	M_3	$M_{\tilde{f}_{L,R}}$	A_f	M_{A^0}	t_β
3500	1800	4500	5000	5000	0	5000	15

SloopS, examples for relic

$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to$					
W^+W^-	Tree		$A_{\tau\tau}$	$\overline{\rm DR}$	MH
a	0.904		-9%	-3%	+34%
b	1.714		-10%	-5%	+30%
ZZ	Tree		$A_{\tau\tau}$	$\overline{\rm DR}$	MH
a	0.061		+2%	+5%	+31%
b	0.254		-6%	-2%	+24%
$b\bar{b}$	Tree		$A_{\tau\tau}$	$\overline{\rm DR}$	MH
a	0.858		-27%	-23%	+5%
b	1.032		-31%	-27%	-1%
$\tau^+\tau^-$	Tree		$A_{\tau\tau}$	$\overline{\rm DR}$	MH
a	0.033		+3%	+9%	+52%
b	0.631		+19%	+18%	+12%

$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to b\bar{b}$	$A_{\tau\tau}$	$\overline{\rm DR}$	MH
$\delta a/a$ EW	-1%	+3%	+31%
$\delta a/a$ QCD	-26%	-26%	-26%
$\delta b/b$ EW	-1%	+3%	+29%
$\delta b/b$ QCD	-30%	-30%	-30%

Mixed case 2: As in Table 3 for the array on the left. The array on the right gives the relative corrections to the $b\bar{b}$ channel for the QCD and EW corrections.

Baro, Semenov, FB, 2007

		Tree	$A_{\tau\tau}$	$\overline{\rm DR}$
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-$ [26%]	a	+11.84	+4.3%	+5.1%
	b	+4.17	+12.7%	+13.4%
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to u\bar{d}$ [12%]	a	+15.28	+6.8%	+7.0%
	b	−5.31	+30.4%	+30.7%
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z^0Z^0$ [9%]	a	+4.28	+10.4%	+9.6%
	b	+1.83	+12.7%	+12.0%
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to Z^0W^+$ [6%]	a	+6.99	+1.7%	+2.1%
	b	−0.51	+85.6%	+86.5%
$\Omega_\chi h^2$		0.00931	0.00909	0.00908
$\frac{\delta\Omega_\chi h^2}{\Omega_\chi h^2}$			−2.4%	−2.5%

Tree-level values of the s-wave (a) and p-wave (b) coefficients in units $10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ in a higgsino scenario

Baro, Chalons, Sun Hao FB 2009

Outlook

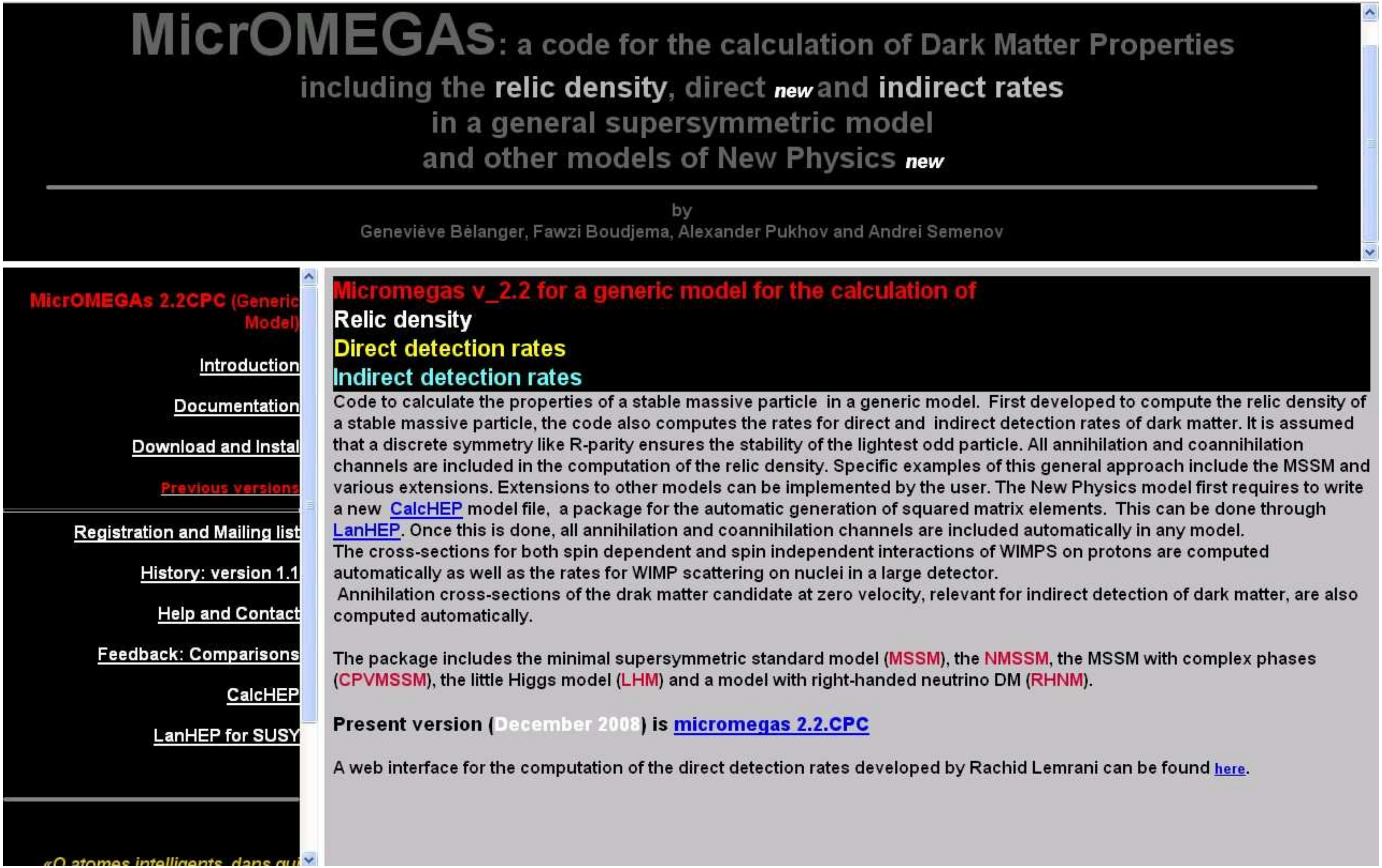
- Indirect: Neutrino signals
- Indirect: Improve the propagation code, clumps,...
- finish off $\bar{D}$
- Link to USINE (then **The DA NNECY CODE(s))**
- Sommerfeld Effects ?
- Incorporating dominant loop effects (Interface to SloopS)
- Relic: Alternative cosmological scenarios
- Pursue implementation of new models

Table 1: Comparison micrOMEGAs2.4, DarkSUSY5.0 and Isajet7.78 and

comparison with other DM codes

	micrOMEGAs	**DarkSUSY**	**IsaTools**
Relic density	$\star$	$\star$	$\star$
resonances	$\star$	$\star$	$\star$
$\sigma_{\chi p}$	$\star$	$\star$	$\star$
$\sigma_{\chi N}$	$\star$	$\star$	$\star$
$\sigma v\|_{v\approx 0}$	$\star$	$\star$	$\star$
Detection rates	$\gamma, e^+, \bar{p}, \nu$	$\gamma, e^+, \bar{p}, \nu, \bar{D}$	
Propagation	**semi-analytic**	**GALPROP** **or semi-analytic**	
Neutrino rates		**Sun, Earth**	
Input GUT scale	**SusPect, Isajet** **SoftSUSY, Spheno**	**Isajet, SuSpect**	**Isajet**
Input EW scale	**Suspect, Isajet**	**SUSY(1loop)+FH**	**Isajet**
SLHA input	**Yes**	**Yes**	**Yes**
Higgs masses	**SpectCalc**	**FH or Isajet**	**Isajet**
hbb	**(Susy-)QCD**	**QCD** **not in DD**	**(Susy-)QCD**
Higgs potential	**Effective**	**Tree**	**Effective**
Collider applications	$2 \to 2, 1 \to 2, 3$ **CalcHEP**	**No**	**Isajet**
$b \to s\gamma$, $B_s \to \mu^+\mu^-$	$+B \to \tau\nu$	**yes**	**yes**
$(g-2)_\mu$, $\Delta\rho$	**yes** **LEP**	**yes** **LEP**	**yes** **LEP**
GUT scale models	**SpectCalc**	**Isajet, Suspect**	**Isajet**
Other models	**CPVMSSM,** **(C)NMSSM** **RHNM,LHM**	**complex(not tested)** **No**	**MSSM+ν_R** **No**
Speed	$\star\star$	$\star$	—
Non SUSY Models	$\star\star$ **Open Source**	— —	— —

micrOMEGAs: Tools for DM/ Collider Physics/ Flavour for a general NP



MicrOMEGAs: a code for the calculation of Dark Matter Properties
including the relic density, direct *new* and indirect rates
in a general supersymmetric model
and other models of New Physics *new*

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MicrOMEGAs 2.2CPC (Generic Model)

Introduction

Documentation

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CalcHEP

LanHEP for SUSY

«O atomes intelligents, dans qui

Micromegas v_2.2 for a generic model for the calculation of
Relic density
Direct detection rates
Indirect detection rates

Code to calculate the properties of a stable massive particle in a generic model. First developed to compute the relic density of a stable massive particle, the code also computes the rates for direct and indirect detection rates of dark matter. It is assumed that a discrete symmetry like R-parity ensures the stability of the lightest odd particle. All annihilation and coannihilation channels are included in the computation of the relic density. Specific examples of this general approach include the MSSM and various extensions. Extensions to other models can be implemented by the user. The New Physics model first requires to write a new CalcHEP model file, a package for the automatic generation of squared matrix elements. This can be done through LanHEP. Once this is done, all annihilation and coannihilation channels are included automatically in any model.
The cross-sections for both spin dependent and spin independent interactions of WIMPS on protons are computed automatically as well as the rates for WIMP scattering on nuclei in a large detector.
Annihilation cross-sections of the drak matter candidate at zero velocity, relevant for indirect detection of dark matter, are also computed automatically.

The package includes the minimal supersymmetric standard model (MSSM), the NMSSM, the MSSM with complex phases (CPVMSSM), the little Higgs model (LHM) and a model with right-handed neutrino DM (RHNM).

Present version (December 2008) is micromegas 2.2.CPC

A web interface for the computation of the direct detection rates developed by Rachid Lemrani can be found here.

SloopS Webpage, Code not public...yet