micrOMEGAs :
A tool for dark matter studies

G. Bélanger
LAPTH

G. B, F. Boudjema, A. Pukhov, A. Semenov
hep-ph/0112278, hep-ph/0405253,
hep-ph/0607059, arXiv:08032360[hep-ph]

Outline

- Motivation
– Relic density
– Dark matter candidates
– Indirect detection
– Direct detection
– Outlook

Motivation

- Strong evidence for dark matter
- CMB (WMAP+SDSS) gives precise information on the amount of dark matter
- Most attractive explanation for dark matter: new weakly interacting particle
- Cosmological measurements strongly constrains models of cold dark matter
- Need for a precise and accurate computation of the relic density of dark matter
- Public codes that compute relic density in MSSM
  - Neutdriver, micrOMEGAs, DarkSUSY, Isatools, SuperIso(2009)

  and many private codes: SSARD (Olive), Roszkowski, Drees …

- Many models for new physics whose main motivation is to solve the hierarchy problem also have a dark matter candidate – symmetry that ensures that lightest particle is stable

- R-parity like symmetry introduced to avoid rapid proton decay or guarantee agreement with electroweak precision

- Examples:
  - MSSM and extensions, UED, Warped Xtra-Dim, Little Higgs, Extended Higgs …..

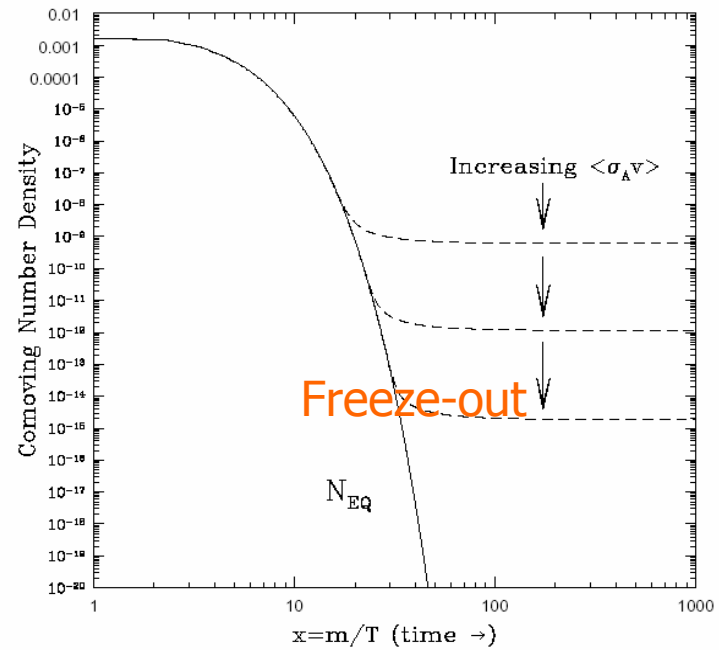
- *Need for a tool that provide precise calculation of the relic density of dark matter in a wide variety of models - micrOMEGAs_2.0*

- *To uncover the nature of dark matter : need complementary detection method both from astroparticle and colliders*

- *Comprehensive tool for dark matter studies : relic density, direct detection, indirect detection, cross section at colliders and decays: micrOMEGAs_2.2*
  - *next release micrOMEGAs_2.4*

Relic density of wimps

- In early universe WIMPs are present in large number and they are in thermal equilibrium
- As the universe expanded and cooled their density is reduced through pair annihilation
- Eventually density is too low for annihilation process to keep up with expansion rate
  - Freeze-out temperature
- LSP decouples from standard model particles, density depends only on expansion rate of the universe



$$\frac{dn}{dt} = -3Hn - < \sigma v > \left[n^2 - n_{eq}^2\right]$$

$$\frac{dY}{dT} = \sqrt{\frac{\pi g_*(T)}{45}} M_p < \sigma v > (Y(T)^2 - Y_{eq}(T)^2)$$

Solving numerically, get present day abundance $Y(T_0)$ and

$$\Omega_{LOP} h^2 = \frac{8\pi}{3} \frac{s(T_0)}{M_p^2 (100(\mathrm{km/s/Mpc}))^2} M_{LOP} Y(T_0) = 2.742 \times 10^8 \frac{M_{LOP}}{GeV} Y(T_0)$$

Weakly interacting particle gives roughly the right annihilation cross section to have $\Omega h^2 \sim 0.1$, so-called 'WIMP miracle'

$$\Omega_X h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle} \quad .$$

Typical annihilation cross-section at FO $< \sigma v > = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{sec}$

Coannihilation

- If M(NLSP)~M(LSP) then $\chi + X \rightarrow \chi' + Y$ maintains thermal equilibrium between NLSP-LSP even after non standard particles decouple from standard ones

- Relic density depends on rate for all processes involving LSP/NLSP → SM

- All particles eventually decay into LSP, calculation of relic density requires summing over all possible processes

Exp(- ΔM)/T

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

- **Important processes are those involving particles close in mass to LSP, for example up to 3000 processes can contribute in MSSM**

- *Need for automation*

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

WIMP nucleon
Direct

micrOMEGAs_2.0..

- A generic program to calculate DM properties in any model
- Assume some " R-parity ", particles odd/even under R (odd particles: ~)
- Need to specify model file in CalcHEP notation : particles, variables, vertices, functions (do by hand or with LanHEP)
- After the model is implemented and checked with CalcHEP
  - Code then automatically looks for "LSP"
  - Computes all annihilation and coannihilation cross-sections
  - Complete tree-level matrix elements for all subprocesses
  - Automatically check for presence of resonances and improves the accuracy near pole
  - Numerical solution of evolution equation and calculation of relic density with non-relativistic thermal averaging and proper treatment of poles and thresholds
    - Gondolo, Gelmini, NPB 360 (1991)145
    - coannihilation : Edsjo, Gondolo PRD56(1997) 1879

- Includes and compiles relevant channels only if needed (Beps)

$$B = \frac{K_1((m_i + m_j)/T)}{K_1(2m_{LOP}/T)} \approx e^{-X\frac{(m_i+m_j-2M_{LOP})}{M_{LOP}}} > B_\epsilon$$

- Calculates the relic density for any LSP (even charged)
- Computes σv, v->0 for LSP,LSP annihilation → indirect detection
- Automatically compute elastic scattering rate on nucleon/nucleus

- CalcHEP is included: computes all 2->2 processes and 1-> 2,3 decays at tree-level
- Some facilities provided for pp collisions
- Interactive link to CalcHEP

- *For new models : constraints and auxiliary routines must be provided by*
- C code

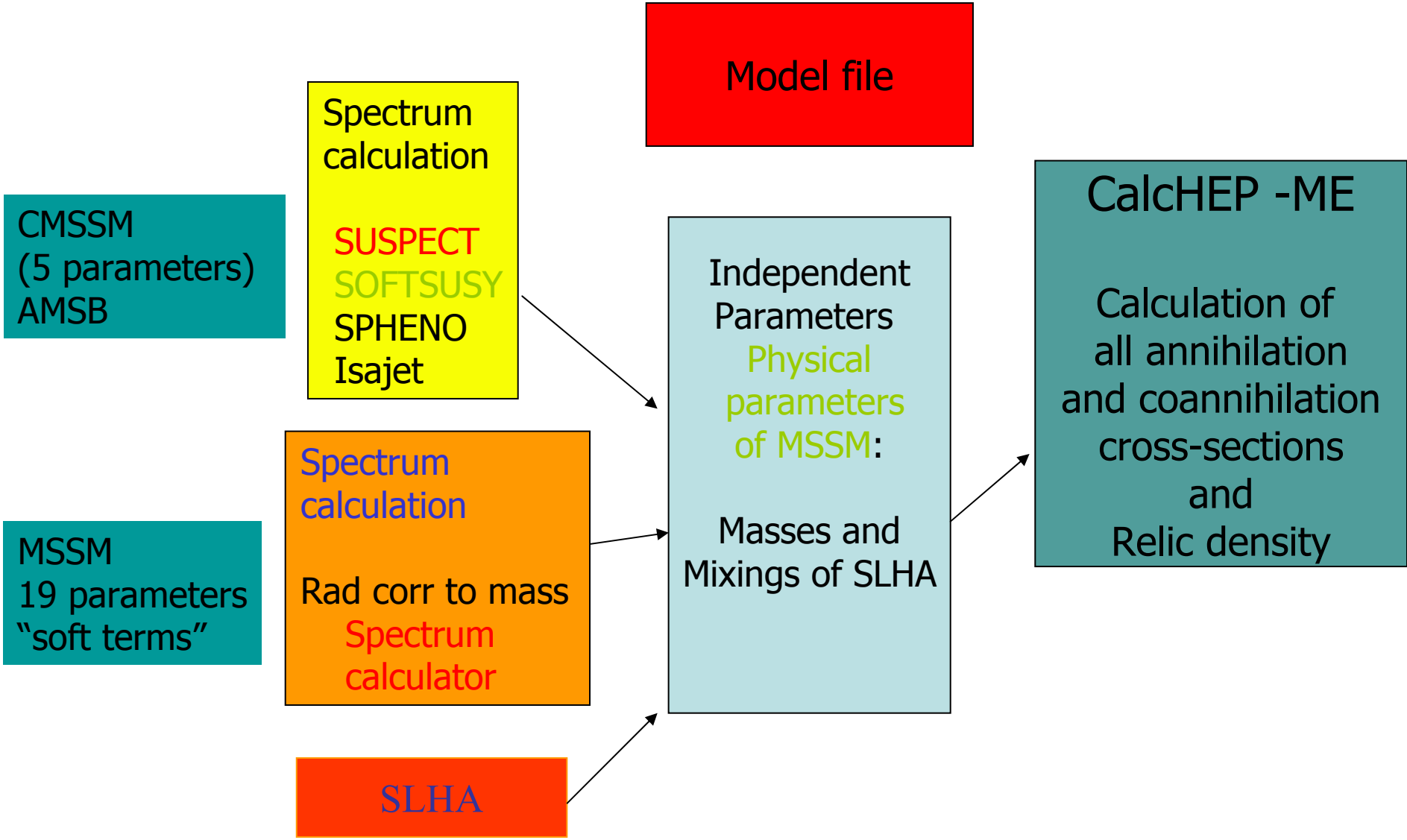
Dark matter models

- Models distributed
  - MSSM
  - NMSSM (with C. Hugonie, hep-ph/0505142)
  - CPV-MSSM (with S. Kraml, hep-ph/0604150)
  - Right-handed neutrino (with G. Servant, arXiv:0706.0526)
  - Little Higgs (A. Belyaev)

- Other models
  - SUSY N=2 (with K. Benakli et al arXiv:0905.1043)
  - Mixed sneutrino (with M. Kakizaki, S. Kraml, E.K. Park arXiv:1008.0580)
  - UED (with M. Kakizaki, in progress)

- From other groups
  - Scalar DM (Lopez-Honorez et al., S. Su)
  - …..

MSSM model file



MSSM-Specific features

- Independent parameters of model are physical parameters of SHLA, flexibility: any model for which the MSSM spectrum can be calculated with an external code can be incorporated easily

- Input parameters to micromegas can be specified at the weak scale or at the GUT scale using some SpectrumCalc program, includes CMSSM, non-univ. SUGRA, AMSB

- ***Uses SUSY Les Houches Accord***

- Radiative corrections to masses can be important – SUSY masses and Higgs masses (via spectrum calculator)

- Package includes other constraints (developed for MSSM) – not automatic

  $b \to s\gamma$ (NLO) , $(g-2)_{\mu}$, $B_s \to \mu\mu$, $B \to \tau\nu$, $\Delta\rho$

Higgs sector

- General CP conserving effective potential

$$
\begin{aligned}
V_{eff} \;=\; & (m_1^2+\mu^2)|H_1|^2+(m_2^2+\mu^2)|H_2|^2-[m_{12}^2(\epsilon H_1H_2)+h.c.] \\
& +\frac{1}{2}[\frac{1}{4}(g^2+g'^2)+\lambda_1](|H_1|^2)^2+\frac{1}{2}[\frac{1}{4}(g^2+g'^2)+\lambda_2](|H_2|^2)^2 \\
& +[\frac{1}{4}(g^2-g'^2)+\lambda_3]|H_1|^2|H_2|^2+[-\frac{1}{2}g^2+\lambda_4](\epsilon H_1H_2)(\epsilon H_1^*H_2^*) \\
& +(\frac{\lambda_5}{2}(\epsilon H_1H_2)^2+[\lambda_6|H_1|^2+\lambda_7|H_2|^2](\epsilon H_1H_2)+h.c.)
\end{aligned}
$$

- Higgs masses computed with high precision, available either in FeynHiggs or via spectrum calculator, with the effective potential have a consistent gauge invariant way of taking these corrections into account

- λ's include higher order corrections, extracted from Higgs masses and mixings (Boudjema, Semenov, hep-ph/0201219)

Higgs sector

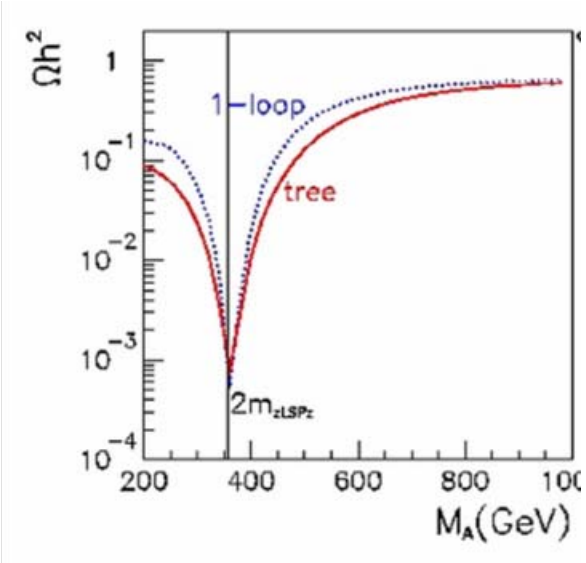
- QCD corrections to Higgs couplings to fermion pairs ($m_{b\ eff}(2M_{LSP})$) $a=\alpha/\pi$

$$M^2_{eff}(Q) = M(Q)^2\left[1+5.67a+(35.94-1.36n_f)a^2 + (164.14-n_f(25.77-0.259n_f))a^3\right]$$

- SUSY-QCD correction to Higgs->bb, effective Lagrangian, relevant at large tanβ
  - Guasch, Hapfliger, Spira, hep-ph/0305101

$$\mathcal{L}_{eff} = \sqrt{4\pi\alpha_{QED}}\frac{m_b}{1+\Delta m_b}\frac{1}{2M_W\sin\theta_W}\left[-Hb\bar{b}\frac{\cos\alpha}{\cos\beta}\left(1+\frac{\Delta m_b\tan\alpha}{\tan\beta}\right) +iAb\bar{b}\tan\beta\left(1-\frac{\Delta m_b}{\tan\beta^2}\right)+hb\bar{b}\frac{1}{\cos\beta}\left(1-\frac{\Delta m_b}{\tan\alpha\tan\beta}\right)\right]$$

Why improved couplings matter

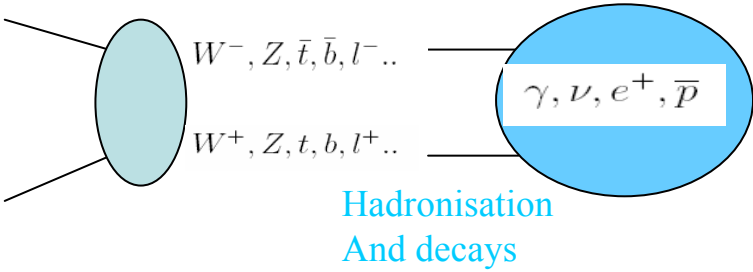


Extensions of MSSM

- Spectrum calculation, constraints on models: make use of existing programs develop independently, when possible interface with SLHA2
  - NMSSM
    - relies on NMSSMTools (NMSPEC and NMHDECAY) for spectrum calculation, indirect constraints (B physics, g-2, Higgs collider constraitns)
    - Ellwanger, Gunion, Hugonie
  - CPVMSSM :
    - interface to CPSuperH (J.S. Lee et al) for spectrum calculation, effective Higgs potential and constraints: edm, Bphysics
    - Interface to Higgs bounds for LEP/Tevatron Higgs constraints (next release)

Indirect detection

- Annihilation of pairs of DM particles into SM : decay products observed



- Searches for DM in 4 channels
  - Antiprotons (Pamela)
  - Positrons/electrons from galactic halo/center (Pamela, ATIC, Fermi..)
  - Photons from galactic halo/ center (Egret, Fermi, Hess..)
  - Neutrinos from Sun (IceCube)

- Rate for production of e^+,p,γ
  - Dependence on the DM distribution (ρ) – not well known in center of galaxy

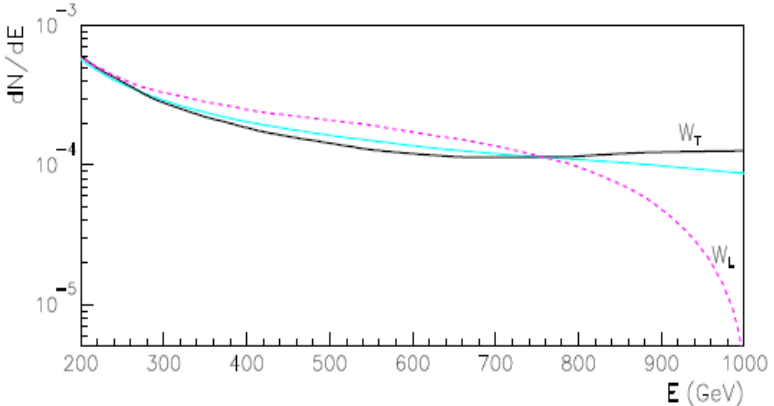
v=0.001c

$$Q(x, \mathbf{E}) = \frac{< \sigma v >}{2} \left(\frac{\rho(\mathbf{x})}{m_\chi} \right)^2 \frac{dN}{dE}$$

Particle spectrum

- Photon/positron.. production in decay of SM + R-even new particles

- dN/dE : basic channels ff, VV, VH, HH
  - Tables extracted from Pythia6.4 – from 10GeV-5TeV
  - For particles of unknown mass (H,Z'..) compute 1->2 decay recursively until only basic channels
- Vector particle polarisation
  - In MSSM only transverse W's lead to harder positron spectrum
  - Determine degree of polar : reconstruct angular distribution from $\chi\chi \rightarrow W e \nu$
  - Decay tables for W_T and W_L



Particle spectrum

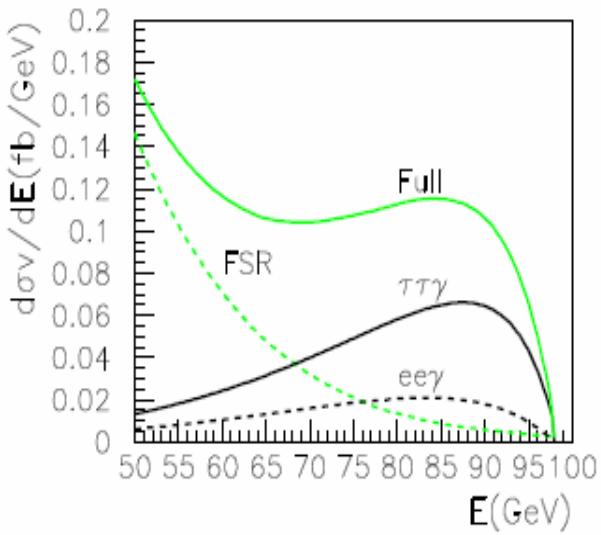
- Computation of σv involves 2-> 2 tree level processes with higher order effects

- Radiative emission, 2->3 process
  - FSR included in Pythia, radiation from internal lines also should be included
  - Remove p-wave suppression in MSSM ($\chi\,\chi \to e^+e^-\gamma$)
  - Large enhancement when t-channel mass close to m(LSP), enhancement $m_\chi^2/(m_T^2-m_\chi^2)$
  - Photon spectrum : option to request all 3-body processes
  - Subtraction procedure from Pythia: no double counting

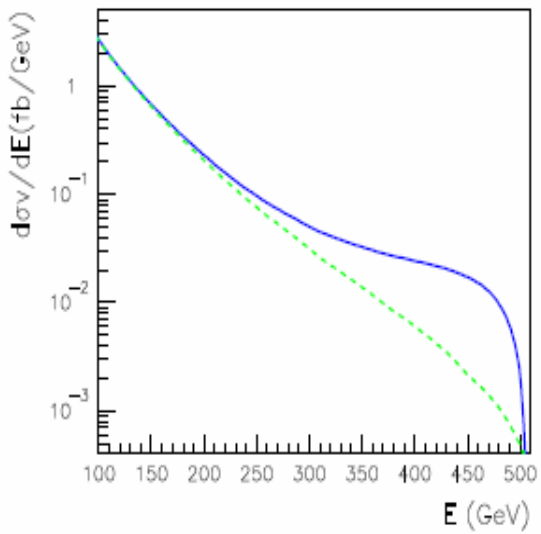
- Monochromatic gamma rays ($\gamma\gamma$,γZ) – loop process but distinctive signature
  - in micromegas_2.4 for MSSM

Photons

- Impact of 3 body final state



MSSM stau coan scenario



$$\chi\chi \to W^+W^-\gamma$$

Dark matter profile

- Integral over line of sight depends strongly on the galactic DM distribution

Halo model	α	β	γ	a (kpc)
Isothermal with core	2	2	0	4
NFW	1	3	1	20
Moore	1.5	3	1.5	28

- DM profile parametrisation

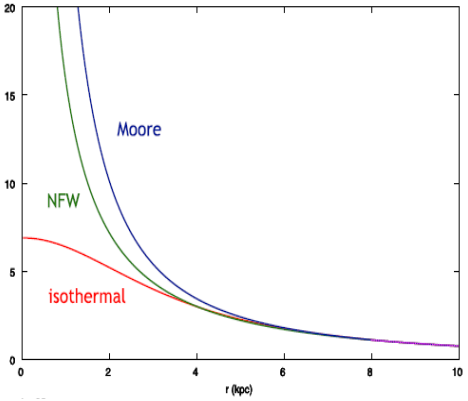
$$\rho_s(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1+(r_\odot/a)^\alpha}{1+(r/a)^\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}$$

$r_\odot = 8$ kpc

$\rho_\odot = 0.3$ GeV.cm^{-3}

- Einasto profile

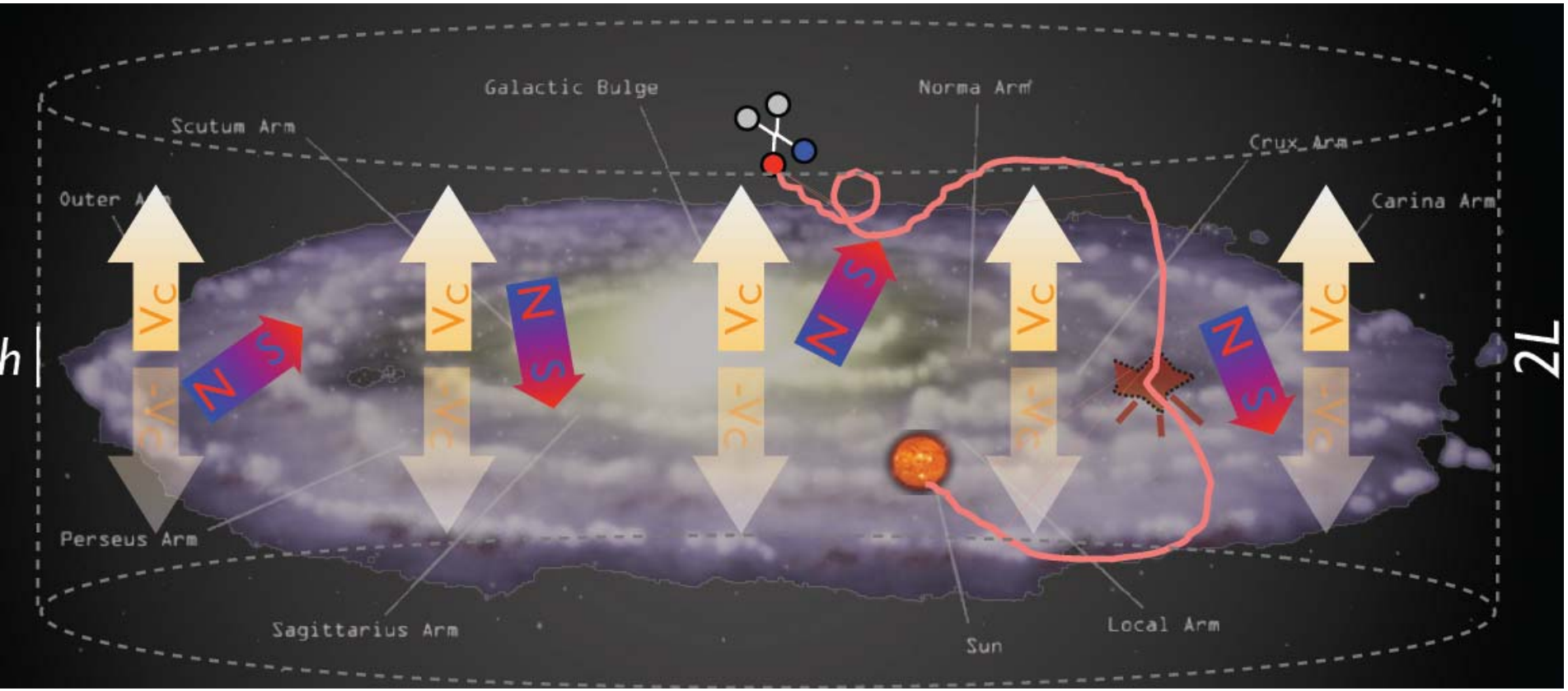
$$F_{halo}(r) = \exp\left[\frac{-2}{\alpha}\left(\left(\frac{r}{r_\odot}\right)^\alpha - 1\right)\right]$$



- N-body simulation
- Different halo profile rather similar except in center of galaxy

Antiprotons and positrons from DM annihilation in halo

M. Cirelli, Pascos2009



$$\frac{\partial N}{\partial t} - \nabla \cdot [K(\mathbf{x}, E)\, \nabla N] - \frac{\partial}{\partial E}[b(E)\, N] = q(\mathbf{x}, E)$$

diffusion Energy losses Source

Propagation of cosmic rays

- *For Charged particle spectrum detected different than spectrum at the source*

$$\frac{\partial N}{\partial t} - \nabla \cdot [K(\mathbf{x}, E)\, \nabla N] - \frac{\partial}{\partial E}[b(E)\, N] = q(\mathbf{x}, E)$$

- Charged cosmic rays deflected by irregularities in galactic magnetic field
  - For strong magnetic turbulence effect similar to space diffusion
- Energy losses due to interactions with interstellar medium
- Convection driven by galactic wind and reacceleration due to interstellar shock wave
- For positron, antiproton : solution propagation equations based on semi-analytical two-zone model
  - Lavalle, Pochon, Salati, Taillet, astro-ph/0603796

Propagation

- Positrons: dominated space diffusion and energy loss (synchroton radiation, Inverse Compton scattering)

$$-\nabla \cdot (K(E)\nabla \psi_{e+}) - \frac{\partial}{\partial E}(b(E)\psi_{e+}) = Q_{e+}(\mathbf{x}, E)$$

$$K(E) = K_0 \beta(E) \left(\mathcal{R}/1\ \mathrm{GV}\right)^{\delta}$$

- Antiprotons: energy loss negligible
  - Negative source term (annihilation of antiproton in interstellar medium)
  - Galactic wind, convective velocity: V_c

$$\left[-K(E)\nabla^2 + V_c \frac{\partial}{\partial z} + 2(V_c + h\Gamma_{tot}(E))\delta(z)\right] \psi_{\bar{p}}(E, r, z) = \frac{\sigma v}{2} \frac{\overline{\rho^2}(r, z)}{M_\chi^2} f_{\bar{p}}(E)$$

- Propagation parameters constrained by B/C

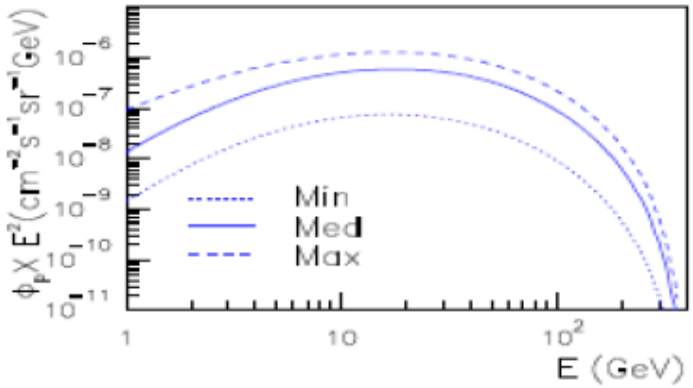
Propagation

- Choice of diffusion parameters

Model	δ	K_0 (kpc^2/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

Donato et al

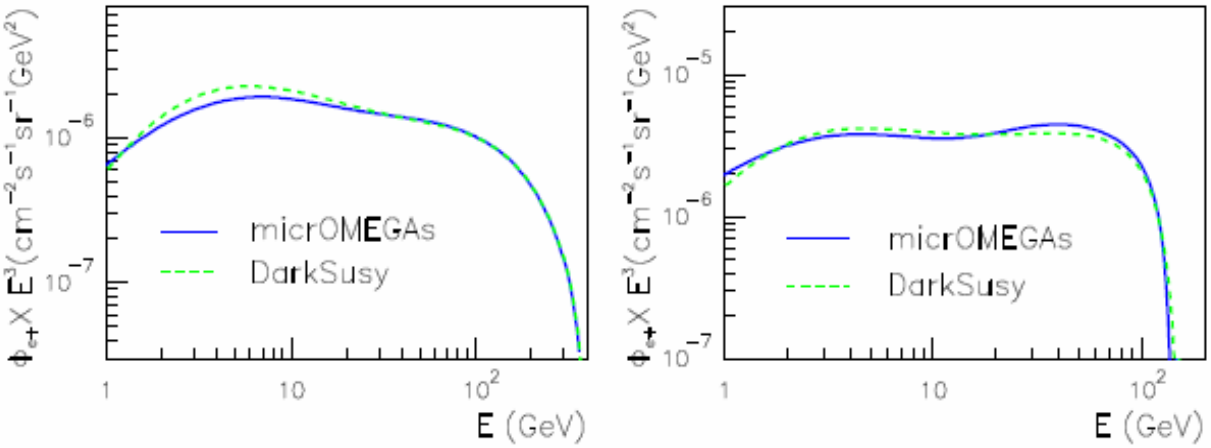
- Strong impact on the predictions



Model 1
$\mu = -440, M_A = 1000$
$M_2 = 800, M_0 = 2500$
$A_t = A_b = 1000$
$\tan\beta = 10$

- At low energies solar modulation effect

Comparison micrOMEGAs/DarkSUSY for positron spectrum



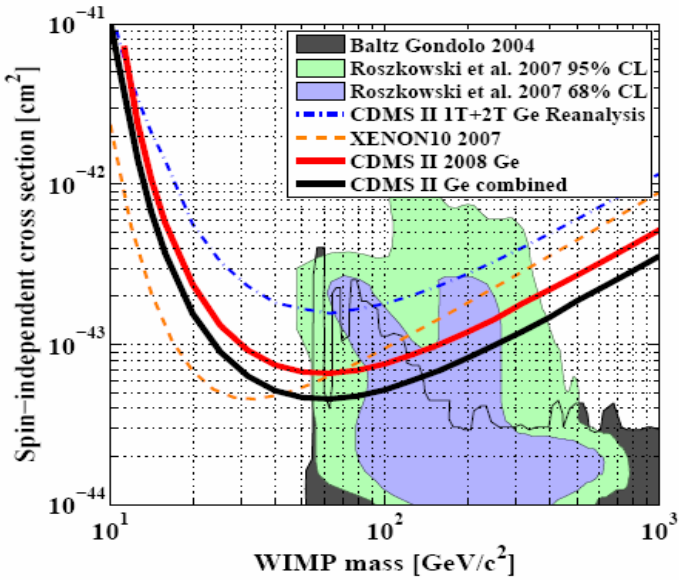
Model 1	Model 2
$\mu = -440, M_A = 1000$	$\mu = -200, M_A = 1000$
$M_2 = 800, M_0 = 2500$	$M_2 = 320, M_0 = 2500$
$A_t = A_b = 1000$	$A_t = -A_b = -2500$
$\tan\beta = 10$	$\tan\beta = 8.$

$\delta = 0.6$, $K_0 = 0.03607$ kpc^2/Myr, $L = 4$ kpc and $V_C = 10$ km/s.

Direct detection

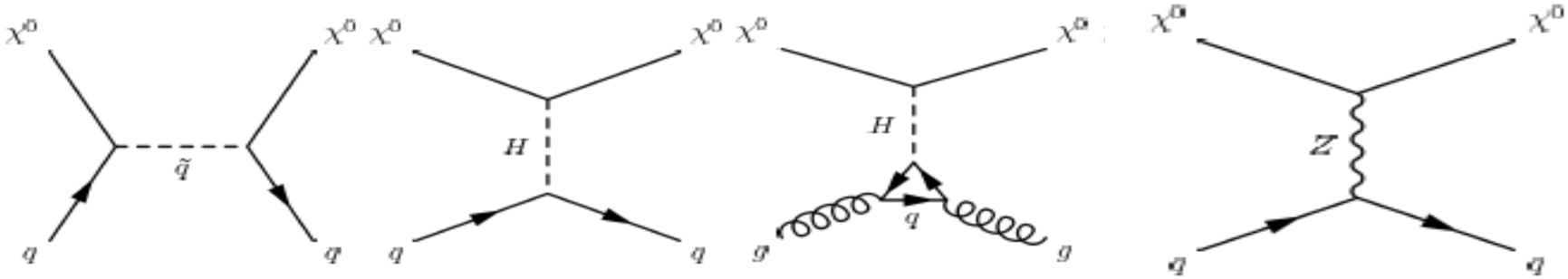
- Elastic scattering of WIMPs off nuclei in a large detector
- Measure nuclear recoil energy, E_R
- Would give best evidence that WIMPs form DM

- Two types of scattering
  - Coherent scattering on A nucleons in nucleus, for spin independent interactions
    - Dominant for heavy nuclei
  - Spin dependent interactions – only on one unpaired nucleon
    - Dominant for light nuclei



Direct detection

- Typical diagrams
- Higgs exchange often dominates



For Dirac fermions Z exchange contributes to SI and SD

WIMP- Nucleon amplitude

- For any WIMP, need effective Lagrangian for WIMP-nucleon amplitude *at small momentum ~100MeV*,
- Generic form for a fermion

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

- For Majorana fermion only 2 operators survive at small q^2

- First need to compute the WIMP quark amplitudes
  - normally computed symbolically from Feynman diagrams+ Fierz
  - Automatic approach (works for all models)
- Effective Lagrangian for WIMP-quark scattering has same generic form as WIMP nucleon

WIMP quark effective Lagrangian

	WIMP Spin	Even operators	Odd operators
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	$2M_\chi A_{\chi,\mu} A_\chi^\mu \overline{\psi}_q \psi_q$	$+i\lambda_{q,o}(A_\chi^{*\alpha} \partial_\mu A_{\chi,\alpha} - A_\chi{}^\alpha \partial_\mu A_{\chi\alpha}^*) \overline{\psi}_q \gamma_\mu \psi_q$
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	$\sqrt{6}(\partial_\alpha A_{\chi,\beta}^* A_{\chi\nu} - A_{\chi\beta}^* \partial_\alpha A_{\chi\nu})$	$i\frac{\sqrt{3}}{2}(A_{\chi\mu} A_{\chi\nu}^* - A_{\chi\mu}^* A_{\chi\nu}) \overline{\psi}_q \sigma^{\mu\nu} \psi_q$
		$\epsilon^{\alpha\beta\nu\mu} \overline{\psi}_q \gamma_5 \gamma_\mu \psi_q$	

- Operators for WIMP quark Lagrangian, extract automatically the coefficients for SI and SD –

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

- In micrOMEGAs: evaluate coefficients numerically using projection operators
- Add all projection operators as new vertices in the model
- Compute χq-χq scattering element at zero momentum transfer
- Interference between one projection operator and effective vertex- single out SI or SD contribution

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

- Use quark and anti-quark scattering elements to split even/odd contributions
- The projection operators are added to the model file by micrOMEGAs
- Warning: in the model file must include couplings proportional to light quark masses (eg. Hqq coupling)

WIMP-quark to WIMP-nucleon

- Coefficients relate WIMP-quark operators to WIMP nucleon operators
  - Extracted from experiments
  - Source of theoretical uncertainties
- Example , scalar coefficients, contribution of q to nucleon mass

$$\langle N|m_q\overline{\psi}_q\psi_q|N\rangle = f_q^N M_N \qquad \lambda_{N,p} = \sum_{q=1,6} f_q^N \lambda_{q,p}$$

$$f_Q^N = \frac{2}{27}\left(1 - \sum_{q\leq 3} f_q^N\right)$$

- Can be defined by user
- Different coefficients can lead to one order magnitude correction in cross section

- Scalar coefficients extracted from ratios of light quark masses, pion-nucleon sigma term and σ_0 (size of SU(3) breaking effect)

- Large uncertainty in s-quark contribution

Nucleon	f_{Tu}	f_{Td}	f_{Ts} [24]	f_{Ts} [25]	f_{Ts} [20, 26]
n	0.023	0.034	0.08	0.14	0.46
p	0.019	0.041	0.08	0.14	0.46

- Lattice calculations have provide new estimates of those coefficients – soon should help reduce uncertainties

- For example varying coefficients within this range can in the MSSM lead to almost one order of magnitude change in cross section
  - Bottino et al hep-ph/0010203, Ellis et al hep-ph/0502001

WIMP-nucleon to WIMP-nucleus

- Rates (SI and SD) depends on nuclear form factors and velocity distribution of WIMPs + local density

$$\frac{dN^{SI}}{dE} = \frac{2M_{det}t}{\pi}\frac{\rho_0}{M_\chi}F_A^2(q)\left(\lambda_p Z + \lambda_n(A-Z)\right)^2 I(E)$$

Nuclear form factors

Particle physics
+ quark content in nucleon

DM velocity distribution

$$I(E) = \int_{v_{min}(E)}^{\infty}\frac{f(v)}{v}dv$$

$$v_{min}(E) = \left(\frac{EM_A}{2\mu_\chi^2}\right)^{1/2}$$

- Modularity and flexibility: can change velocity distribution, nuclear form factors, quark coefficients in nucleon

Outlook/Conclusion

- *Complete indirect detection:*
  - *Neutrino capture in Sun/Earth*
- *Pursue implementation of new models*
- *Alternative cosmological scenarii (with S. Bailly)*
- *Incorporating one-loop for dominant processes in MSSM – beyond improved Higgs vertices*
- *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 : one of the public tools available to perform these analysis, only one that apply to wide variety of DM models*
- Download: micromegas_2.4
  - http:://lappweb.in2p3.fr/lapth/micromegas

About Sloops ….

(Fawzi could not be here)

Why one-loop

- Relic abundance extracted from cosmological measurements about 10-15% accuracy, will improve with Planck (few percent)

- Tree-level computation of annihilation cross sections might not be precise enough to constrain cosmological scenario after reconstruction of fundamental parameters of particle physics model

- (SUSY)-QCD corrections are expected to be large, EW ones could be large

Then for an accurate and reliable relic density prediction at one-loop order we need :

→ A coherent renormalisation scheme and a choice of input parameters.

→ To generate counter-terms, for SUSY gigantic task.

→ To compute a huge amount of loop diagrams.

→ Loop Integrals library to handle Gram determinant when $v \to 0$.

→ To deal with IR and collinear divergencies→ include bremsstrahlung.

→ To evaluate many processes entering $\langle \sigma v \rangle$.

- SloopS: an automatic code for computation of one-loop diagrams in the MSSM
  - Baro, Boudjema, Semenov : arXiv:0710.1821

One-loop processes relevant for DM

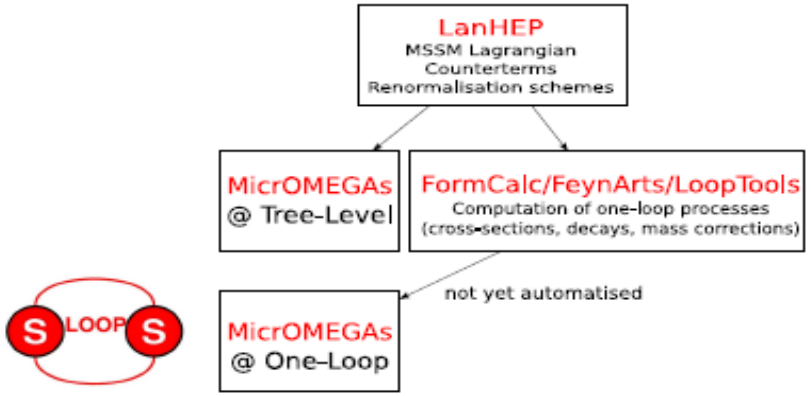
One-loop calculation EW + QCD corrections

- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\gamma, Z\gamma, gg$: Boudjema,Semenov,Temes, *Phys. Rev.* D72, 055024 (2005)
- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to ZZ, W^+W^-$: Baro,Boudjema,Semenov, *Phys. Lett.* B660 (2008) 550
  Baro,Boudjema,Chalons, Sun Hao, *Phys. Rev* D81 (2008) 015005
- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau^+\tau^-, b\bar{b}$: Baro,Boudjema,Semenov, *Phys. Lett* B660 (2008) 550
- Co-annihilation with $\tilde{\tau}$: Baro,Boudjema,Semenov, *Phys. Lett* B660 (2008) 550,

QCD corrections

- Co-annihilation with $\tilde{t}$ Freitas *Phys. Lett.* B652 (2007) 280
- Annihilation into massive quarks Hermann,Klasen,Kovarik *Phys. Rev.* D79 (2009)
  Herrmann, Klasen, *Phys. Rev.* D76 (2007) 117704
  Herrmann, Klasen and Kovarik, *Phys. Rev.* D80 (2009) 085025

Sloops



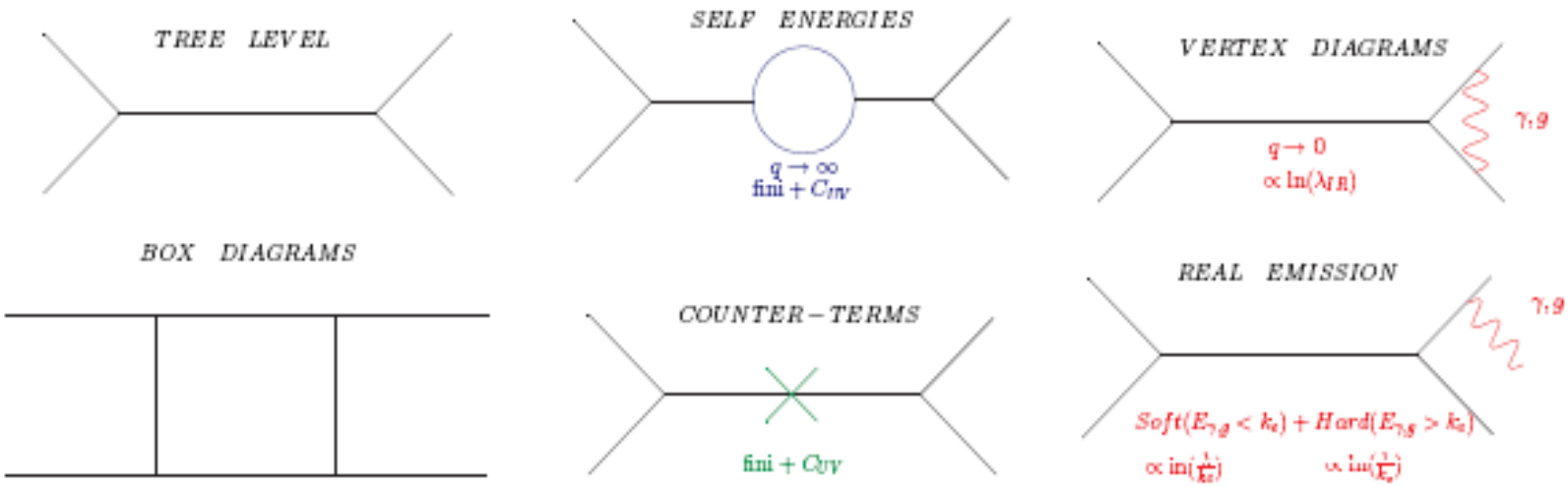
- Evaluation of one-loop diagrams including a complete and coherent renormalisation of each sector of the MSSM with an OS scheme.
- Modularity between different renormalisation schemes.
- Non-linear gauge fixing.
- Handles a large number of Feynman diagrams.
- Checks : results UV,IR finite and gauge independent.

http://code.sloops.free.fr/

RADIATIVE CORRECTIONS-RENORMALISATION

DIVERGENCES

- Due to perturbative development in the coupling constant.

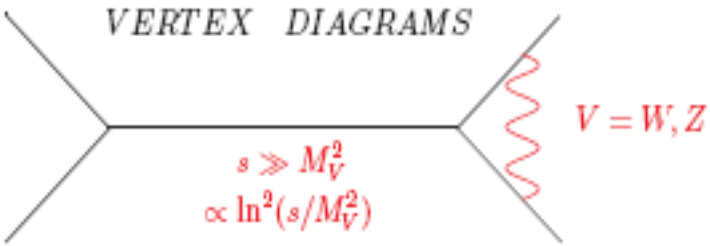


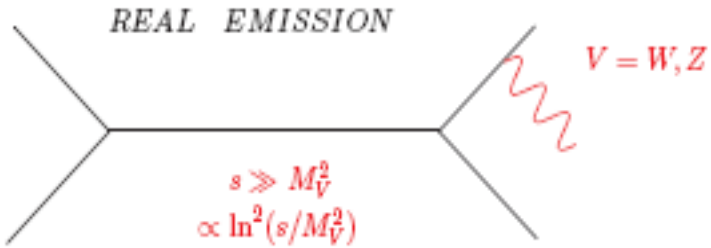
REGULARISATION

Isolate infinite parts in loops

- UV : $\ln \Lambda_{UV}$ with cut-off, $1/\epsilon_{UV}$ poles in DR.
- IR : $\ln \lambda_{IR}$ with cut-off, $1/\epsilon_{IR}$ poles in DR.

A WORD ABOUT INFRARED DIVERGENCIES





- Originate from
  - ↪ Massless gauge bosons (γ, g) coupling to on-shell external legs.
  - ↪ Soft and collinear regions of integration over boson momenta (appear as double log $\ln^2(\lambda_{IR})$ or $1/\epsilon_{IR}^2$).
- Adding real emission remove unphysical dependency in the cut-off λ_{IR} or $1/\epsilon_{IR}^2$.
- Integration over 3-particles phase space can be complicated.
- Usually for DM calculation $2 \to 2$ processes are enough, but if real corrections $\simeq$ vertex corrections, $2 \to 3$ processes should also be included.
- If c.m energy $\sqrt{s} \gg M_V$, EW bosons behave like a photon $\Rightarrow$ Mass singularities in soft and collinear logs $\propto \ln^2(s/M_W^2)$

ON-SHELL RENORMALISATION OF THE MSSM SECTORS

FERMION + GAUGE SECTOR

Input parameters as in the Standard Model $m_f, \alpha(0), M_W, M_Z$

HIGGS SECTOR

Input parameters : $M_{A^0}, t_\beta = v_2/v_1$. Several definitions for δt_β :

- $\overline{DR}$: δt_β is a pure divergence
- MH : δt_β is defined from the measurement of the mass m_H
- $A^0\tau\tau$: δt_β is defined from the decay $A^0 \to \tau^+\tau^-(vertex \propto m_\tau t_\beta)$

SFERMIONS SECTOR

Input parameters : 3 sfermions masses $m_{\tilde{d}_1}, m_{\tilde{d}_2}, m_{\tilde{u}_1}$ and 2 conditions for $A_{u,d}$

NEUTRALINOS/CHARGINOS SECTOR

Input parameters : 2 charginos $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}$ and 1 neutralino $\tilde{\chi}_1^0$

ANNIHILATION INTO FERMIONS

Second example : annihilation into $b\bar{b}$

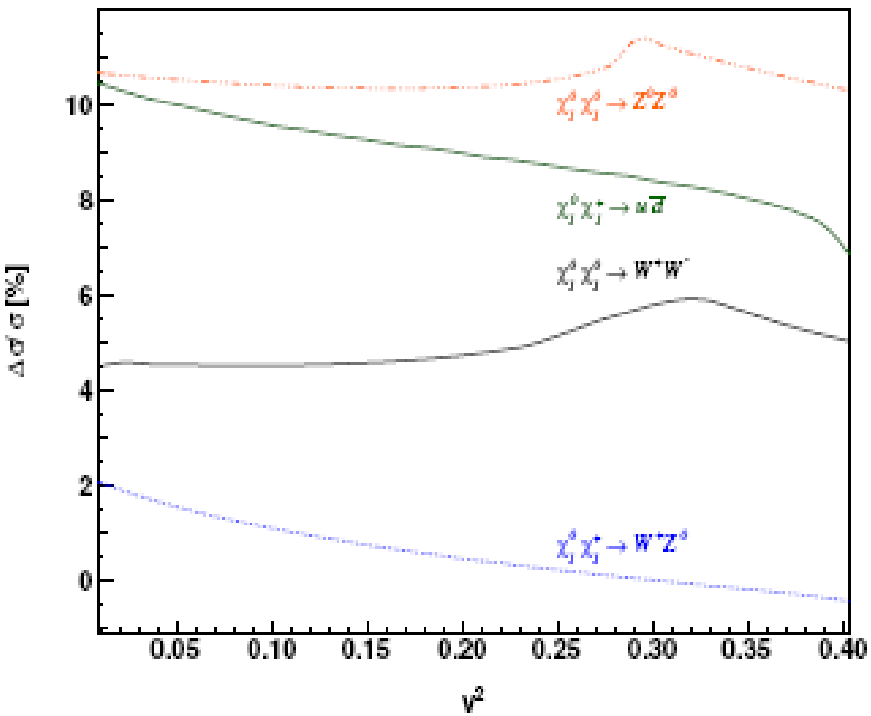
- Mixed case : bino-higgsino
- Important A^0-exchange in s-channel $m_{\tilde{\chi}_1^0} = 106$ GeV, $m_{A^0} = 300 GeV$
- $\sigma v = a + bv^2$
- δt_β scheme dependency
- Important corrections to $A^0 \to b\bar{b}$ vertex $\to$ anomalous dimension, Δm_b
- Modified Yukawa coupling implemented in `micrOMEGAs`

$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to b\bar{b}$	$A_{\tau\tau}$	$\overline{\mathrm{DR}}$	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%

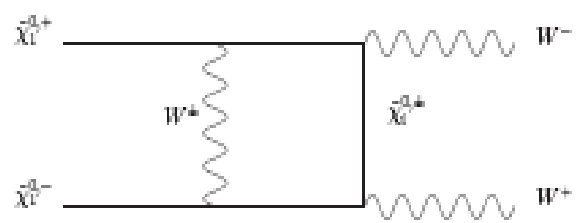
- Baro,Boudjema,Chalons,Sun Hao, *Phys. Rev* **D81** (2008) 015005
- Most difficult channels : Gauge invariance plays a prominent role.

Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{L},\tilde{Q}}$	A_i	M_{A^0}
Value	400	350	-250	4	1000	650	0	800

$$\tilde{\chi}_1^0 = 0.11\tilde{B} - 0.31\tilde{W} - 0.70\tilde{H}_1^0 - 0.63\tilde{H}_2^0$$



- Bulk of corrections to the s-wave coefficient
- Small δt_β scheme dependence
- QCD corrections to $u\bar{d} \simeq 3$ %
- Bump = $\tilde{\chi}_1^\pm$ threshold in boxes, not present at Tree-Level
- $a + bv^2$ expansion doesn't work anymore at 1-L

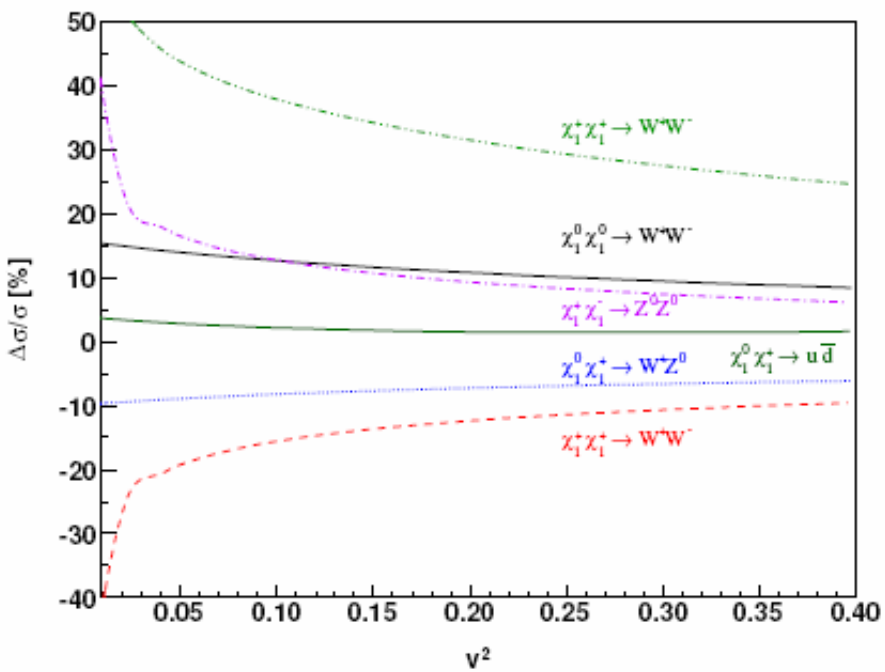


	$A_{\tau\tau}$	$\overline{\mathrm{DR}}$	MH
$\delta\Omega h^2/\Omega h^2$	-2.4%	-2.5%	-3.3%

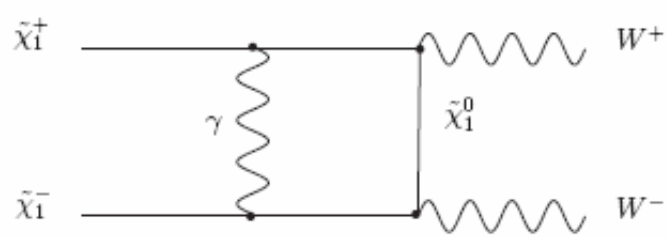
ANNIHILATION INTO GAUGE BOSONS : LIGHT-WINO

Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{u}_L}$	$M_{\tilde{e}_L}$	$M_{\tilde{u}_R,\tilde{e}_R}$	A_i	M_{A^0}
Value	550	210	-600	30	1200	387	360	800	0	700

$$\tilde{\chi}_1^0 = 0.005\tilde{B} - 0.99\tilde{W} - 0.15\tilde{H}_1^0 - 0.05\tilde{H}_2^0$$



- At 1-L new feature appear for $v \to 0$: Coulomb effect
- Possible to capture its one-loop manifestation
- Degeneracy lifted between processes
- Large corrections
- Almost no δt_β scheme dependence
- Strong cancellations between QCD/EW corrections



	$A_{\tau\tau}$	$\overline{DR}$	MH
$\delta\Omega h^2/\Omega h^2$	-1.9%	-1.9%	-1.9%

CONCLUSIONS AND PERSPECTIVES

- Importance of radiative corrections in the relic density calculations, can be very large.
- Need to control them to be able to extract informations from it and to constrain the underlying cosmological scenario.
- For some cases scheme dependence.
- For a heavy neutralino scenarios taking into account $2 \to 3$ processes is necessary.
- Large corrections due to soft/collinear logs and Sommerfeld enhancement.
- Corrections can be even larger for Indirect Detection, rate and spectra for specific signatures.
- In all cases for $\Omega_\chi h^2$ @ 1-2% $\Rightarrow$ one-loop corrections mandatory.
- Study of the dependency of the results on the chargino/neutralino renormalisation scheme.
- Improve the interface with `micrOMEGAs`.