micrOMEGAs :
a tool for dark matter studies

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LAPTH - Annecy

GB, F. Boudjema, A. Pukhov, A. Semenov
hep-ph/0112278,0405253,0607059,0803.2360
+Brun,Salati, Rosier, arXiv:1004.1092

German Egyptian School
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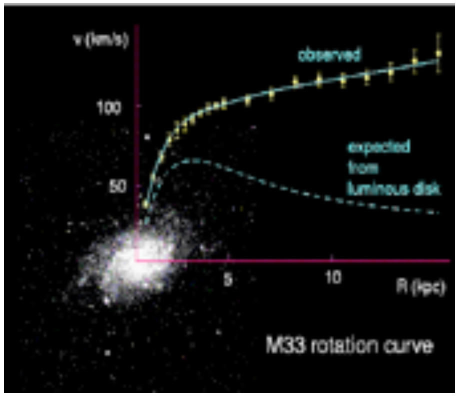
Outline

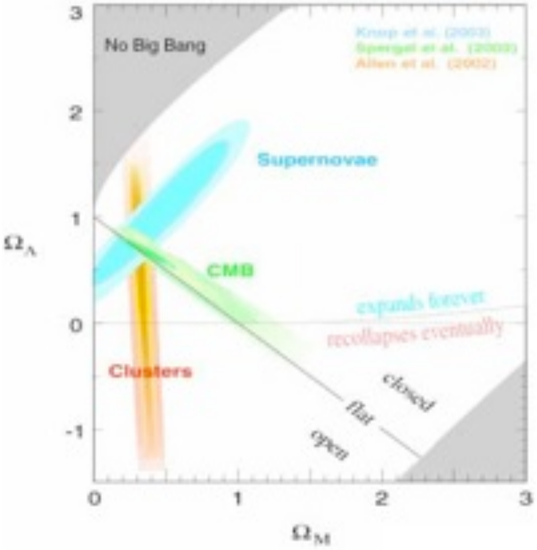
- Motivation
- General description
  - Relic density
  - Direct detection
  - Indirect detection
  - Collider observables
- Dark matter models

- Include new features of micromegas_3.0
- Download
  - http:://wwwlapp.in2p3.fr/lapth/micromegas

Motivation

- Strong evidence for DM at different scales, galaxies, galaxy clusters,
- Small anisotropies in CMB provide accurate testing of cosmological models and give precise information on amount of dark matter
- WMAP9 (arXiv:1212.5226)
  - $\Omega h^2 = 0.1147 +/- 0.0051$
- Most attractive explanation: a new Weakly Interacting Massive Particle (WIMP)
- Cosmological observations -strong constraints on models of CDM
- Need precise predictions for relic density of DM

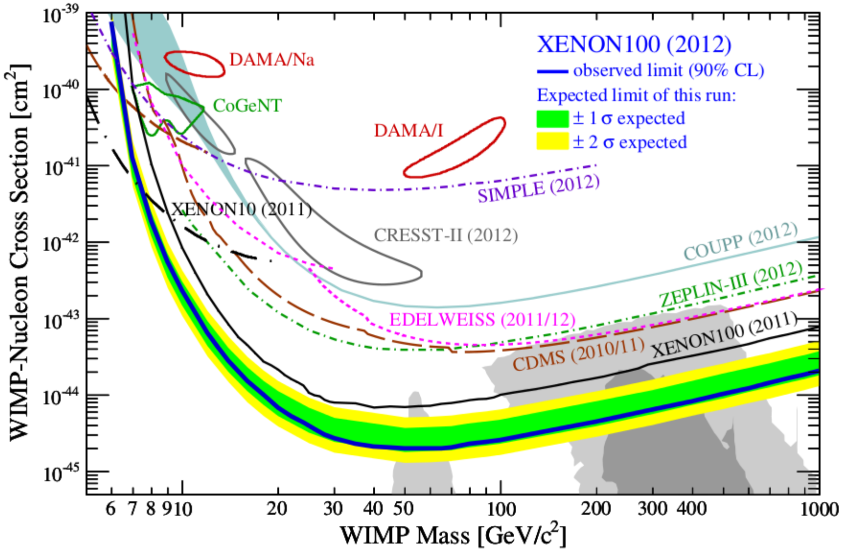


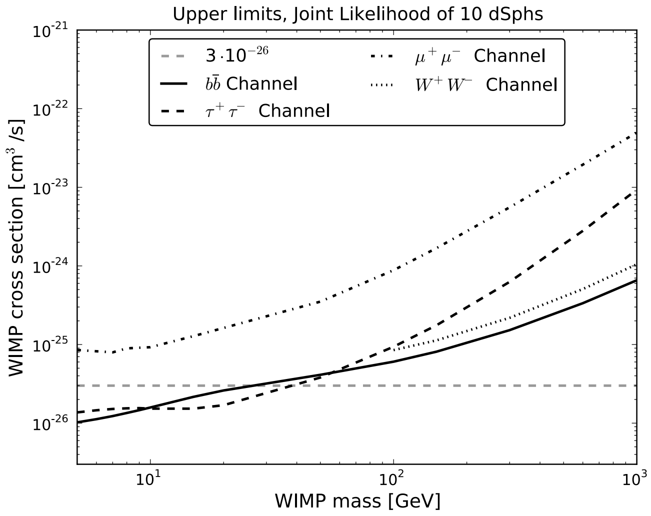


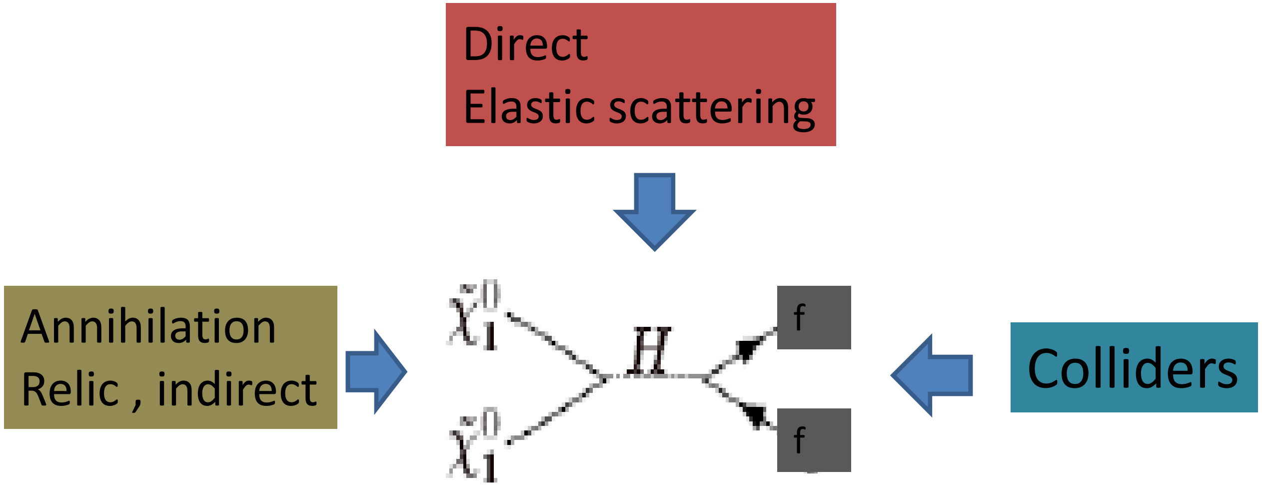
- Many models for new physics whose main motivation is to solve the hierarchy problem also have a WIMP - DM candidate – symmetry that ensures that lightest particle is stable
  - MSSM, UED, Little Higgs, extended Higgs
- R-parity like symmetry introduced to avoid rapid proton decay or guarantee agreement with electroweak precision

- Searches for new particles present in these models at colliders (LHC)
- Apart from a Higgs-like particle, nothing found in LHC7 - wait for start of LHC13 in 2015.

- Direct detection are constraining WIMP-nucleon cross-section
- Some experiments see a signal
  - DAMA, CoGeNT
- Indirect detection constraining DM annihilation cross-section
  - FermiLAT
- + hints of signals
  - anomaly in positron spectrum (PAMELA)
  - Monochromatic gamma-ray line (Fermi-LAT)
- Searches are being pursued
  - e.g. Xenon, Fermi, AMS, Hess, IceCube ....







Direct
Elastic scattering

Annihilation
Relic , indirect

Colliders

(DM is not detected,
Look at other new particles)

Particle physics model

- *Comprehensive tool for dark matter studies : precise calculation of relic density, direct detection, indirect detection, cross section at colliders and decays in a wide variety of models: micrOMEGAs2.4...*

Other public tools for DM studies in MSSM: DarkSUSY, Isared, SuperISO

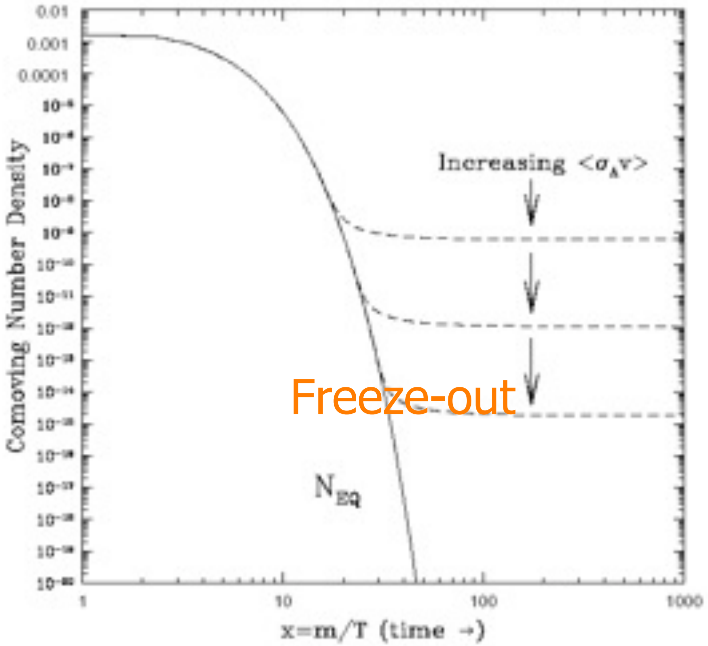
Guiding principles

- Human make mistakes - computer not
  - Automation
- Several groups are developing specialized codes
  - Link them
- 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

Relic density

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



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

Depletion of χ due to annihilation

Creation of χ from inverse process

- Thermally average cross-section

$$\langle \sigma v \rangle = \frac{\int d^3p_1 d^3p_2 f(E_1) f(E_2) \sigma v}{\int d^3p_1 d^3p_2 f(E_1) f(E_2)} \qquad f(\mathbf{p}) = exp\left(\frac{E-\mu}{T} \pm 1\right)^{-1}$$

- Include all processes annihilation DM into SM particles

$$\chi\bar{\chi} \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-, q\bar{q}, W^+W^-, ZZ$$

- In non-relativistic limit

$$n_\chi = \frac{g}{(2\pi)^3} \int f(\mathbf{p}) d^3\mathbf{p} \qquad n_\chi^{eq} \approx g(m_\chi T/2\pi)^{\frac{3}{2}} exp(-m_\chi/T).$$

- Solving Boltzmann equation, define abundance   Y=n/s

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

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 $\Omega h^2 \sim 0.1$

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

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

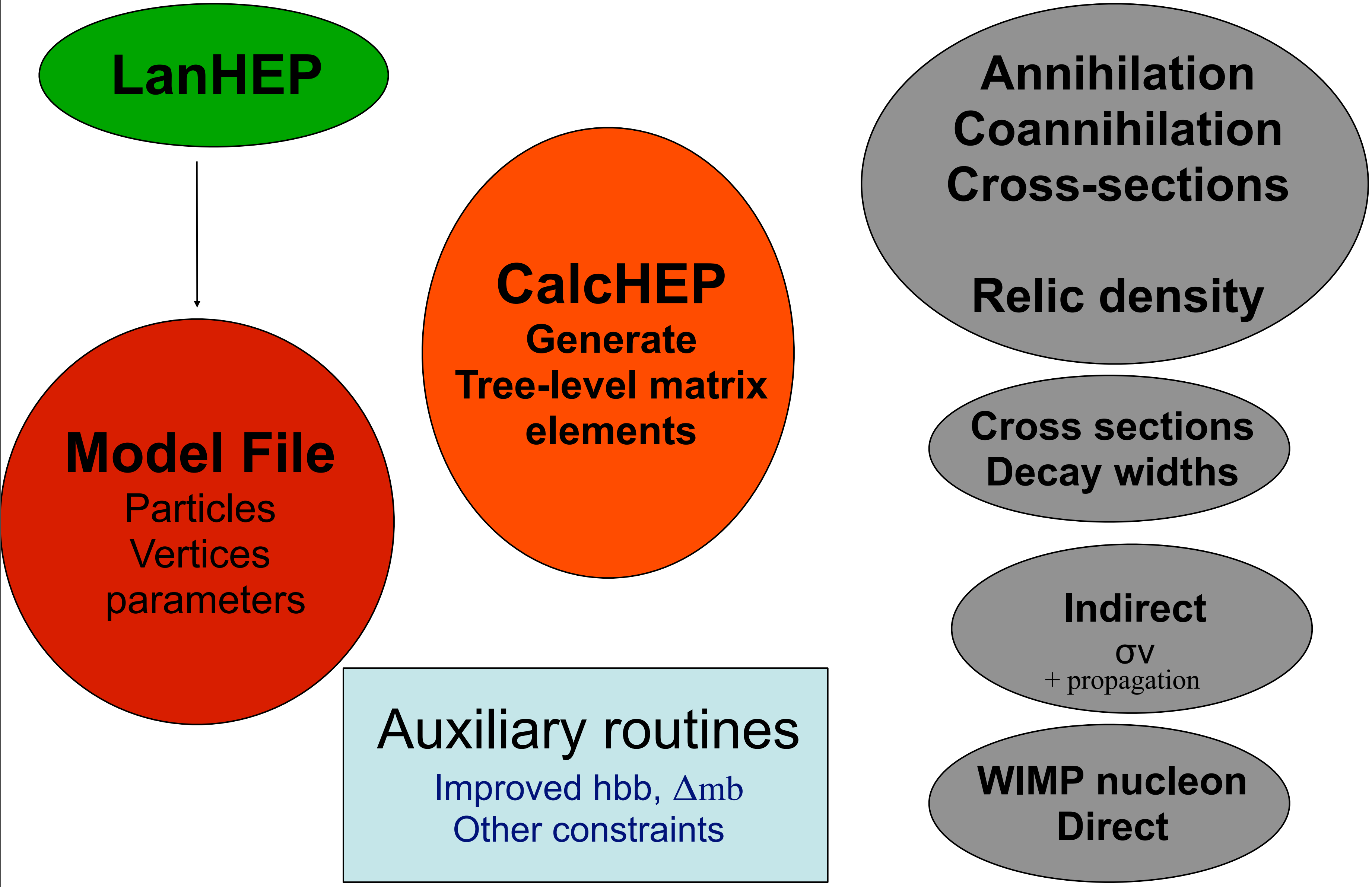
Exp(- ΔM)/T

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

- **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
+ propagation

WIMP nucleon
Direct

micrOMEGAs_2.X

- 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/SARAH/Feynrules)
- 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 other DM observables in astroparticle and colliders
  - σv, v->0 for LSP,LSP annihilation and signatures for γ and positron/antiproton including propagation
  - Automatically compute elastic scattering rate on nucleon/nucleus

- *For new models : constraints and auxiliary routines must be provided by the user in fortran or C routine*
- C code

New features of relic density

- Include three-body final states
  - In some cases annihilation into 3-body final state can be as large as 2-body, best example annihilation into W pairs kinematically suppressed (C. Yaguna, arXiv: 1003.2730)
  - For m_{DM}~M_W effect easily factor 2
  - Switch to include 3/4-body processes with one/two virtual W/Z
  - Straigthforward to compute but slow
- Semi-annihilation
  - In general, discrete symmetry does not have to be Z_2
  - processes involving different number of "odd particles"
    xx --> x* SM
    - T. Hambye, 0811.0172, T. Hambye, M. Tytgat, 0907.1007
- Asymmetric dark matter

The Z_3 case

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

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

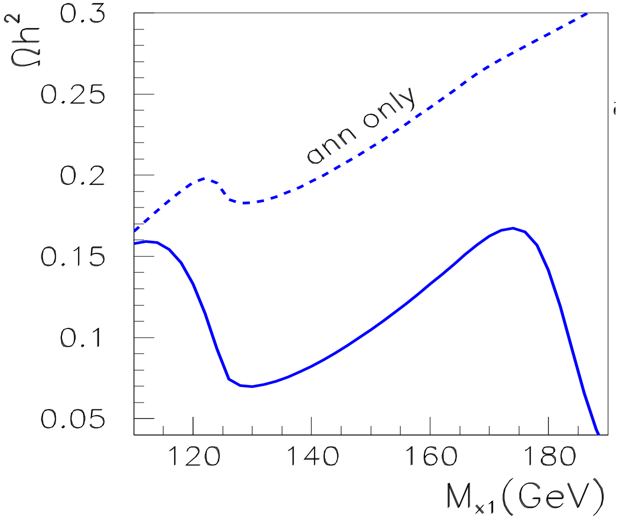
$$\sigma_v \equiv v\sigma^{xx^*\to XX} + \frac{1}{2}v\sigma^{xx\to x^*X} \quad \text{and} \quad \alpha = \frac{1}{2}\frac{\sigma_v^{xx\to x^*X}}{\sigma_v}$$

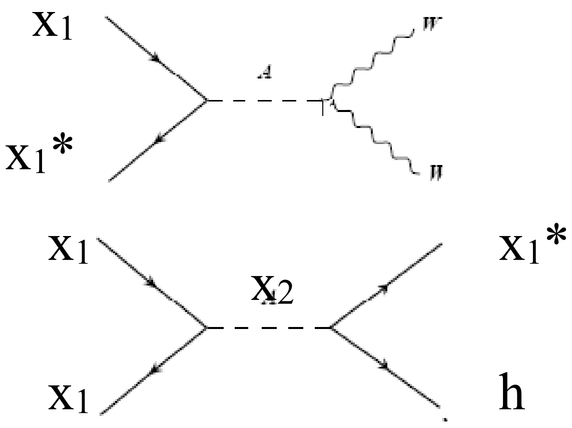
$$3H\frac{dY}{ds} = \sigma_v\left(Y^2 - \alpha Y\overline{Y} - (1-\alpha)\overline{Y}^2\right).$$

- Modified equation solved numerically (Y=Y_{eq}+ΔY) with usual micrOMEGAs procedure ΔY - >ΔY/(1-α/2)

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

Impact of semi-annihilation





- Inert doublet + complex singlet (H_2, S, do not couple to quarks)
- Dark sector : complex x_1,x_2,H^+, Z_3 charge=1
- Decrease of relic density when semi-anni. contribute
- semi-annihilation enhanced when $M_{x1}=M_{x2}/2$
  - GB, K. Kannike, A. Pukhov, M. Raidal, JCAP 1204(2012) 010

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 $Y = 2(Y^+Y^-)^{1/2}$

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

- Similar to equation for self-conjugate - solve num.

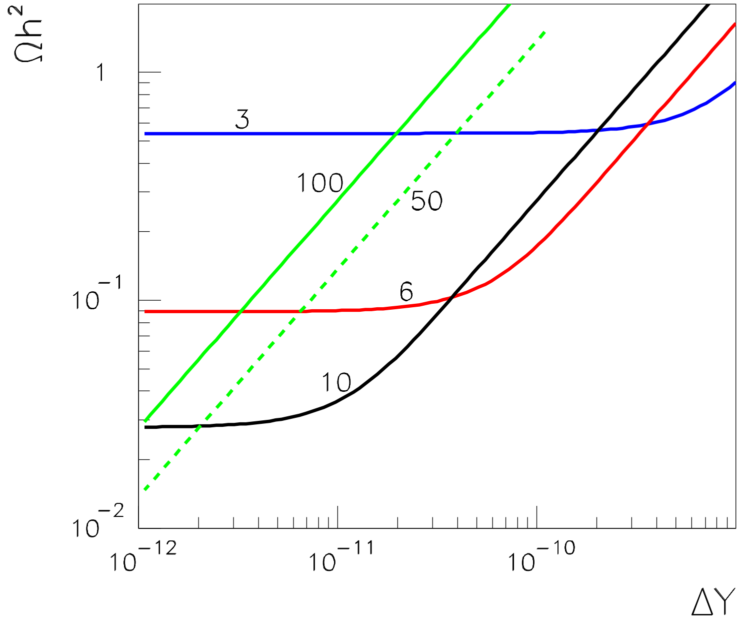
- Relic density

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

- For each specie

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

- Note 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

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

Direct detection

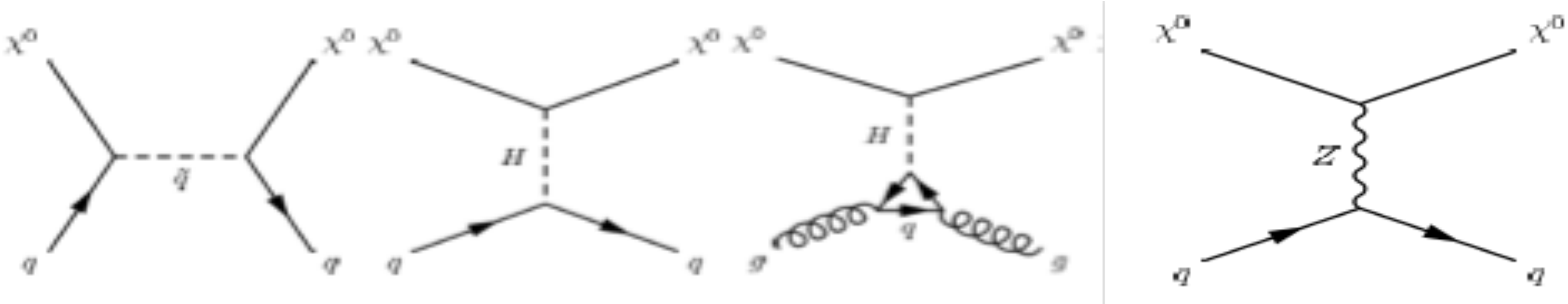
Direct detection

- 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

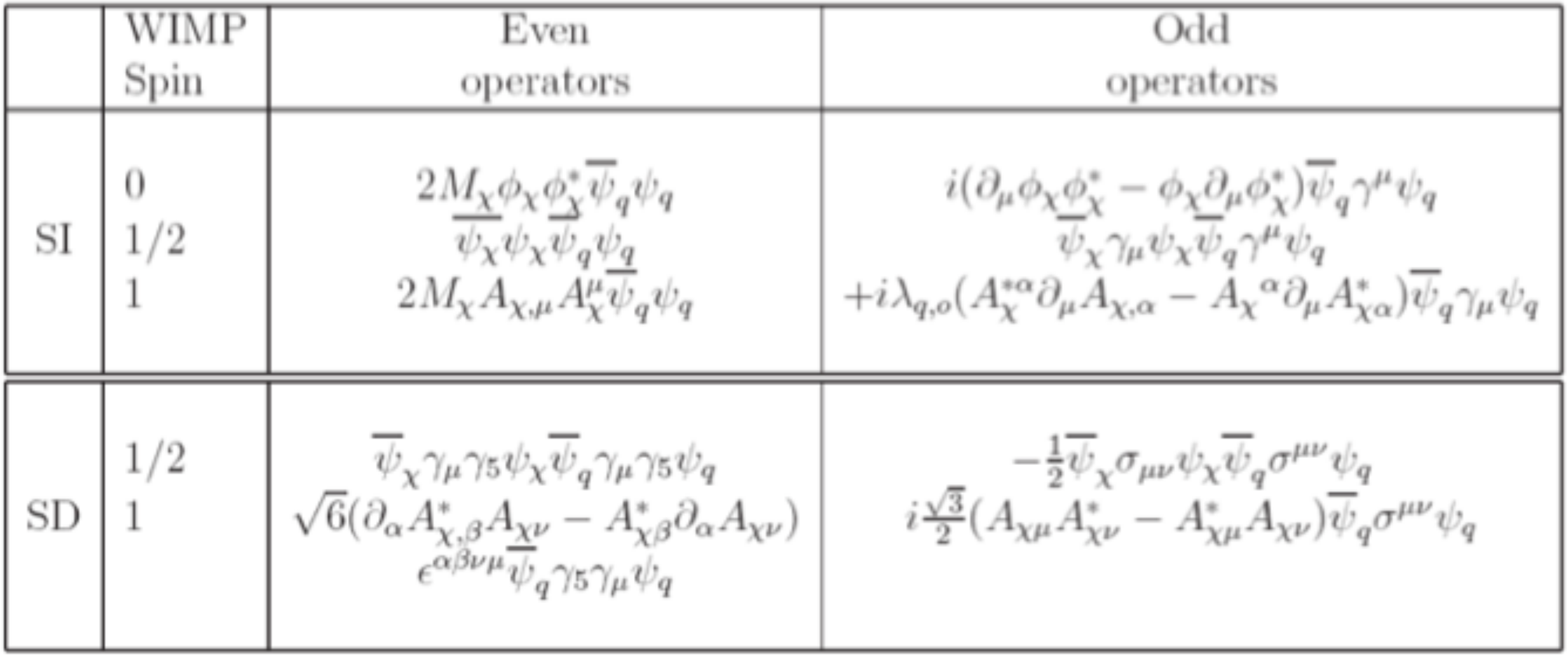
- For any WIMP, need effective Lagrangian for WIMP-nucleon amplitude *at small momentum ~100MeV*,
- Generic form for a fermion

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

- 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	$\sqrt{6}(\partial_\alpha A_{\chi,\beta}^* A_{\chi\nu} - A_{\chi\beta}^*\partial_\alpha A_{\chi\nu})$ $\epsilon^{\alpha\beta\nu\mu}\overline{\psi}_q\gamma_5\gamma_\mu\psi_q$	$i\frac{\sqrt{3}}{2}(A_{\chi\mu}A_{\chi\nu}^* - A_{\chi\mu}^*A_{\chi\nu})\overline{\psi}_q\sigma^{\mu\nu}\psi_q$

- Operators for WIMP quark Lagrangian, procedure to 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

$$\langle N|m_q\overline{\psi}_q\psi_q|N\rangle = f_q^N M_N$$

$$\lambda_{N,p} = \sum_{q=1,6} f_q^N \lambda_{q,p}$$

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

- Can be defined by user
- Different coefficients can lead to large corrections in cross section
  - Bottino et al hep-ph/0010203, Ellis et al hep-ph/0502001

- Traditionally scalar coefficients extracted from ratios of light quark masses, pion-nucleon sigma term and σ_0

$$\sigma_{\pi N} = m_l \langle p|\bar{u}u + \bar{d}d|p\rangle$$

$$\sigma_0 = m_l \langle p|\bar{u}u + \bar{d}d - 2\bar{s}s|p\rangle$$

- $\sigma_{\pi N}$=55-73MeV σ_0=36+/-7MeV -> Large uncertainty in s-quark contribution
- Lattice calculations have provide new estimates of s-quark content σ_s tend towards low value
  - average of lattice results
  - σ_s=42+/-5MeV
  - f_s^p=0.045+/-0.005

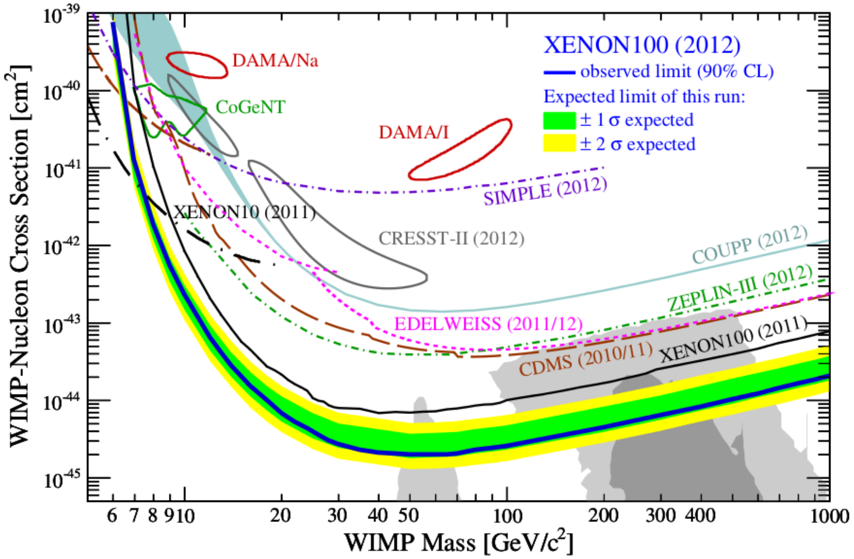
σ_s	$\sigma_{\pi N}$
8 ± 21	
43 ± 10	
54 ± 8	
22 ± 37	
31 ± 16	50 ± 10
34^{+31}_{-27}	42^{+21}_{-6}
70 ± 68	31 ± 5
22 ± 20	32 ± 2
21^{+44}_{-6}	45 ± 6
125 ± 59	43 ± 6
50 ± 18	
	37 ± 10

- WIMP-nucleon cross-section

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

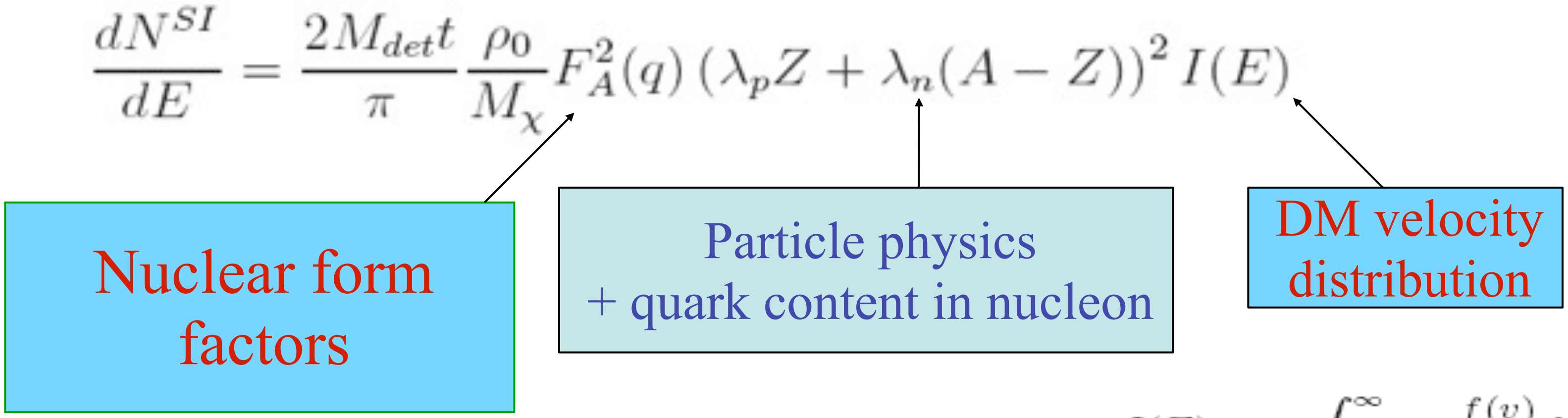
quark-nucleon amplitudes related to quark amplitudes with coefficients extracted from lattice

- Can be directly compared with experimental limits



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

- DM velocity distribution
- Maxwell isothermal,

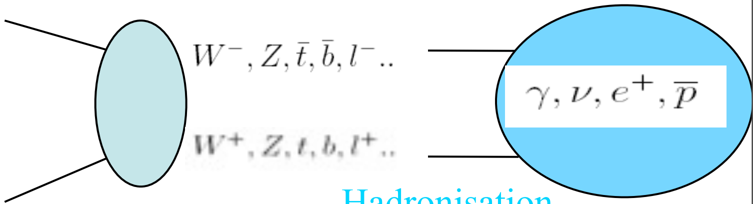
$$\frac{c_{\rm norm}}{\rm v} \int_{|\vec{v}|<v_{esc}} d^3\vec{v} \exp\left(-\frac{(\vec{v}-V_{Earth})^2}{v_{rot}^2}\right) \delta({\rm v}-|\vec{v}|)$$

- truncated at v_{esc}
- user can implement other velocity distribution
- Global parameters

Name	default value	units	Symbol	Comment
Rsun	8.5	kpc	$R_\odot$	Distance from Sun to center of Galaxy
rhoDM	0.3	GeV/cm^3	$\rho_\odot$	Dark Matter density at Rsun
Vesc	600	km/s	v_{esc}	galactic escape velocity
Vearth	225.2	km/s	v_{Earth}	Galaxy velocity of Earth
Vrot	220	km/s	v_{rot}	rotation velocity at Sun orbit

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)
  -



Hadronisation
And decays

v=0.001c

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

Photons

- Flux calculation

$$\Phi_{\gamma,\nu} = \frac{1}{8\pi}\boxed{\frac{<\sigma_{ann}v>}{m_\chi^2}}\boxed{\sum_{f.s.}\left(\frac{dN_{\gamma,\nu}}{dE}\right)_{f.s.}}\boxed{\int_{l.o.s.}\rho_s^2}$$

- Photon production
  - In decay of SM particles + R-even new particles
  - dN/dE : basic channels ff, VV, VH, HH and polarization of gauge bosons
  - For particles of unknown mass (e.g. Z'..) compute 1->2 decay recursively until only basic channels
  - Annihilation into 3 body ($\chi\chi \to e^+e^-\gamma$)

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

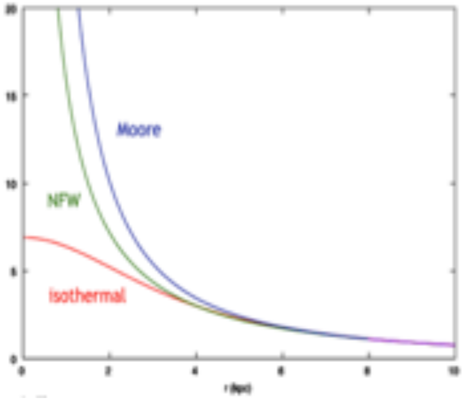
Dark matter profile

- Dark matter profile parametrisation

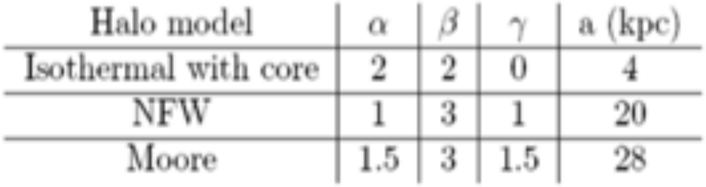
$$\rho_s(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1+(r_\odot/a)^\alpha}{1+(r/a)^\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}$$

$r_\odot = 8$ kpc

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



- Different halo profile rather similar except in center of galaxy



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

- Also Einasto profile

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

Monochromatic gamma-rays

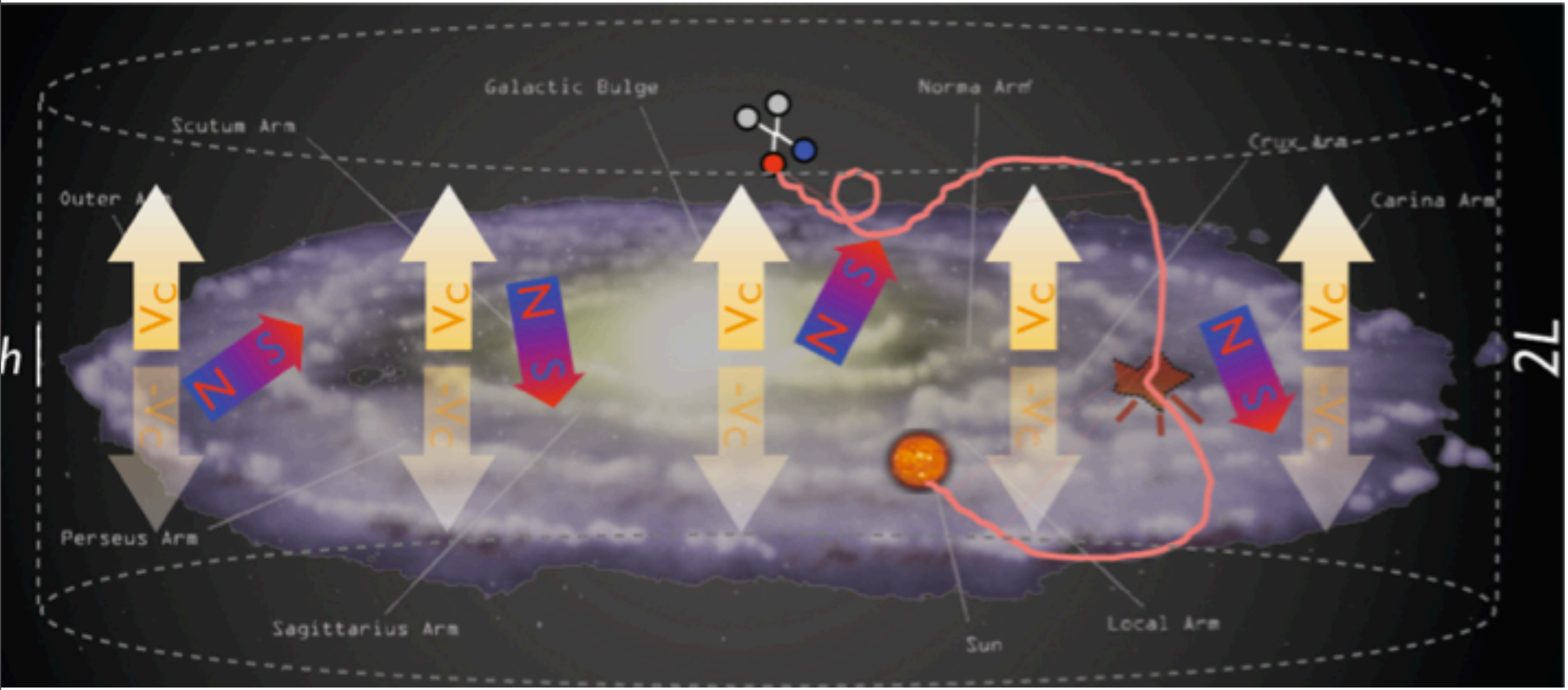
- Monochromatic gamma rays ($\gamma\gamma,\gamma Z$) and (γh) are loop-induced (suppressed) BUT lead to very distinctive signal
  - C. Weniger, 1204.2797, T.Bringmann et al, 1203.1312 (signal in Fermi-LAT? m~130GeV $\sigma v \sim 10^{-27} cm^3/s$)

NEW

- Available for MSSM and some extensions (NMSSM)
  - 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
- In generic models, not available, only have the Higgs contribution (through $h\gamma\gamma$ effective vertices - see later)

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
  - Lavalle, Pochon, Salati, Taillet, astro-ph/0603796

Propagation

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

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

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

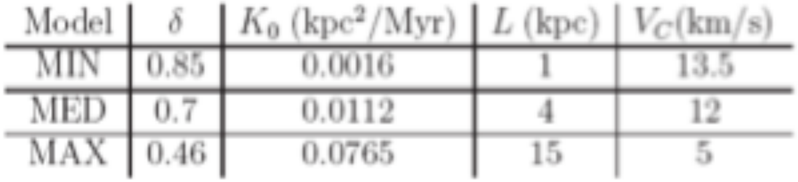
- Antiprotons: energy loss negligible
  - Negative source term (annihilation of antiproton in interstellar medium
  - Galactic wind, convective velocity: V_c

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

- Propagation parameters constrained by B/C

Propagation

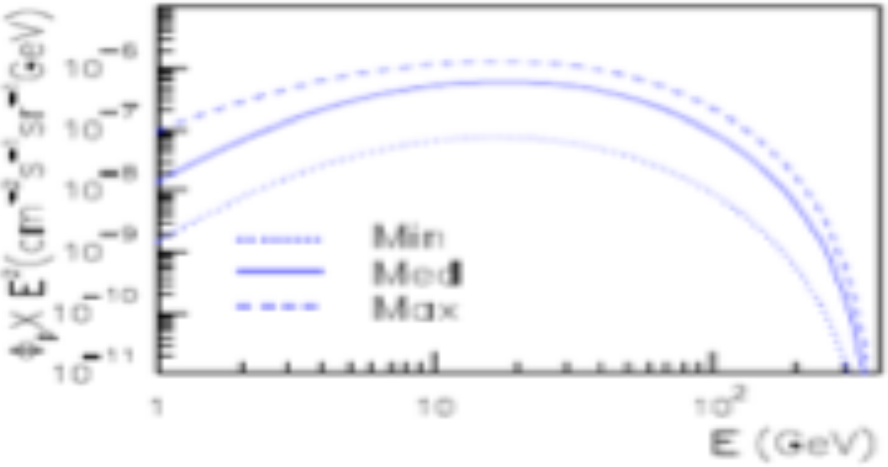
- Choice of diffusion parameters (global parameters of micrOMEGAs)

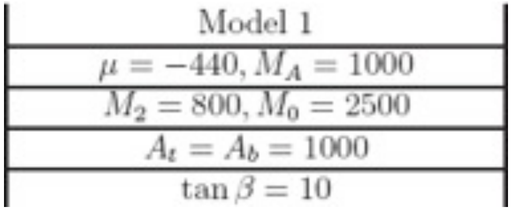


Model	δ	K_0 (kpc^2/Myr)	L (kpc)	V_C(km/s)
MIN	0.85	0.0016	1	13.5
MED	0.7	0.0112	4	12
MAX	0.46	0.0765	15	5

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

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

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

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

- Annihilation

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

- Number of DM particles

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

- 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

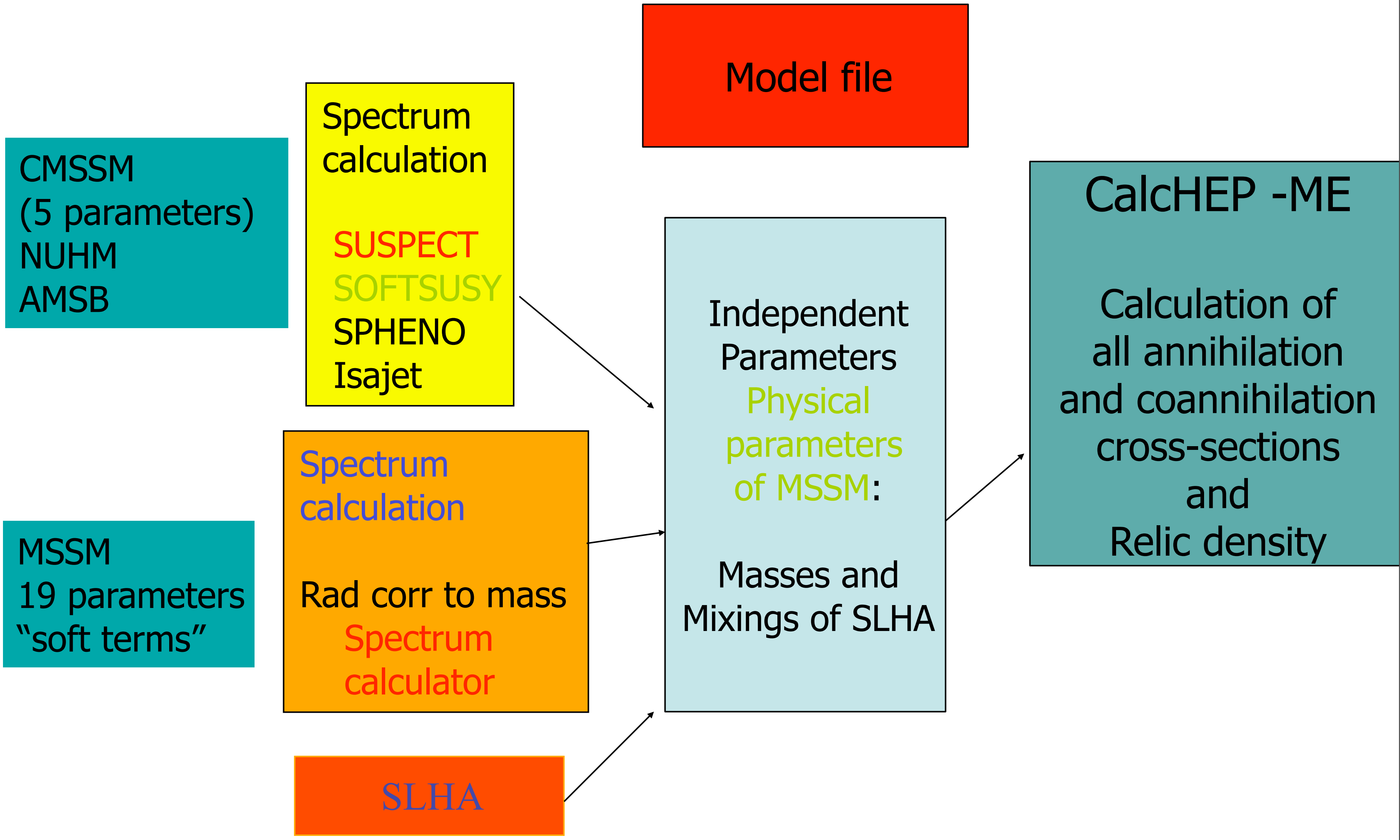
$$\frac{d\phi_\nu}{dE_\nu} = \frac{1}{4\pi d^2} \left(\Gamma_{\chi\chi} Br_{\nu\nu} \frac{dN_{\nu\nu}}{dE} + \Gamma_{\chi\bar{\chi}} \sum_f Br_{f\bar{f}} \frac{dN_f}{dE} \right)$$

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

- Neutrinos that reach the Earth interact with rock below or water/ice in detector -> muon flux
- Both neutrino flux and muon flux are computed

MSSM

Parameters of MSSM model file



Model file

CMSSM
(5 parameters)
NUHM
AMSB

Spectrum
calculation

SUSPECT
SOFTSUSY
SPHENO
Isajet

MSSM
19 parameters
“soft terms”

Spectrum
calculation

Rad corr to mass
Spectrum
calculator

SLHA

Independent
Parameters
Physical
parameters
of MSSM:

Masses and
Mixings of SLHA

CalcHEP -ME

Calculation of
all annihilation
and coannihilation
cross-sections
and
Relic density

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***
- Includes other constraints (developed for MSSM) – not automatic yet

  $b \to s\gamma$ (NLO) , $(g-2)_{\mu}$, $B_s \to \mu\mu$, $B \to \tau\nu$, $\Delta\rho$
- Radiative corrections to masses can be important – SUSY masses and Higgs masses (via spectrum calculator)

Higgs sector

- General CP conserving effective potential

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

- 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)

Also include QCD corrections to higgs couplings to fermion pairs and SUSY-QCD corrections to hbb relevant at large tanβ

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 constraints)
    - New implementation of Higgs potential - Higgs to Higgs couplings directly given in NMSSMTools
    - 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

New

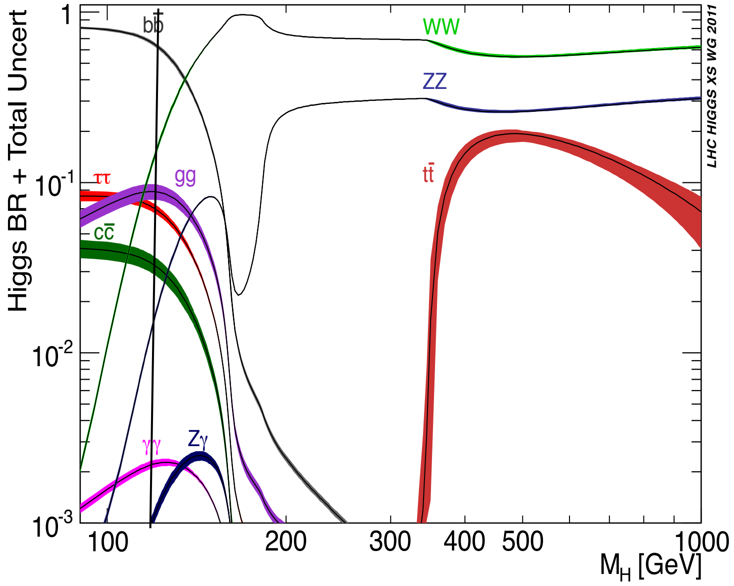
Dark matter models

- 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)
- Models not yet public
  - SUSY N=2 (with K. Benakli, M. Goodsell.. arXiv:0905.1043)
  - UED (with M. Kakizaki)
  - MSSM+RHneutrino (with M. Kakizaki, S. Kraml, E.K. Park)
  - UMSSM (J. DaSilva)
  - IDM
  - Inert doublet+singlet Z3 (with K. Kannike, M. Raidal)
  - BMSSM (F. Boudjema, G. Drieu La Rochelle)
- Many more models implemented by users

Collider physics

- CalcHEP is included: computes all 2->2(3) processes and 1-> 2,3 decays at tree-level
- Some facilities provided for pp collisions (function that computes directly pp process - summing over processes at parton level)
- Interactive link to CalcHEP

- New: improved Higgs sector
  - 3 body decays (WW*,ZZ*)
  - loop-induced decays (gg,γγ)



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)

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

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

- Add QCD corrections
  - e.g. for gluons

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

  - Good agreement with HDECAY for SM-like Higgs

- Reduced couplings are computed within micrOMEGAs - provided in a SLHA file

$$c_{hXX} = g^2_{hXX}(NP)/g^2_{hXX}(SM)$$

- Can compute signal strength

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

- Also use for more extensive constraints on the multi-Higgs sector, for example using interface HiggsBounds (Bechtle et al) which contains compilation of several Higgs searches at Tevatron/LHC
- Interface Higgsbounds via SLHA file - indicates whether point excluded at 95% CL

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*