Determining the WIMP mass using the complementarity between direct and indirect searches and the ILC

Andreas Goudelis

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Based on N.Bernal, A.G., Y.Mambrini, C.Muñoz,
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Modified version submitted to JCAP

Laboratoire de Physique Théorique - Orsay

Outline

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4. Dark Matter at Colliders
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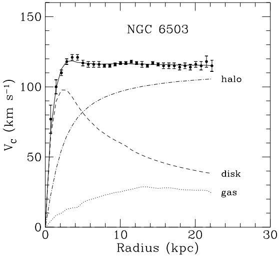
Why Dark Matter?

Galactic Rotation Curves



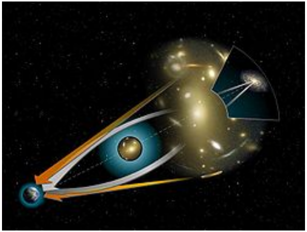
Normally, for $r > r_{\text{vis}}$ one would expect

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

instead

$$v(r) \approx \text{const}$$

Gravitational Lensing

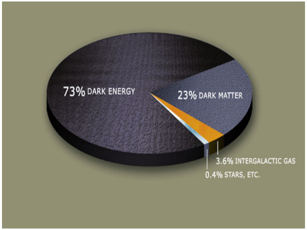


Light bends differently than predicted from GR, if only luminous matter is taken into account.

And also:

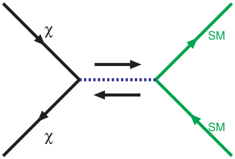
- Primordial Nucleosynthesis
- Large Scale Structure
- Cosmic Microwave Background

At the end of the Day, for ΛCDM



WIMP DM - Relic Density

Principle of "Thermal Relics": (The simplest scenario!)



- Begin from a state of thermodynamical equilibrium.
- The universe expands $\Longrightarrow$ its temperature falls. SM particles no longer energetic enough to produce $\chi\chi$ pairs
- $\Longrightarrow$ χ's density falls asymptotically.

A gross estimation of a particle's relic density can be provided by

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

Weakly Interacting Massive Particles

So:

$$\Omega_\chi \sim \frac{1}{\langle \sigma v \rangle} \sim \frac{m_\chi^2}{g_\chi^4}$$

Substitute

$$(m_\chi, g_\chi) \sim (m_{\text{weak}}, g_{\text{weak}}) \Longrightarrow \text{Correct relic density!!!}$$

This observation gives rise to the **WIMP hypothesis**.

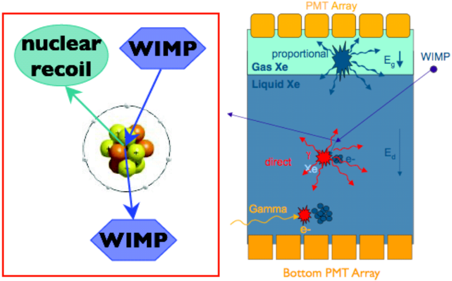
A number of BSM theories provide very good candidates:

- SUSY: Neutralino, gravitino, right-handed sneutrino
- KKDM: Lightest Kaluza-Klein excitation (UED models)
- Little Higgs Models

A common feature: Impose some kind of discrete symmetry in the Lagrangian to keep the lightest BSM-sector particle stable.
(But also avoid fast proton decay!)

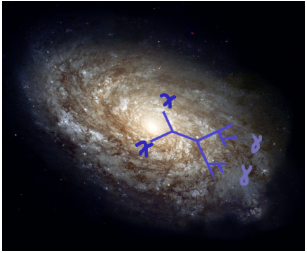
DM Detection Methods

Direct Detection



Dark Matter is detected through its collisions with target nuclei of a (typically large) ground-based detector.

Indirect Detection



DM annihilation into SM particles in the galactic halo. The main detected particles: γ-rays, e^+, antiprotons as primary or secondary products of WIMP annihilations.

Direct Detection: The event rate

$$\frac{dN}{dE_r} = \frac{\sigma_{\chi-N} \cdot \rho_0}{2\, M_r^2\, m_\chi} F(E_r)^2 \int_{v_{\min}(E_r)}^{v_{\rm esc}} \frac{f(v)}{v}\, dv$$

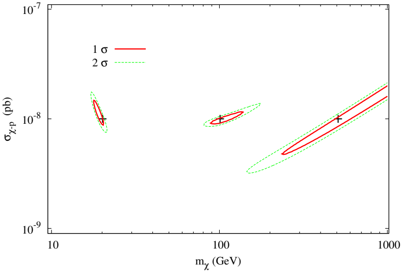
Where:

- N: Number of scatterings $(\mathrm{s}^{-1}\mathrm{kg}^{-1})$
- E_r: Nuclear recoil energy (~few keV)
- m_χ: WIMP mass
- $M_r = \frac{m_\chi\, m_N}{m_\chi + m_N}$: WIMP - Nucleus Reduced Mass
- $\sigma_{\chi-N}$: WIMP-Nucleus cross-section (Spin-independent coupling)
- ρ_0: Local WIMP density (0.3 GeV cm^{-3})
- $f(v)$: WIMP local velocity distribution (Maxwell-Boltzmann)
- F: Nuclear form factor (Woods-Saxon)

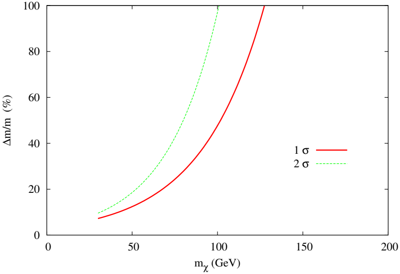
⇒ **Our choice: The XENON 100kg experiment.**

Direct Detection: Mass Discrimination

Mass and cross-section discrimination capacity



Mass Resolution



In fact:

$$m_\chi \ll m_N \Rightarrow \frac{dN}{dE_r} \simeq e^{-E_r/m_\chi^2}$$

$$m_\chi \gg m_N \Rightarrow \frac{dN}{dE_r} \simeq e^{-E_r}$$

⇒ **Better discrimination capacity for small masses**

Here we ignore backgrounds/theoretical uncertainties. For more details, see discussion!

Indirect Detection: The γ-ray flux

$$\begin{aligned}\Phi_\gamma(E_\gamma) &= 0.94\cdot 10^{-13}\mathrm{cm}^{-2}\mathrm{sec}^{-1}\mathrm{GeV}^{-1}\mathrm{sr}^{-1}\sum_i Br_i \frac{dN_\gamma^i}{dE_\gamma} \\ &\times \left(\frac{\langle\sigma v\rangle}{10^{-29}\mathrm{cm}^3\mathrm{sec}^{-1}}\right)\left(\frac{100\mathrm{GeV}}{m_\chi}\right)^2 \bar{J}(\Delta\Omega)\Delta\Omega\end{aligned}$$

Where:

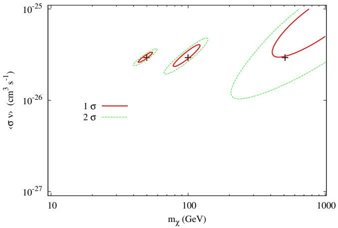
- Br_i: Branching Ratio of annihilation into i-th SM particle
- dN_γ^i/dE_γ: Functions describing SM particles' decays into γ-rays (PYTHIA + fit)
- $\langle\sigma v\rangle$: Total WIMP self-annihilation cross-section ($\approx 3\cdot 10^{-26}\mathrm{cm}^3\mathrm{sec}^{-1}$)
- $\bar{J}$: Astrophysical factor: Depends on DM distribution.

	a (kpc)	α	β	γ	$\bar{J}(4\cdot 10^{-3}\mathrm{sr})$
NFW	20	1	3	1	$5.859\cdot 10^2$
$\mathrm{NFW_c}$	20	0.8	2.7	1.45	$3.254\cdot 10^4$
Moore et al.	28	1.5	3	1.5	$2.574\cdot 10^4$
$\mathrm{Moore_c}$	28	0.8	2.7	1.65	$3.075\cdot 10^5$

⇒ **Our choice: The GLAST experiment**

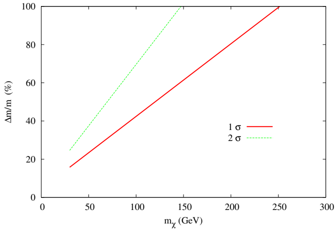
Indirect Detection: Mass Discrimination

Mass and cross-section discrimination capacity for a NFW halo profile



Mass Resolution

(95% C.L.)

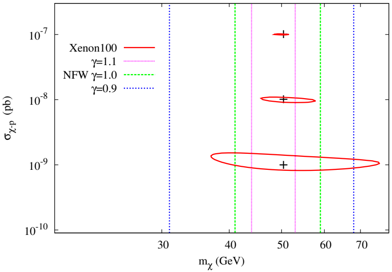


- Again, better resolution for smaller masses (due to strong differences in the spectrum form in the $[1, 300]$GeV region!).
- Strong dependence on the halo profile.
- No clumpiness included (factor of $\sim 2 - 10$)

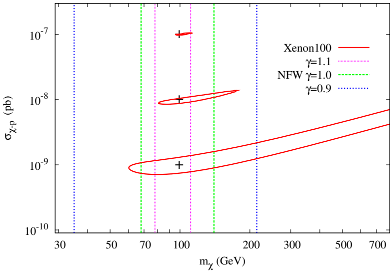
Interesting theoretical/experimental uncertainties, also left for discussion!

Direct vs Indirect Detection

Example for $m_\chi = 50$**GeV**



Example for $m_\chi = 100$**GeV**

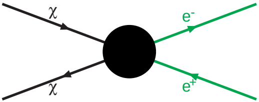


- Comparable precision ⇒ Experiments complementary for low/intermediate masses.
- For higher masses, uncertainties become more important.
- Complementarity more obvious for not too optimistic astrophysical considerations and $\sigma_{\chi-p}$ cross-sections.

ILC: The Method

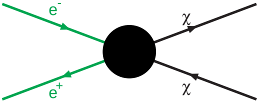
The General Idea: Birkedal, Matchev, Perelstein, arXiv:hep-ph/0403004

WIMP Pair - Annihilation (Galaxy - WMAP)



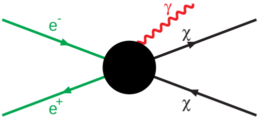
⇓ (Detailed Balancing)

WIMP Pair - Production (Colliders - Invisible)



⇓ (Collinear Approximation)

Radiative WIMP Production (Colliders - Visible!)



ILC: Radiative WIMP Production Rate

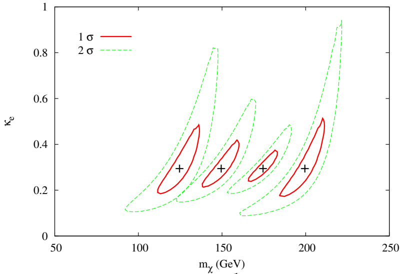
$$\frac{d\sigma(e^+e^- \to 2\chi + \gamma)}{dx d\cos\theta} \approx \frac{\alpha\kappa_e\sigma_{an}}{16\pi}\frac{1+(1-x)^2}{x}\frac{1}{\sin^2\theta}2^{2J_0} \times (2S_\chi+1)^2\left(1-\frac{4{m_\chi}^2}{(1-x)s}\right)^{1/2+J_0}$$

Where:

- $x = 2E_\gamma/\sqrt{s}$
- θ: Photon emission angle
- σ_{an}: Total annihilation cross-section (WMAP) ($\backsim$ 7pb)
- J_0: Dominant (s- or t-) annihilation channel
- S_χ: WIMP's spin
- $\kappa_e = \sigma_e^{(J_0)}/\sigma_{an}$: Annihilation fraction into e^+e^- pairs.

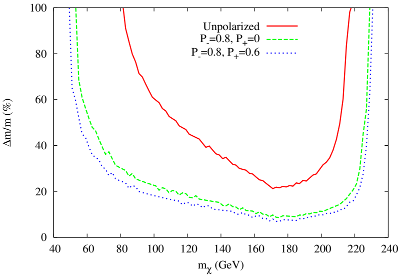
ILC: Mass Discrimination

WIMP mass - annihilation fraction discrimination capacity



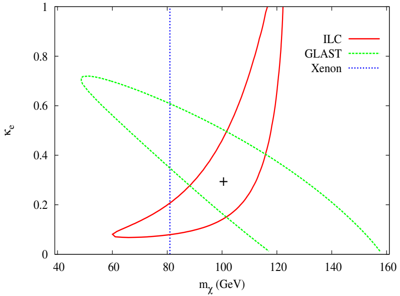
(500GeV Unpolarized beams, 500fb^{-1} integrated luminosity)

Relative error in WIMP's mass discrimination



- Discrimination capacity peaks significantly for $m_\chi = 175$GeV (optimal combination of uncut spectrum - phase space).
- Significant improvement in mass resolution for polarized beams.

DM Experiments/ILC complementarity



An example at 95% CL:

- $m_\chi = 100$GeV
- 3 years of exposure,
- $\sigma_{\chi-p} = 10^{-8}$ pb
- NFW profile and a
- 500 GeV unpolarized linear collider with an integrated luminosity of 500fb^{-1}

m_χ	XENON	GLAST	ILC
50 GeV	$-5/+7$ GeV	± 10 GeV	–
100 GeV	$-19/+75$ GeV	$-33/+39$ GeV	$-40/+20$ GeV
175 GeV	$-65/$ GeV	-125 GeV	$-20/+15$ GeV
500 GeV	–	–	–

Summarizing...

- We presented a simple way to exploit simultaneously different kinds of experiments to extract **model-independent** information on WIMP Dark Matter.
- For quite reasonable (i.e. not too optimistic) considerations on the WIMP-nucleus scattering cross-section and the DM halo profile we saw that different kinds of experiments can act highly complementary:
  → The precision is comparable.
  → Possibility to cover different regions in the parameter space.

... in preparation:

- Can **PAMELA/ATIC** observations come in terms with **SUSY** models?
- And on a totally different subject: Z' **at the LHC**

Merci !!!

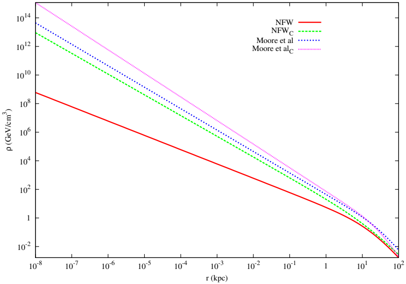
... to use in emergency ...

Halo Profiles

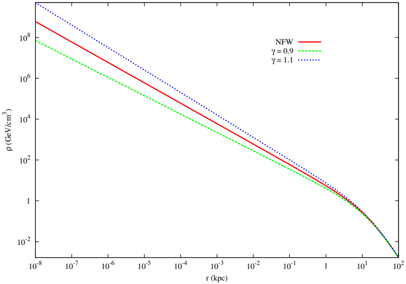
The most usual parametrization:

$$\rho(r) = \frac{\rho_0 [1 + (R_0/a)^\alpha]^{(\beta-\gamma)/\alpha}}{(r/R_0)^\gamma [1 + (r/a)^\alpha]^{(\beta-\gamma)/\alpha}}$$

Some well motivated profiles

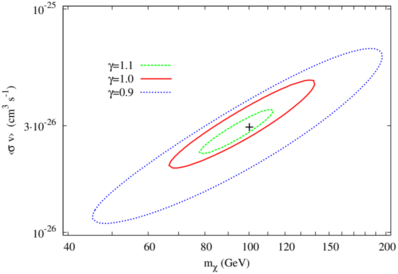


Fun with γ!!!



Halo Profiles: Influence on observations

More fun with γ!!!



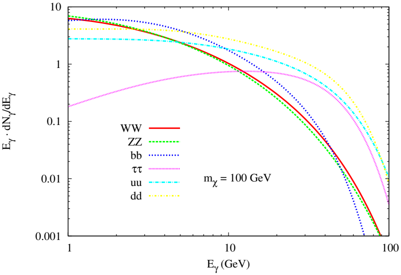
- Among the most important uncertainties: Flux can be enhanced/suppressed by orders of magnitude!
- Estimations based on N-body simulations. Open question: role of baryons?
- Observations seem to favour rather small γ values ($\gamma \leq 1$)

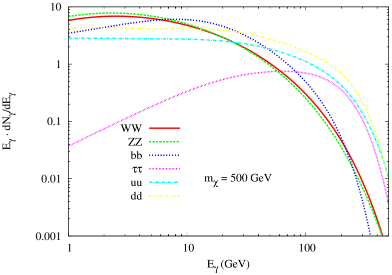
Spectral Functions

PYTHIA result fit performed through functions of the form:

$$\frac{dN_\gamma^i}{dx} = \exp[F_i(\ln(x))]$$

with $x = E_\gamma / m_\chi$ and F being 7th order polynomial functions.





- The τ spectrum has a characteristic hard form, other leptons have zero contribution.

Some Points on the ILC Treatment

- The detailed balancing equation:

$$\frac{\sigma(\chi+\chi\to X_i+\bar{X}_i)}{\sigma(X_i+\bar{X}_i\to\chi+\chi)}=2\frac{v_X^2(2S_X+1)^2}{v_\chi^2(2S_\chi+1)^2}$$

We can expand the total thermally averaged CS:

$$\sigma_i v=\sum_{J=0}^{\infty}\sigma_i^{(J)}v^{2J}\overset{v\ll c}{\Longrightarrow}\sigma_{an}=\sum_i\sigma_i^{(J_0)}$$

For soft/collinear photons:

$$\frac{d\sigma(e^+e^-\to 2\chi+\gamma)}{dx d\cos\theta}\approx\mathcal{F}(x,\cos\theta)\tilde{\sigma}(e^+e^-\to 2\chi)$$

Form Factor and Stuff...

- Woods-Saxon form factor:

$$F(E_r) = \frac{3j_1(qR_1)}{qR_1} e^{-(qs)^2}$$

- WIMP-Nucleus and WIMP-proton CS:

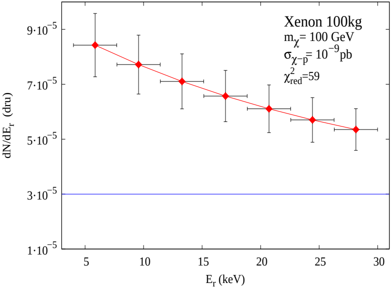
$$\sigma_{\chi-N} = \sigma_{\chi-p}(Am_r/M_r)^2$$

where

$$\begin{aligned} M_r &= \frac{m_\chi m_p}{m_\chi + m_p} \\ m_r &= \frac{m_\chi m_N}{m_\chi + m_N} \end{aligned}$$

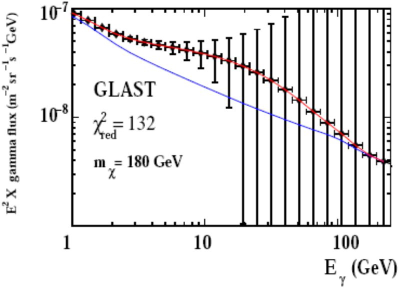
Signal Examples

XENON 100kg event rate expectation:



(7 energy bins $[4.5, 26.9]$ keV)

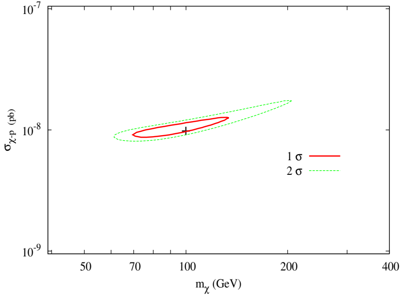
GLAST γ-ray flux expectation:



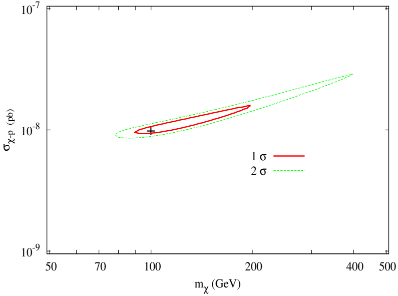
An NFW halo profile has been supposed.

Direct Detection: Background Uncertainties

Constant bkg equal to maximal signal value



Exponential bkg that mimics signal

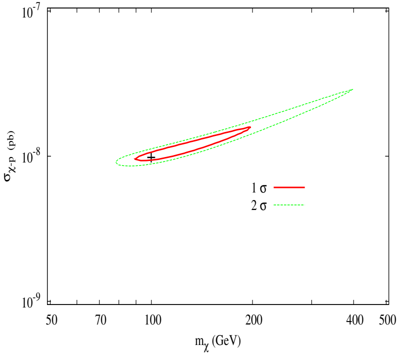


- Good knowledge of backgrounds is essential!!!
- Experiments claim to be practically background-free...

Direct Detection: Uncertainties in velocity distribution

The general form:

$$f(v_\chi)\, d^3 v_\chi = \frac{1}{(v_\chi^0)^3 \pi^{3/2}}\, e^{-(v_\chi / v_\chi^0)^2}\, d^3 v_\chi$$

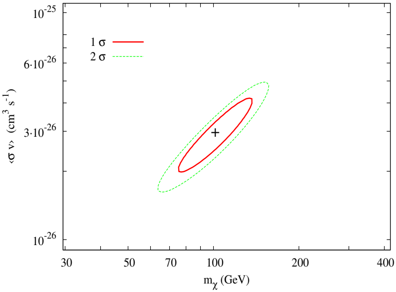


Inirect Detection: Background Uncertainties

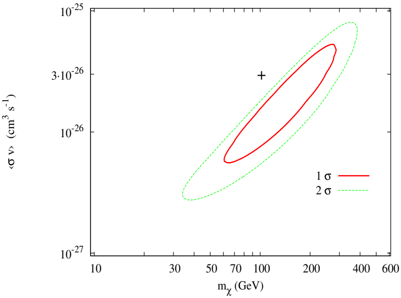
The main background uncertainty at low energies: **EGRET**

- Uncertainties in the spectrum overall normalisation
- Uncertainties in the power-law spectral index

Varying the normalisation



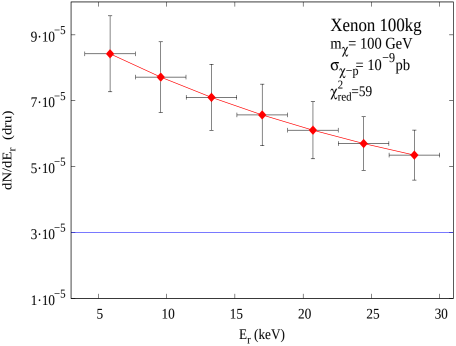
Varying the spectral index



!!! Uncertainties important: At low energies, maximal signal statistics !!!

Direct Detection: The XENON experiment

- Situated at the Gran Sasso NL, Italy
- Currently: 15kg of liquid Xenon. Goal: 1T. Simultaneous measurement of scintillation and ionization.



Indirect Detection: The GLAST experiment

Generalities...

- Detects γ-rays coming from DM annihilations in the GC.
- Scheduled for launch in May 2008 for a 5-year mission.
- Will perform an all-sky survey in the energy range [1,300]GeV.
- Effective Area: $\sim 10^4 \mathrm{cm}^2$, Angular Resolution: $0.1^0 \times 0.1^0$.
- Will examine the inner $\sim$ 7pc of the Milky Way.

GLAST's Background

- Diffuse γ-ray measurements from HESS.
- HESS point-source ($\sim$Sgr A*, $E_\gamma \geq 160$GeV)
  → Possibly related to some astrophysical accelerator.
- HESS might be underestimating the low-energy background from the GC.
  (Zaharijas and Hooper, arXiv:astro-ph/0603540)
- EGRET point source (Near the galactic center)
  → Difficult to interpret as coming from DM annihilation.
  (Dodelson, Hooper and Serpico, arXiv:0711.4621[astro-ph])

Our choice: Interpolation between HESS and EGRET data.

ILC: Subtleties

Approach valid for soft/collinear photons → **Undetectable!**

- Nevertheless, it gives satisfactory results outside the soft/collinear region for **nonrelativistic** WIMPs.

To ensure the WIMPs' non-relativistic nature we impose the following kinematical cuts:

$$\frac{\sqrt{s}}{2}\left(1-\frac{8m_\chi^2}{s}\right) \leq E_\gamma \leq \frac{\sqrt{s}}{2}\left(1-\frac{4m_\chi^2}{s}\right).$$

- Main background process: Radiative neutrino production (CalcHEP 2.5).

Discrimination Method

Analysis based on extended likelihood function:

$$L = \frac{(N_{th}^{scan})^{N_{Exp}}}{N_{Exp}!} \exp\left(-N_{th}^{scan}\right) \prod_{i=1}^{N_{Exp}} f(E; m_\chi, \sigma_{\chi-p})$$

- Calculate the theoretical number of events, N_{th}, for the input mass and cross-section.
- Draw an "experimental" nb of events, N_{Exp}, from a Poisson distribution.
- Scan the (m_χ, $\sigma_{\chi-N}$) parameter space and find the experiment's estimation, taking into account the theoretical nb of events of every point in the PS, N_{th}^{scan}.
- Generate a large number of experiments, repeat the procedure, pick the one that averages all experiments' results.
- From this experiment, plot (m_χ, $\sigma_{\chi-N}$) non-discrimination regions.

$\Longrightarrow$ This method allows to account for random deviations from the expected number of events.