Recasting Direct Detection Limits Within MicrOMEGAs And Implication For Non-Standard DarkMatter Scenarios

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based on G. Belanger, A. Mjallal, A. Pukhov in preparation

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- Provide a tool that allows to reinterpret the 90% limits obtained by the experimental collaborations within their specific framework.
- Apply them to a wider set of Dark Matter (DM) models and DM velocity distributions.

Outline

- Introduction
- Direct Detection Framework.
- Recasting DD Limits With MicrOMEGAs
- Applications
- Conclusion

Direct DM Detection
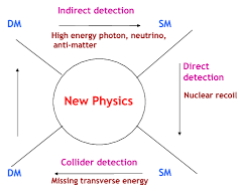
- It is based on the search of the scattering between DM particles and nuclei in a detector.
- This process is observable through the recoiling nucleus, with an energy:

$$E_R = \frac{1}{2} m_\chi v^2 \frac{4 m_\chi m_N}{(m_\chi + m_N)^2} \frac{1 + \cos\theta}{2}$$

- No evidence for DM have been found.
- For DM masses above roughly 6 GeV, the best limits are currently obtained by XENON-1T.

Direct Detection Framework

Assumptions:

- Point-Like interaction (e.g: $\lambda_N \bar{\psi}_\chi \gamma_\mu \psi_\chi \bar{\psi}_N \gamma^\mu \psi_N$)
- Equal proton and neutron spin-independent (SI) cross sections.
- Specific choice of DM density ($\rho_{DM} = 0.3 \frac{GeV}{cm^3}$)
- Maxwell velocity distribution of DM with these parameters $v_{Rot} = 220 \frac{Km}{s}$, $v_{Esc} = 544 \frac{Km}{s}$ and $V_{Earth} = 232 \frac{km}{s}$.

Direct Detection Framework

- The spectrum of DM recoils in case of heavy nuclei is:

$$\frac{dN^{SI}}{dE} = T M_{det} \frac{\rho_{DM}}{2 M_\chi \mu_{\chi A}^2} \sigma^{SI} F^2(E) \int_{v_{min}} \frac{f(\vec{v})}{v} d\vec{v}$$

where $f(\vec{v})$ is the velocity distribution function of DM,
$v_{min} = \sqrt{\frac{E M_A}{(2 \mu_{\chi A}^2)}}$ and $F(E)$ is nucleus form factor.

- SI DM-nucleons cross sections:

$$\sigma_{\chi N}^{SI} = \frac{4}{\pi} \mu_{\chi N}^2 \lambda_N^2 \ , \ \ N = n, p$$

- Multiplying $\frac{dN^{SI}}{dE}$ by detector 's acceptance $p(E)$ (say Xenon)
  and then computing the likelihood, one can get the SI
  exclusion limits on DM-nucleon cross sections.

Note that $\mu_{\chi N} = \frac{M_\chi M_N}{M_\chi + M_N}$.

SI Xenon1T Reconstruction

- To repeat exactly Xenon1T analysis, we need detailed information on events distribution, background estimation and the used of nuisance parameters for all points of event space.
- Since we have incomplete informations, we assume that there is some effective subspace of the total space of events where no events were detected.
- In this region, the probability to register DM event after applying all cuts is $p_{eff}(E)$.
- Our goal is to recover $p_{eff}(E)$ using Xenon1T data, in order to recast exclusion for different condition.

- The likelihood function reads

$$L = e^{-\mathcal{L} \int_0^{E_{max}} \left(p_{eff}(E)\frac{dN}{dE} + \frac{dB}{dE} \right) dE}$$

$\mathcal{L}$ is the exposure.

- Maximal likelihood is reached for zero DM signal event. We introduce
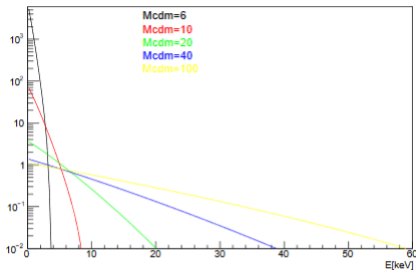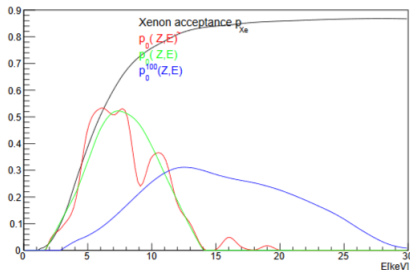
$$p_{val} = \frac{L}{L_{max}} = e^{-\mathcal{L} \int_0^{E_{max}} p_{eff}(E)\frac{dN}{dE} dE}$$

- We exploit the exclusion provided by Xenon to derive an integral equation for the acceptance $p_{eff}(E)$.

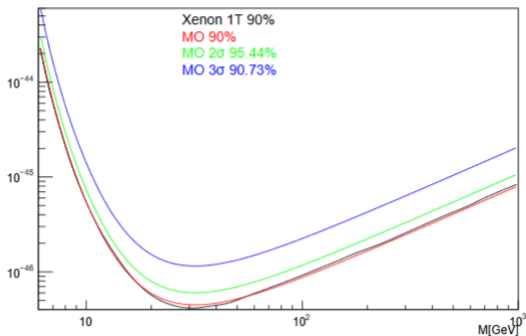$$\mathcal{L} \int p_{eff}(E)\frac{dN^{90}(M_\chi)}{dE} dE = log\left(1/p_{val}\right) = 2.3$$

Recovering p_{eff}

- Solving this equation, we reconstruct $p_{eff}(E)$.

- Our acceptance match very well the Xenon one near threshold, i.e. for $E < 6\,KeV$ and so we reproduce very well the exclusion at low masses since this is the only relevant region for DM masses below $10\,GeV$.
- Right plot represents the predictions for the recoil energy distribution of Xenon nuclei for an exposure $\mathcal{L} = 279 * 900 - days - Kg$ and σ^{90} correspondent to each mass in the figure.

- We observe an excellent agreement between the Xenon1T excluded cross sections and our reconstruction.
- Maximal difference is roughly 10% and is reached for $M_{DM} = 20 GeV$.

SI PICO-60 Reconstruction

- To reconstruct the PICO-60 exclusion curve for SI interactions, we assume an acceptance described by a step function starting from zero and rising to 100% at a certain threshold energy.
- The value of the threshold is optimized in order to match the PICO-60 exclusion curve.
- We use two methods to derive the exclusion, a likelihood method and a method based on Feldman-Cousins.
- In both case the optimum value for the threshold is 1.6keV, which is slightly higher than the value used by PICO-60.
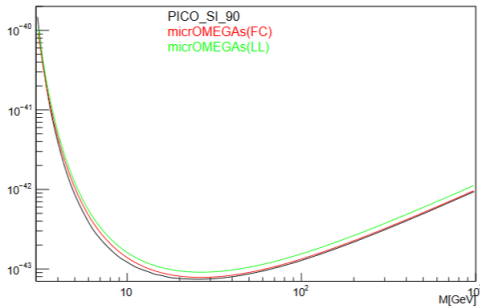
90% SI exclusion limits on $\sigma_{\chi p}$ by PICO-60 experiment.

The likelihood method leads to difference of at most 20% level for large masses, $M_{DM} > 100\,GeV$ while the Feldman-Cousins method gives an excellent agreement for all masses.

SD PICO-60 Reconstruction

SD and SI interactions have very similar recoil energy spectra, therefore we use the recasting done for SI interactions and apply it directly to SD ones for both PICO-60 and Xenon1T.
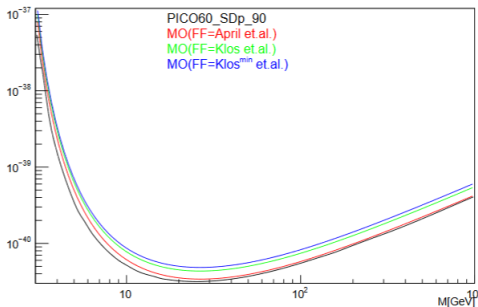
90% SD excluded cross section $\sigma_{\chi p}$ by PICO experiment. Comparison of PICO and micrOMEGAs reconstruction. There are different sets of form factors and different curves reflect the impact of the uncertainty on form factors.
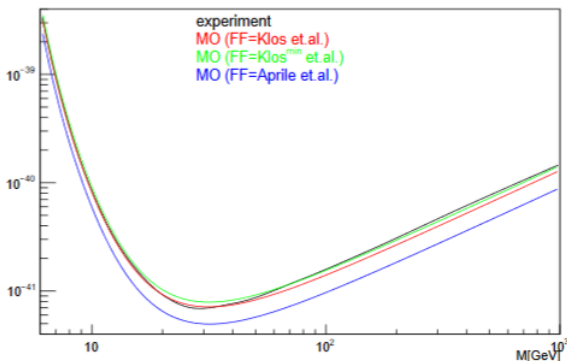
90% SD excluded cross section $\sigma_{\chi n}$ by Xenon1T experiment. Comparison of Xenon1T and micrOMEGAs reconstruction for different sets of form factor. (see also Klos et al, Phys. Rev. D88 (2013) 083516 , Fitzpatrick et al, JCAP 1302 (2013) 004)

We can use our reconstruction of DD experimental limits to study these cases:

- Case of a light mediator.
- Dependence of exclusion cross section on cosmological parameters.
- Millicharged Dark matter.

ZpPortal Model

- We consider the case of a Z' portal with pure-vector couplings to the SM and a Dirac fermion DM. The Lagrangian is given by:

$$\mathcal{L}_{int} = -g_\chi Z'_\mu \bar{\chi} \gamma^\mu \chi - \sum_f g_f Z'_\mu \bar{f} \gamma^\mu f$$

Motivations:

- Possibility to provide strong DM self-interactions and explain anomalies in galaxy clusters.
- Possibility to enhance the direct detection signal in models with feebly coupled particles.

Light Mediator

- We consider a long-range interaction between a DM particle and a nucleus A, with t-channel light propagator

$$\frac{1}{t - M_{med}^2} = \frac{-1}{2M_A E_R + M_{med}^2}$$

(see also Hambye et al., arXiv:1807.05022)

- For the typical minimal recoil energy in Xenon1T $E_R \sim 2KeV$, $M_{Xe} \sim 130GeV$ we can have $2M_A E_R \sim (22MeV)^2$.

- For any DM model, DD routines in micrOMEGAs calculates the amplitudes for CDM-nucleon elastic scattering at zero momentum and so the resulting recoil spectrum ($\frac{dN_A^{std}}{dE_R}$) has to be improved.

- DM recoil spectrum becomes:

$$\frac{dN_A}{dE_R} = \frac{M_{med}^4}{\left(M_{med}^2 + 2M_A E_R\right)^2} \frac{dN_A^{std}(\sigma_0)}{dE_R}$$

Results For Zp Model
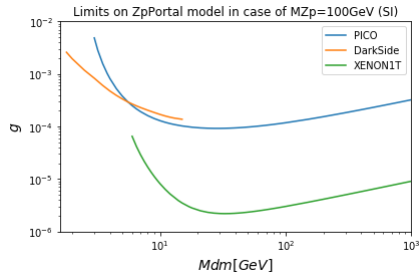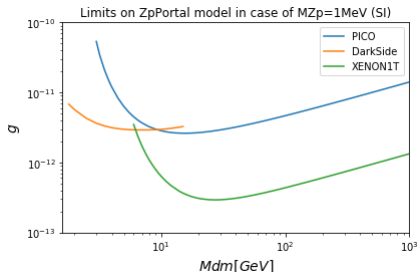
where $g = g_f g_\chi$.

- We always have the best exclusion from Xenon1T for high DM mass.
- In case of light mediator, we can probe smaller couplings and so testing FIMP DM model is possible.

Velocity Distribution

Maxwell

- It is the Standard isotropic isothermal spherical DM halo (SHM), in which velocities are isotropic and follow Gaussian law.

$$f(v) = \frac{1}{(2\pi\sigma^2)^{3/2}} \exp\left[-\frac{(\vec{v} + \vec{v}_{Earth})^2}{2\sigma^2}\right]$$

  where $\sigma = \frac{v_{Rot}}{\sqrt{2}}$.

SHMpp

- Proposed in ref: Evans, O'Hare, McCabe, arXiv:1810.11468 .
- New data suggest that our stellar halo lies in a strongly radially anisotropic population, the 'Gaia Sausage'.
- It is described as:

$$f(v) = (1 - \eta)f_{Maxwell}(v) + \eta f_S(v)$$

Velocity Distribution

where η is the DM density in the Sausage and f_S is the velocity distribution of the Gaia Sausage. It is a function of the anisotropy β.

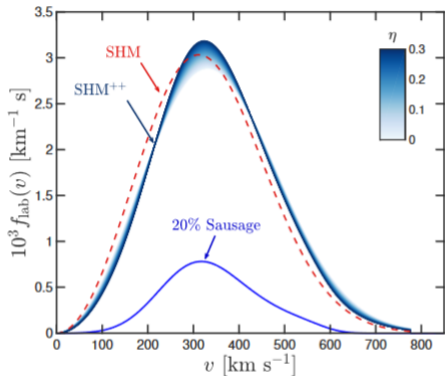These parameter are fit to Gaia data.

SHMpp parameters:

$$\rho_{DM} = 0.55 \pm 0.17 \, GeV/cm^3$$

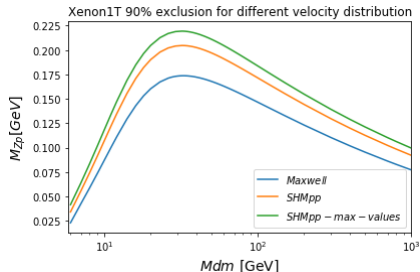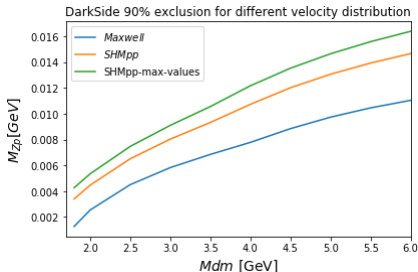$$v_{Rot} = 233 \pm 3 km/s$$

$$v_{Esc} = 580 \pm 63 km/s$$

$$\beta = 0.9 \pm 0.05$$

$$\eta = 0.2 \pm 0.1$$

Results For Different Velocity Distribution

Fixing the couplings we get:

The strongest dependence on the velocity distribution is observed for small DM mass. For Xenon1T, we get the largest correction on the value of MZp excluded for $Mdm \simeq 6\,GeV$ (80%). While for DarkSide, the largest correction is for $Mdm \simeq 1.8\,GeV$ (238%). By increasing the value of ρ_{DM} we improve the sensitivity and so we can test even smaller cross sections (higher MZp).

- It is the SM plus an extra abelian gauge field that couples to a massive Dirac fermion ("Dark QED") and that mixes with SM 's hypercharge through the kinetic term:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\slashed{\partial} + ie'\slashed{A}' + iM_{mcp}\right)\psi - \frac{k}{2}A'_{\mu\nu}B^{\mu\nu}$$

Where $k << 1$ and $B_{\mu\nu} = \cos(\theta_\omega)A_\mu - \sin(\theta_\omega)Z_\mu$
$A'_\mu \to A'_\mu - kB_\mu$, we get:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\slashed{\partial} + ie'\slashed{A}' - ike'\slashed{B} + iM_{mcp}\right)\psi \ .$$

So DM couples to the photon and it has a millicharge $q = ke'\cos(\theta_\omega)$.

Photon can be tread as light mediator with a very small mass, thus allowing to write the energy distribution as:

$$\frac{dN_A^{ph}}{dE_R} = \frac{m_{ph}^4}{(2M_A E_R)^2} \frac{dN_A^{std}(\sigma_{\chi P})}{dE_R}$$
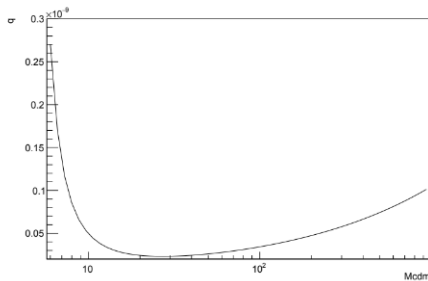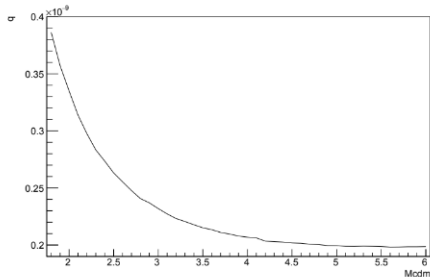
where $\sigma_{\chi P} = 16\pi\alpha_{EM}^2 q^2 \frac{\mu_{\chi P}^2}{m_{ph}^4}$

(see also Hambye et al., arXiv:1807.05022).

Note however that the parameter m_{ph} cancels out.

DarkSide and Xenon1T exclusion limits on the parameter space of DM.

- However, millicharged DM loose energy before it reaches the detector through scattering with nucleus or electrons and so it may not produce a recoiling energy above threshold.
- There is an upper limit on DM charge 'q'. (work in progress)

Conclusion

MicrOMEGAs has a new module that allows:

- Impose DD limits on a variety of DM models (WIMP, light mediator, millicharged DM).
- take into account different velocity distributions, nuclear form factors
- Currently included : Xenon1T, Pico60, DarkSide50, CRESST3 (in progress).

We are planning to include other experiments when they improve on these results