Exploring Inelastic Dark Matter Signatures with DUNE

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- The Inelastic Dark Matter model.

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How does DUNE work?

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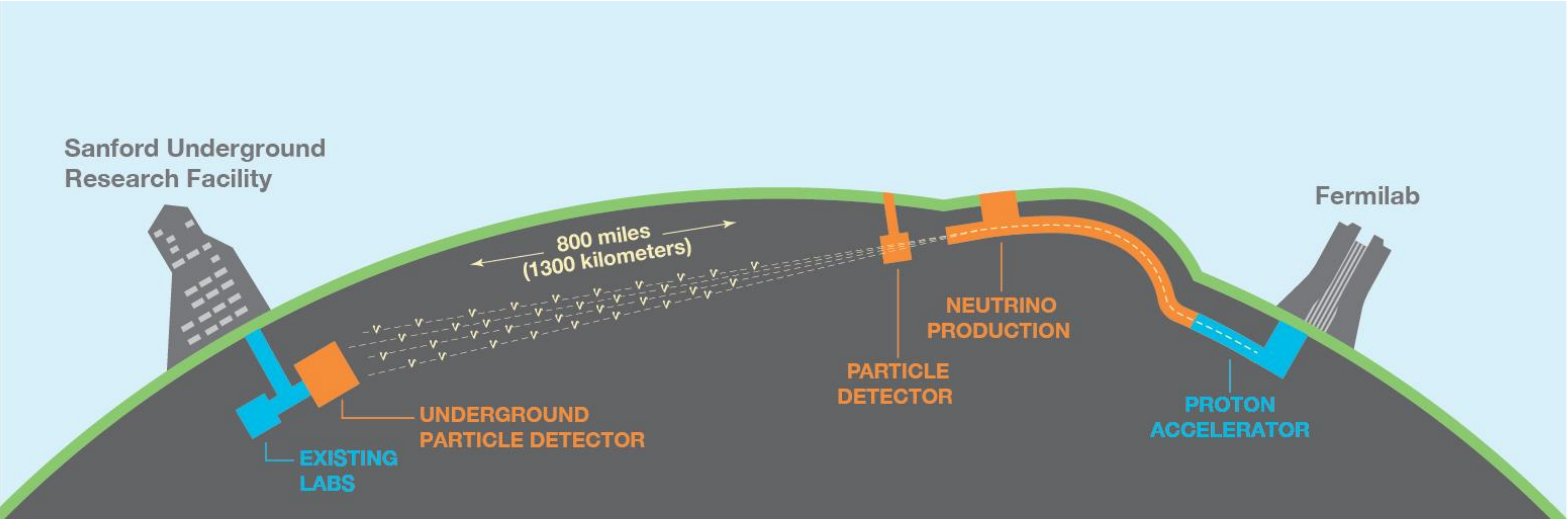

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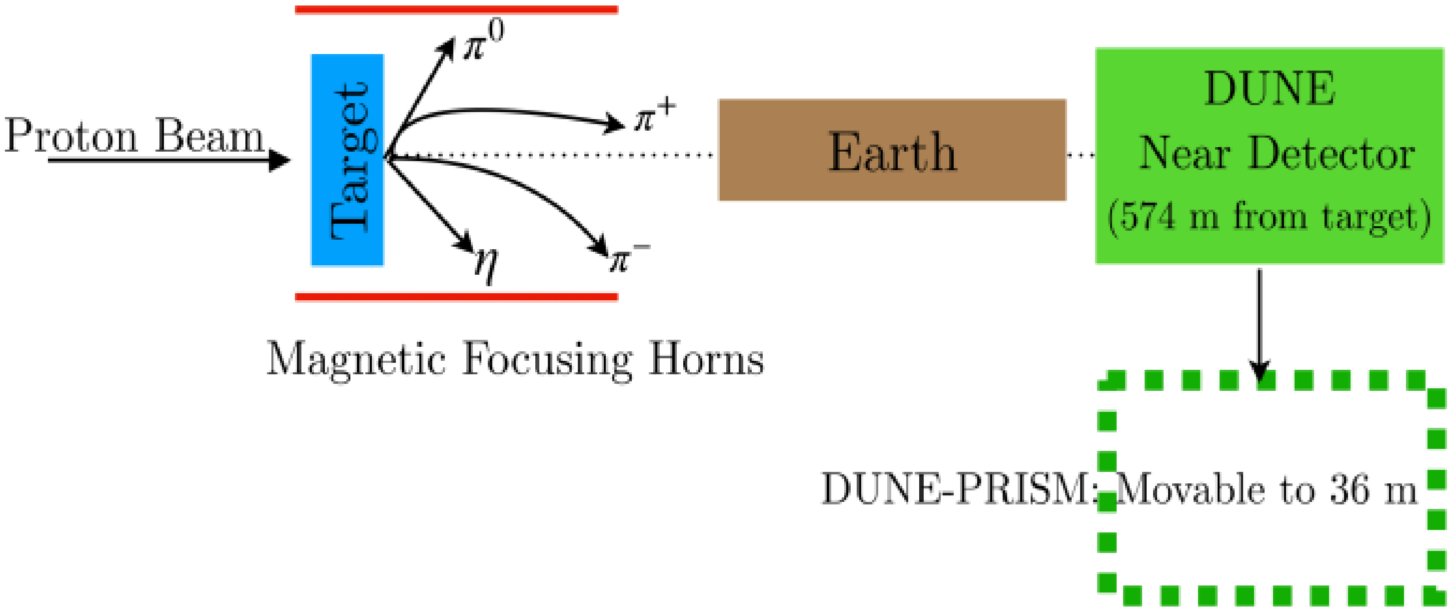
How does DUNE work?



DUNE-PRISM Sensitivity to Light Dark Matter. De Romeri V. , Kelly K. and Machado P.

The Inelastic Dark Matter model

The Inelastic Dark Matter Model

Let us consider the following Lagrangian:

$$\mathcal{L}_\psi = i\bar{\psi}\,\not{D}\psi - m_D\bar{\psi}\psi - f\phi\bar{\psi}^c\psi + \text{h.c.}$$

Where:

$$D_\mu = \partial_\mu - ig_X\hat{X}_\mu$$

When symmetry breaking is applied to the scalar field, the Dirac field splits into two Majorana states

$$\phi = \frac{v_\phi + \hat{h}'}{\sqrt{2}}$$

$$\chi_1 = \frac{\psi - \psi^c}{\sqrt{2}} \qquad \chi_2 = \frac{\psi + \psi^c}{\sqrt{2}}$$

$$\begin{aligned}\mathcal{L}_\psi =& \frac{1}{2}\left(i\bar{\chi}_1\,\not{\partial}\chi_1 + i\bar{\chi}_2\,\not{\partial}\chi_2 - m_{\chi_1}\bar{\chi}_1\chi_1 - m_{\chi_2}\bar{\chi}_2\chi_2\right)\\ &+ \frac{i}{2}g_X\hat{X}\mu\left(\bar{\chi}_2\gamma^\mu\chi_1 - \bar{\chi}_1\gamma^\mu\chi_2\right) + \frac{f}{2}\hat{h}'\left(\bar{\chi}_1\chi_1 - \bar{\chi}_2\chi_2\right)\end{aligned}$$

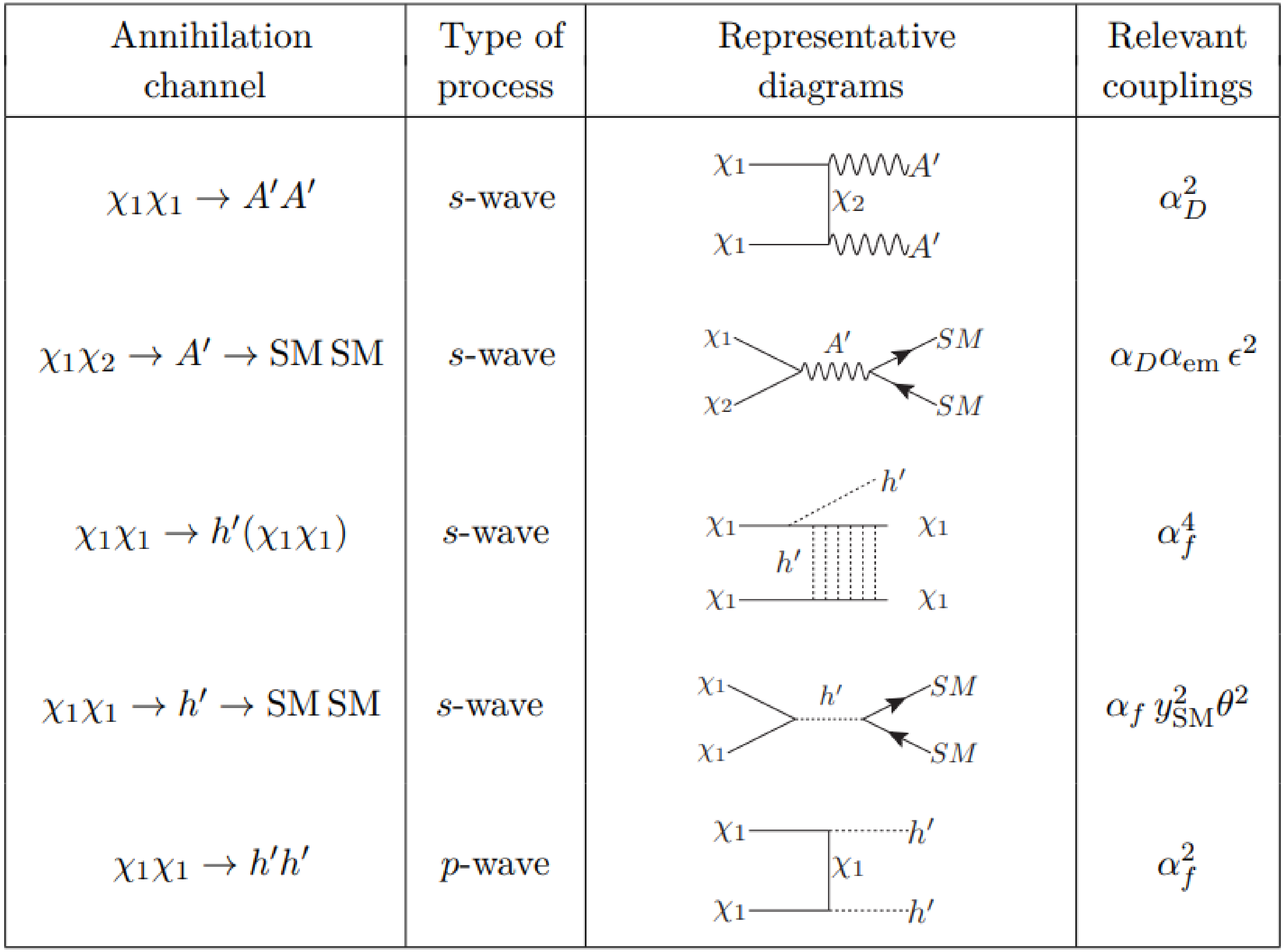
On the other hand, the dark scalar field and the SM Higgs doublet appear in the Lagrangian as follows

$$\begin{aligned}V(\phi, H) = \lambda_H\left(H^\dagger H - \frac{\nu_H^2}{2}\right)^2 + \lambda_\phi\left(\phi^*\phi - \frac{\nu_\phi^2}{2}\right)^2\\ + \lambda_{\phi H}\left(H^\dagger H - \frac{\nu_H^2}{2}\right)\left(\phi^*\phi - \frac{\nu_\phi^2}{2}\right)\end{aligned}$$

And the vector field is coupled to the hypercharge field as follows:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{\epsilon}{2c_{\text{W}}}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu}$$

Contributions by Channel



Annihilation channel	Type of process	Representative diagrams	Relevant couplings
$\chi_1\chi_1 \to A'A'$	s-wave		α_D^2
$\chi_1\chi_2 \to A' \to \mathrm{SM\,SM}$	s-wave		$\alpha_D\alpha_{\mathrm{em}}\,\epsilon^2$
$\chi_1\chi_1 \to h'(\chi_1\chi_1)$	s-wave		α_f^4
$\chi_1\chi_1 \to h' \to \mathrm{SM\,SM}$	s-wave		$\alpha_f\, y_{\mathrm{SM}}^2\theta^2$
$\chi_1\chi_1 \to h'h'$	p-wave		α_f^2

Long-lived dark Higgs and inelastic dark matter at Belle II. Duerr M., Garcia-Cely C., et al.

Parameter space

$$\{M_{\chi_1},\, M_{A'},\, M_\phi,\, y,\, \theta,\, \Delta/M_{\chi_1},\, \alpha_D\}$$

Likelihood

We developed an algorithm in Python that utilizes the likelihood and the genetic algorithm known as differential evolution

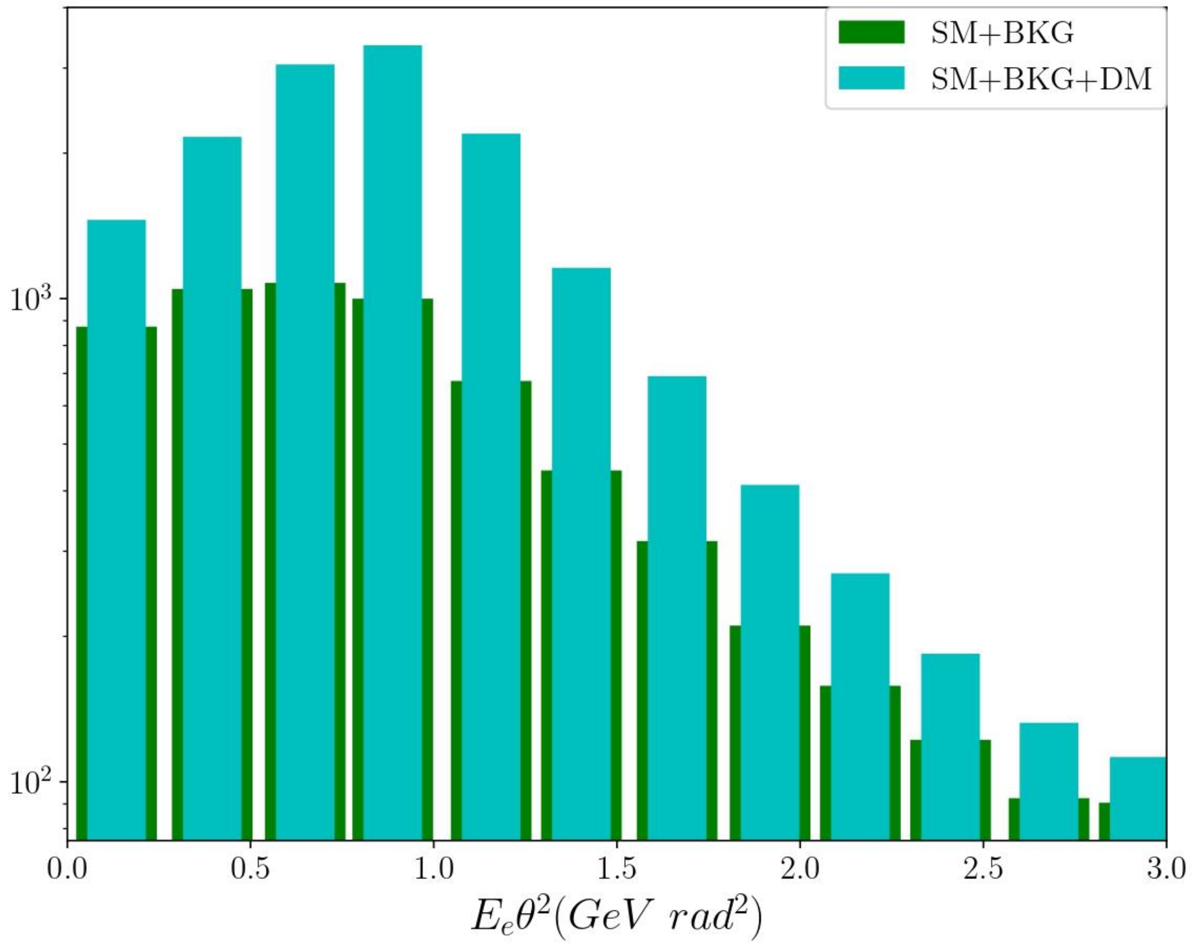
$$\chi^2_{obs} = \sum_{i=1}^{N} \chi^2_i(\mathcal{O}^i_{Th}) = \sum_{i=1}^{N} \left(\frac{\mu^i_{Th} - \mu^i_{Obs}}{\Sigma^i} \right)^2 \quad \Sigma^i = \sqrt{(\Sigma^i_{th})^2 + (\Sigma^i_{obs})^2}$$

We consider only a single observable, which is the relic density. The likelihood is described by

$$\chi^2_{obs} = \left(\frac{\Omega h^2 - 0.12}{\Sigma^\Omega} \right)^2 \qquad \Sigma^\Omega = \sqrt{(0.1\Omega h^2)^2 + (0.001)^2}$$

Analizing and results

Signals and background

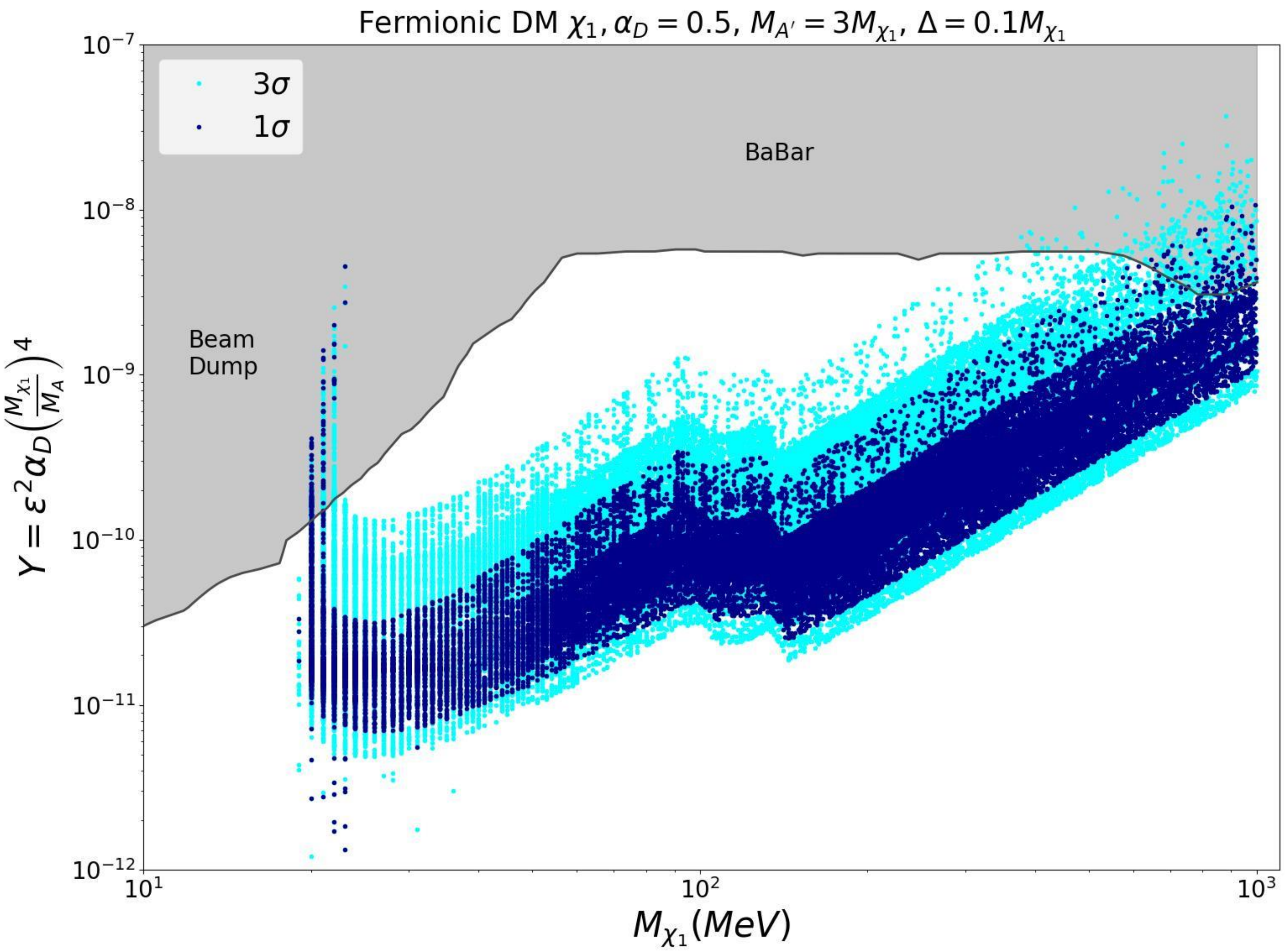


Expected number of events for different range.

The benchmark point considered is the one described in the text with:

$$M_{\Upsilon'} = 0.01$$
$$\epsilon^2 = 1X10^{-10}$$

Parameter Space for the Dark Matter Particle

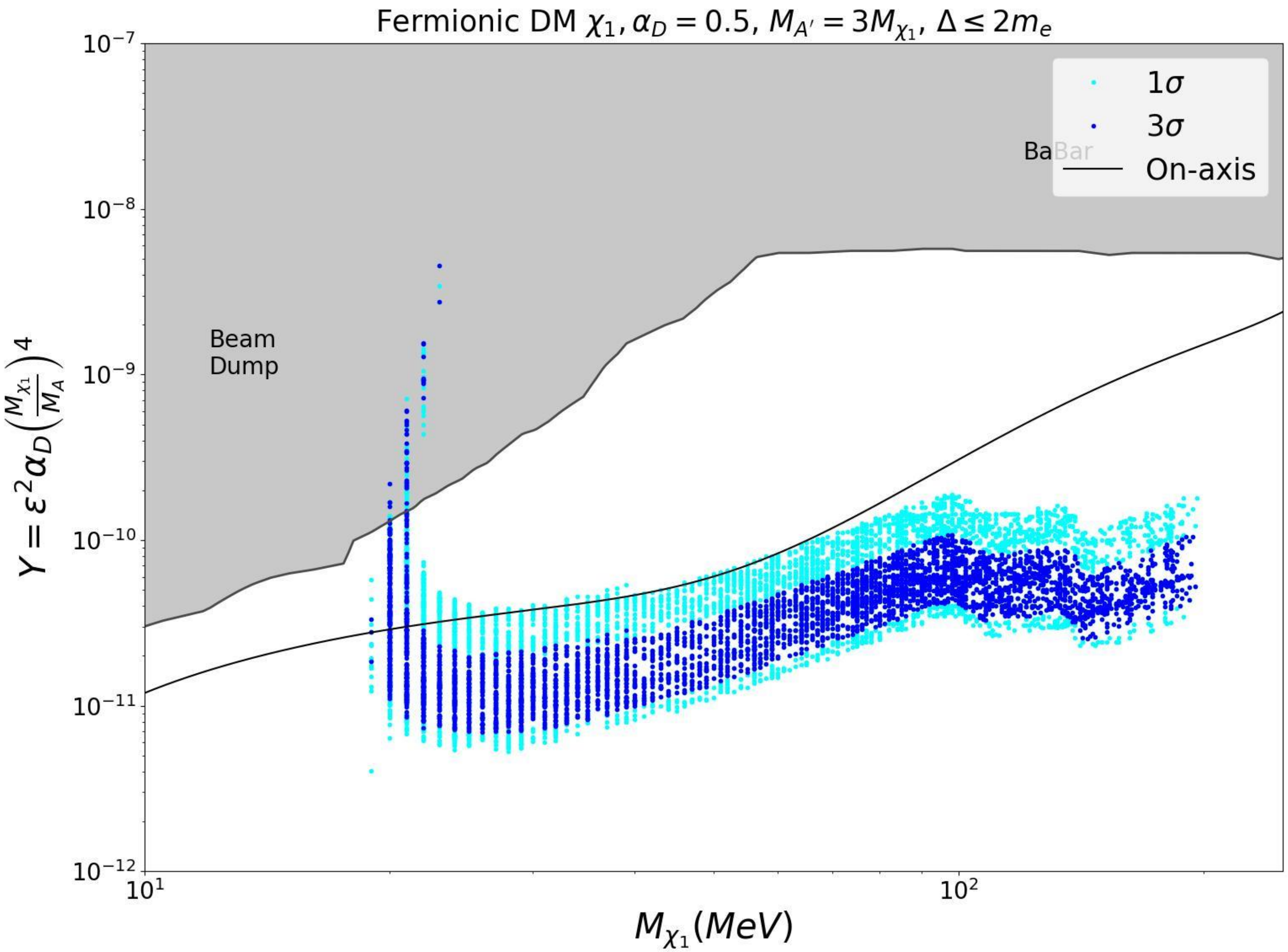


In this image, we can observe a series of points that satisfy the dark matter abundance.

However, some regions are already constrained by the Beam Dump and BaBar experiments.

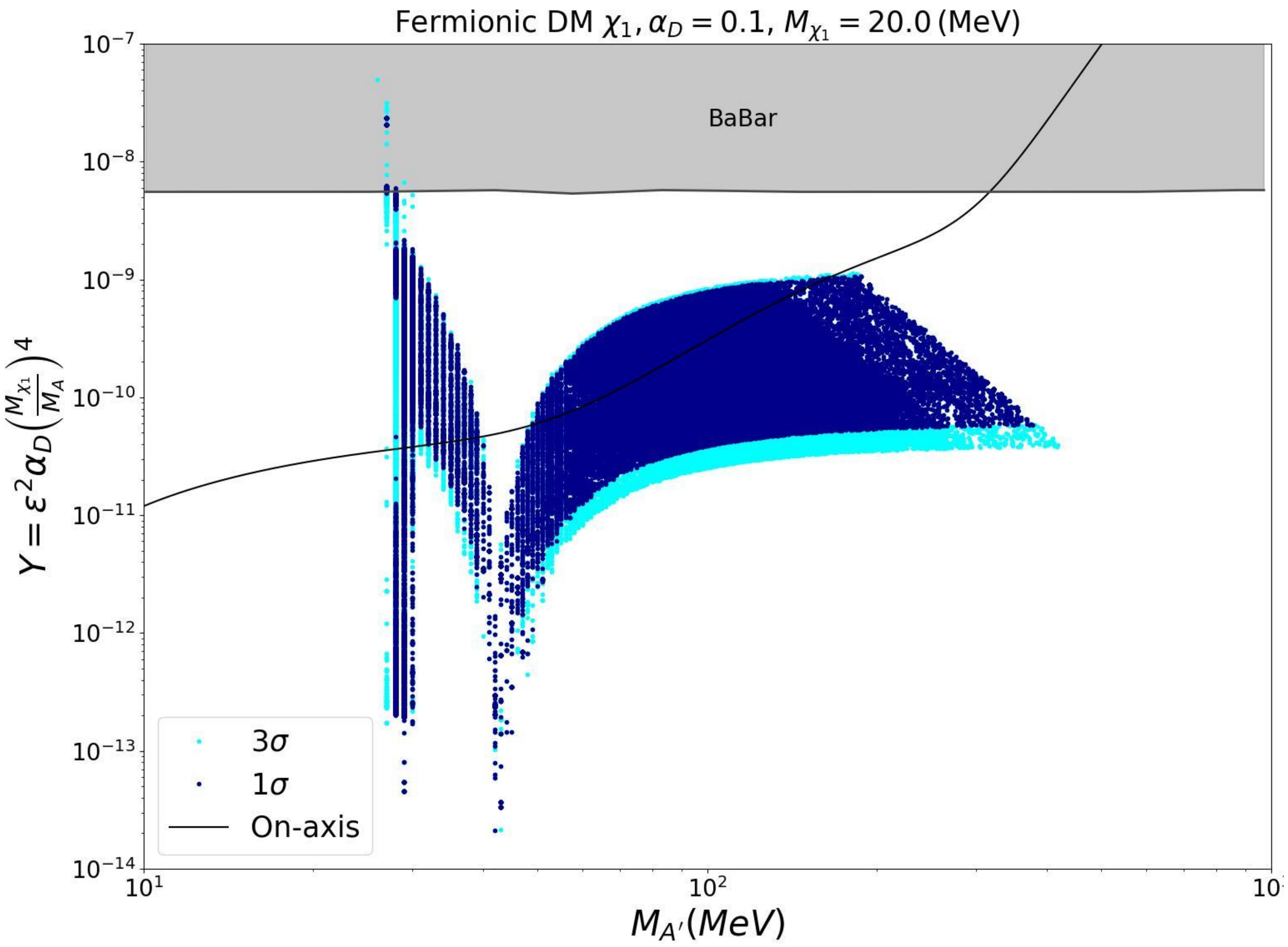
Parameters	Range
$M_{A'}$	$3M_\chi$
$M_{\chi 1}$	$(1 \times 10^1, 1 \times 10^3)$MeV
M_ϕ	$(1.5, 2.5)M_\chi$
y	$(1 \times 10^{-14}, 1 \times 10^{-7})$
θ	1×10^{-4}
$\Delta/M_{\chi 1}$	0.10
α_D	0.5

The Principal Parameters Space in DUNE



When the mass splitting is below twice the electron mass, an interaction between both Majorana fields and the electrons is allowed, generating both fields a scattering signal.

Parameter Space for the Dark Photon



It is also possible to study a mass region for the dark photon, where the points satisfy the matter abundance and can also be constrained through the DUNE experiment, without the need to consider the Off-axis system.

Parameters	Range
$M_{A'}$	$(1 \times 10^1, 1 \times 10^3)\text{MeV}$
M_{χ_1}	20MeV
M_ϕ	$(1.5, 2.5)M_\chi$
y	$(1 \times 10^{-14}, 1 \times 10^{-7})$
θ	1×10^{-4}
Δ/M_{χ_1}	0.10
α_D	0.5

Conclusions

Conclusions

- An energy spectrum was obtained through which, despite the similarities between neutrino and dark matter interactions, it is possible to differentiate the number of events for each, enabling the detection of dark matter signals in the DUNE experiment.

- The detailed analysis of the parameter space reveals that the model meets the sensitivity limits of the DUNE experiment, suggesting the possibility of experimental validation or the imposition of additional constraints in this space. However, a broader region of the parameter space remains that could be explored through other experiments operating at similar energy levels.

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Thank you very much

Appendix

Chi-Square Value for Nuisance Parameters

$$\chi^2 = \frac{(N_{DM} - (1+\alpha)N_{SM} - (\alpha+\beta)N_{BKG})^2}{N_{DM}} + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2$$