Inelastic Dark Matter searches at ProtoDUNE

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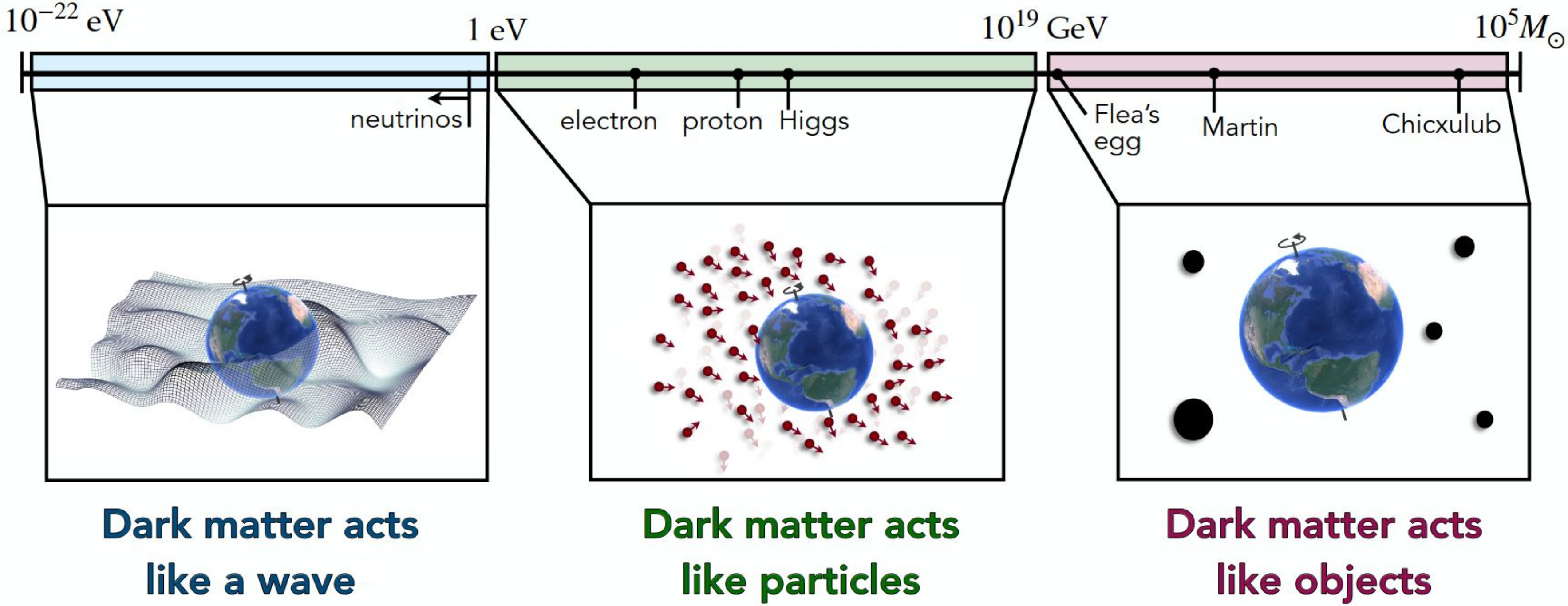
WIP, in collaboration with *P. Coloma, J. Hernandez-Garcia, J. Lopez-Pavon, S. Urrea*

DESY Theory Workshop 2025, Hamburg

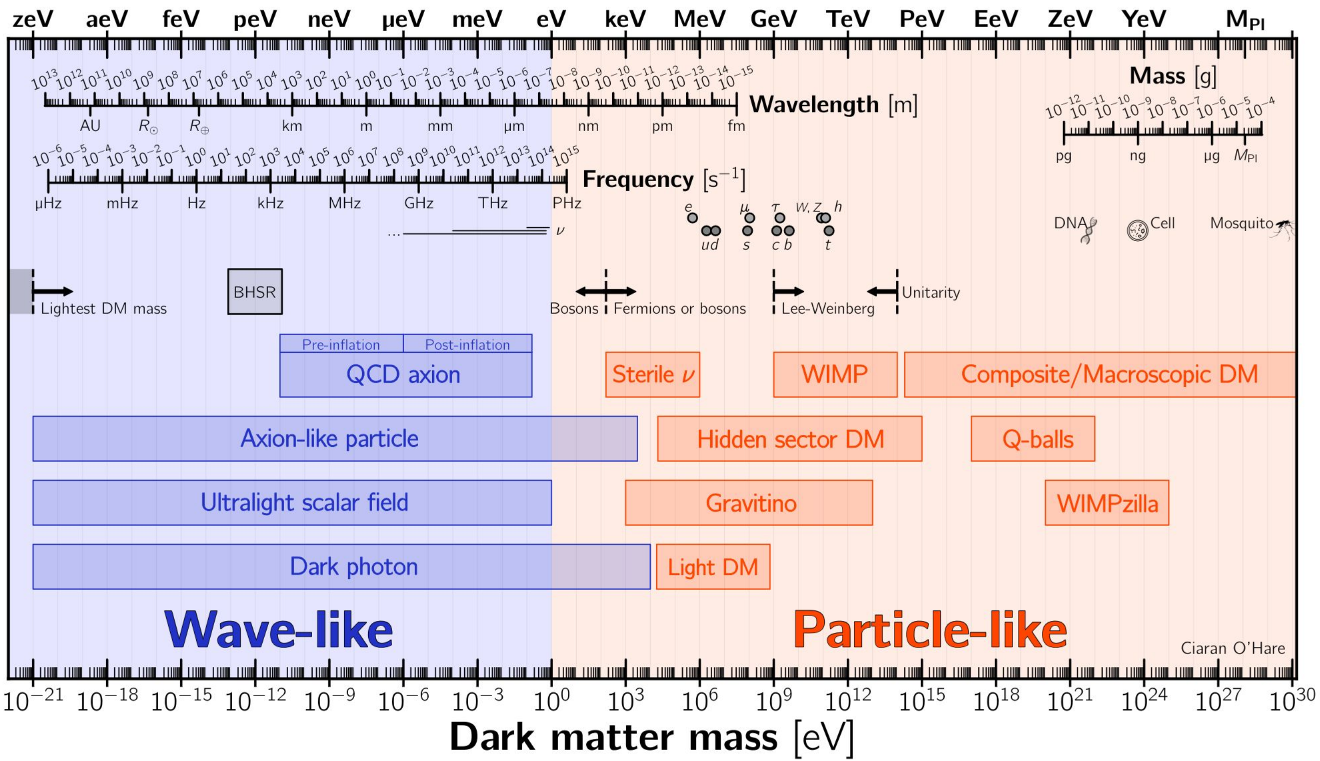
25 September 2025

Different Dark Matter candidates



Ciaran O'Hare

Different Dark Matter candidates



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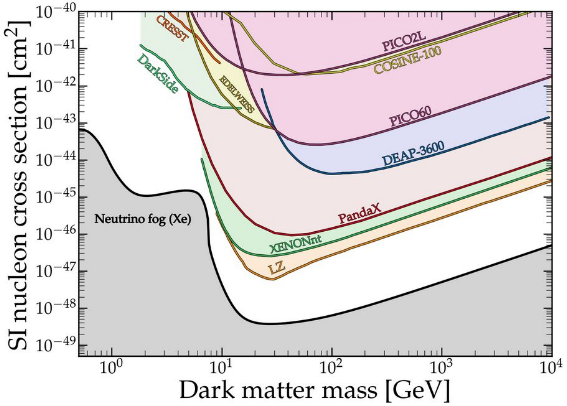
Different Dark Matter candidates

particle dark matter

WIMP *(GeV - TeV)*

not ruled out ***yet***, but stringent constraints.



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Different Dark Matter candidates

particle dark matter

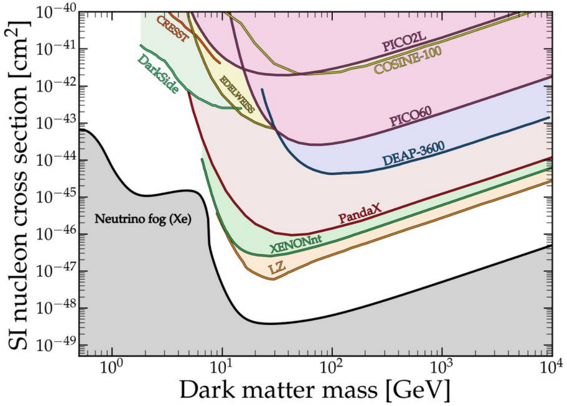
Light Dark Matter *(MeV - GeV)*

In the standard thermal WIMP story, masses <GeV lead to an overabundance of DM **(Hut-Lee-Weinberg bound)**

..but we can circumvent this bound by having e.g. mediators below the weak scale

WIMP *(GeV - TeV)*

not ruled out ***yet***, but stringent constraints.



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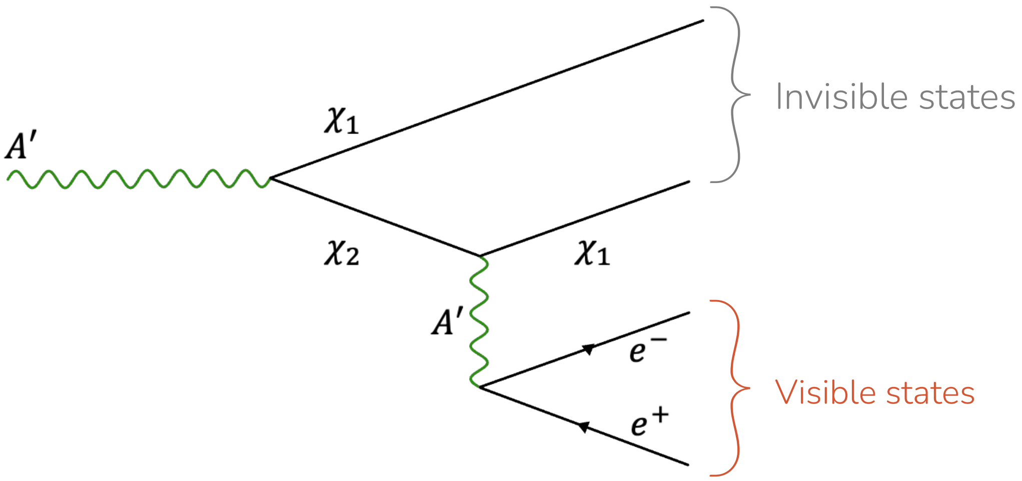
Quick intro on inelastic dark matter



Extend the SM with a dark U(1) and two Majorana states:

$$\mathcal{L}_{kin-mix} = \frac{\varepsilon}{2c_W} X_{\mu\nu} B^{\mu\nu}$$

After diagonalizing the kinetic mixing term:

$$\mathcal{L}_{int} \supset A'_\mu \left(g_{\rm D} \mathcal{J}^\mu_{\rm D} - e\varepsilon \mathcal{J}^\mu_{\rm EM} \right)$$

In the case of the iDM, the dark current takes the form:

$$\mathcal{J}^\mu_{\rm iDM} = \overline{\chi_1} \gamma^\mu \chi_2 + \text{h.c.}$$

→ *Purely off-diagonal*

ProtoDUNE experimental setup

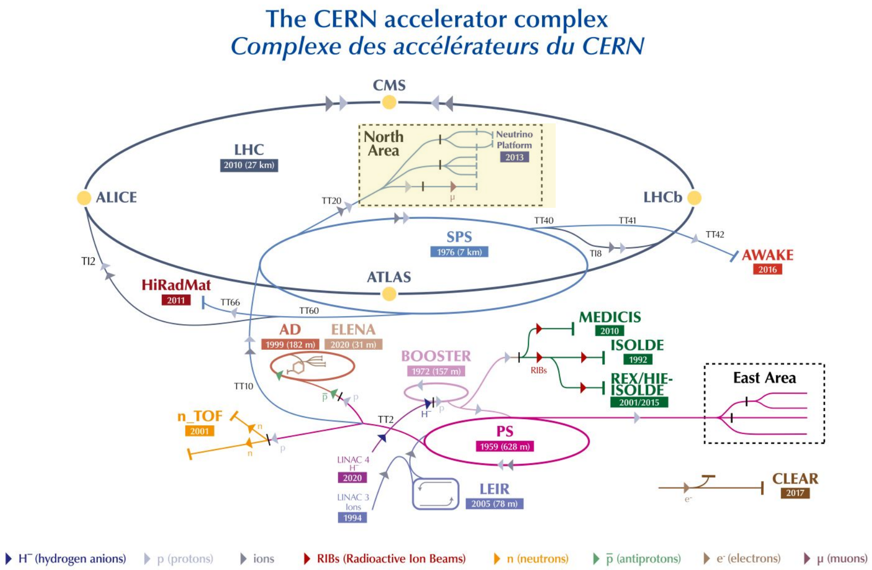


Fig.1 in 2203.09202

ProtoDUNE experimental setup

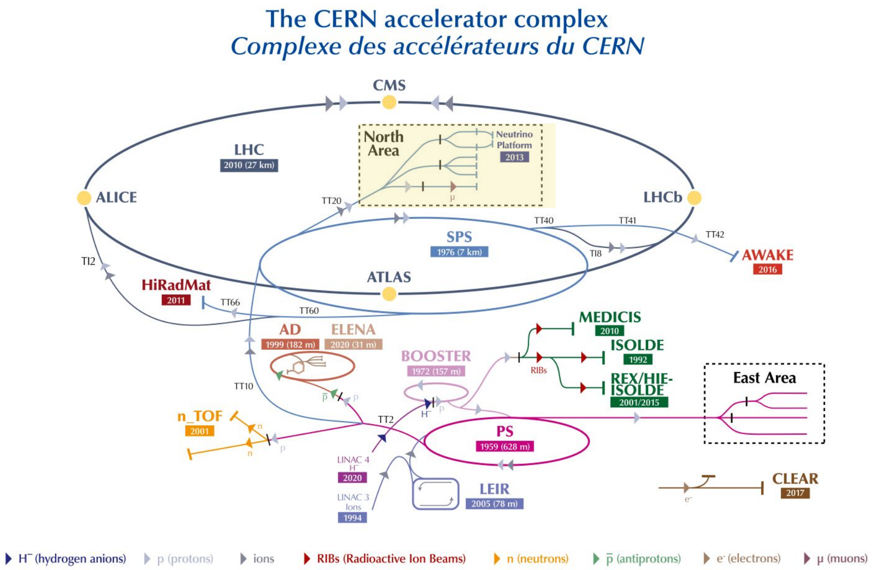
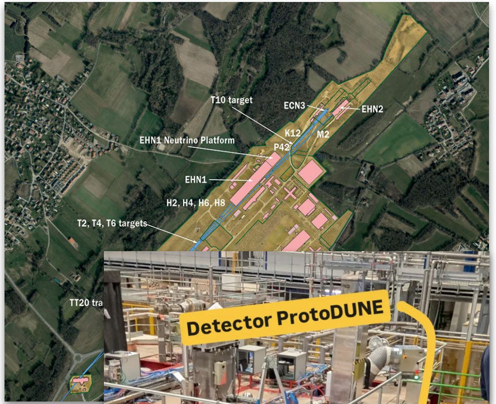
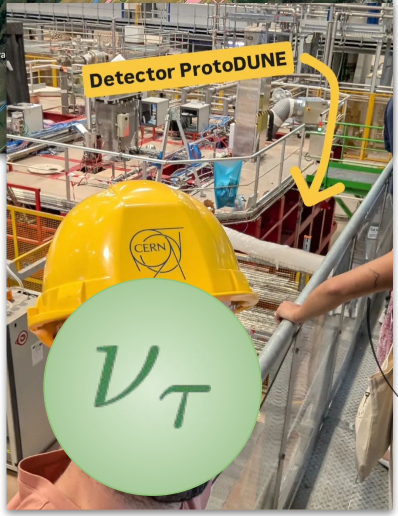


Fig.1 in 2203.09202

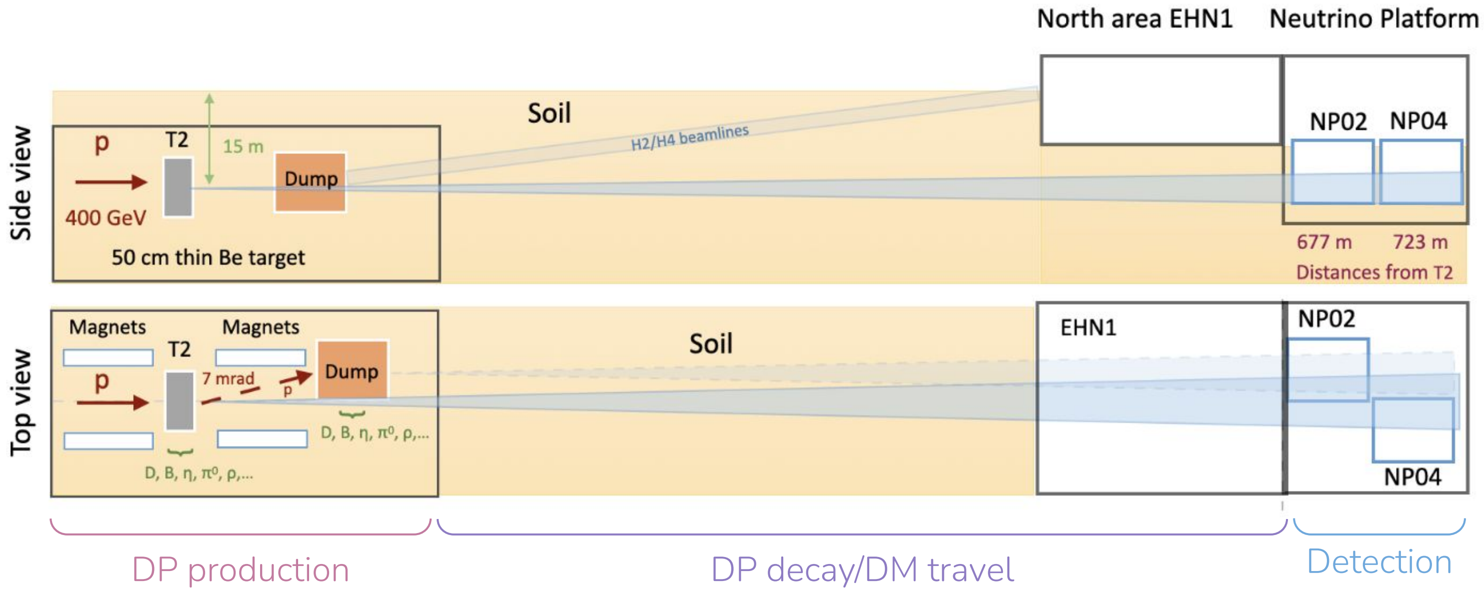




I have proof that's me

ProtoDUNE experimental setup

P. Coloma, J. López-Pavón, L. Molina-Bueno and S. Urrea, JHEP 01 (2024), 134 doi:10.1007/JHEP01(2024)134



Meson yields (per PoT):

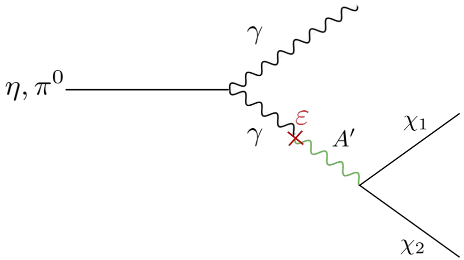
π^0	η	ρ	ω	ϕ	J/ψ	Υ
4.03	0.46	0.54	0.53	0.019	$4.4 \cdot 10^{-5}$	$2.3 \cdot 10^{-8}$

Original proposal:
- ★ HNLs
- ★ Millicharged particles

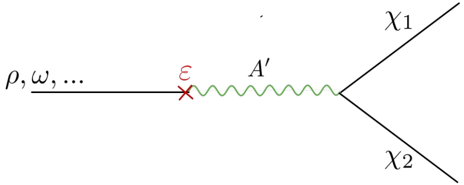
Production and detection @ ProtoDUNE

Production

Pseudoscalar mesons

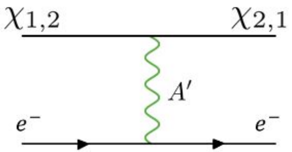


Vector mesons

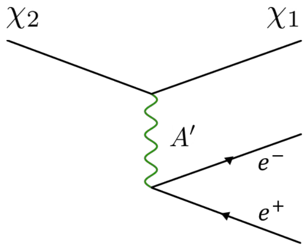


Detection

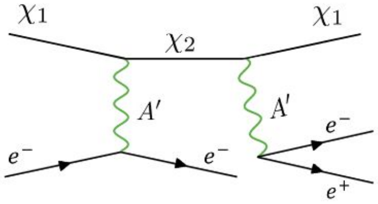
Scattering inside the detector



Decay of the heavier state

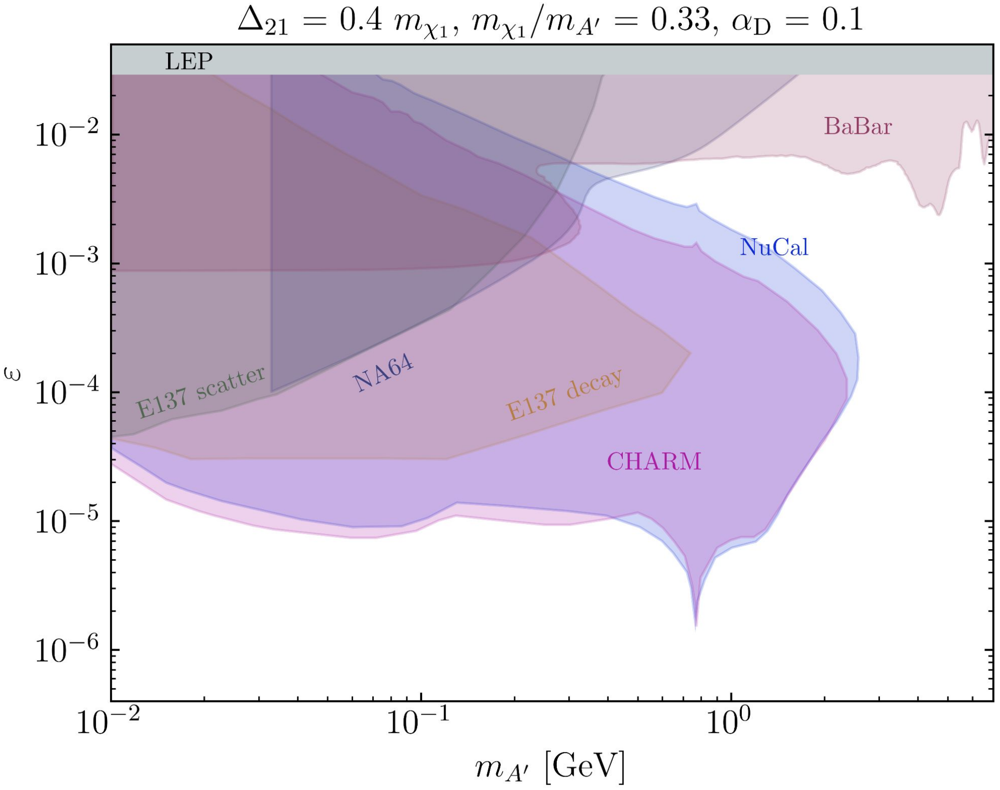


Scattering + decay (double bang)



Bounds on dark photon in the iDM model

Bounds from M. Mongillo et al., Eur. Phys. J. C 83, 391 (2023)

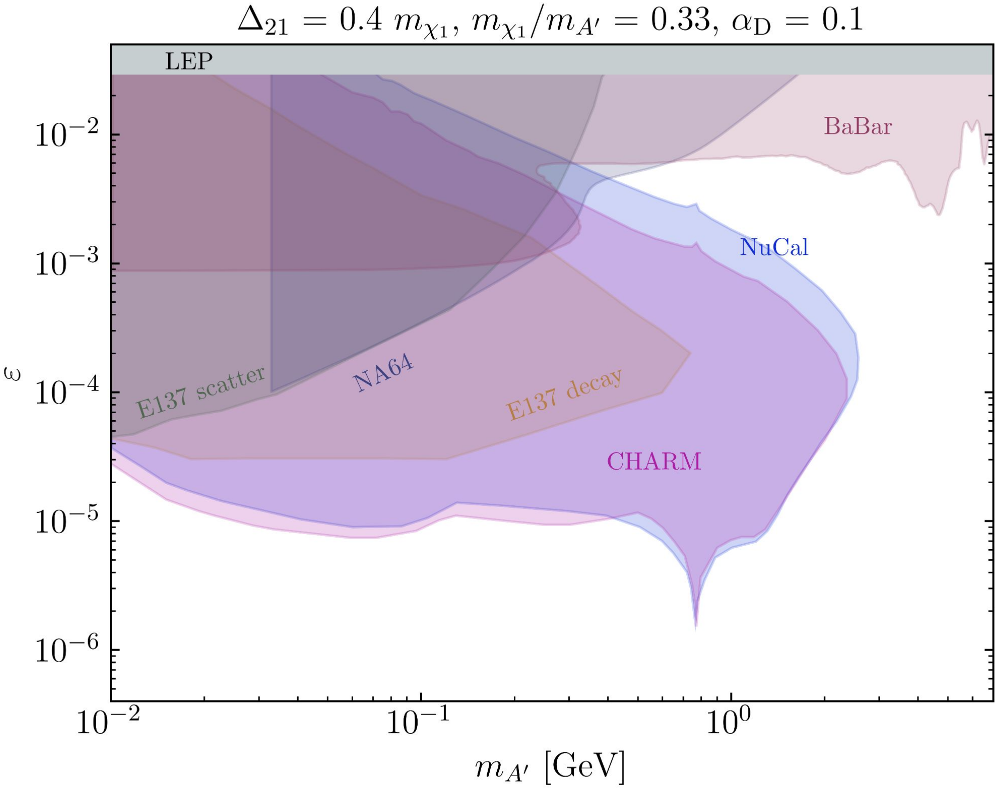


Bounds on dark photon in the iDM model

Bounds from M. Mongillo et al., Eur. Phys. J. C 83, 391 (2023)

Benchmark point considered:

$$r = m_{\chi_1}/m_{A'} = 1/3$$
$$\alpha_D = \frac{g_D^2}{4\pi} = 0.1$$
$$\Delta = \frac{m_{\chi_2} - m_{\chi_1}}{m_{\chi_1}} = 0.4$$



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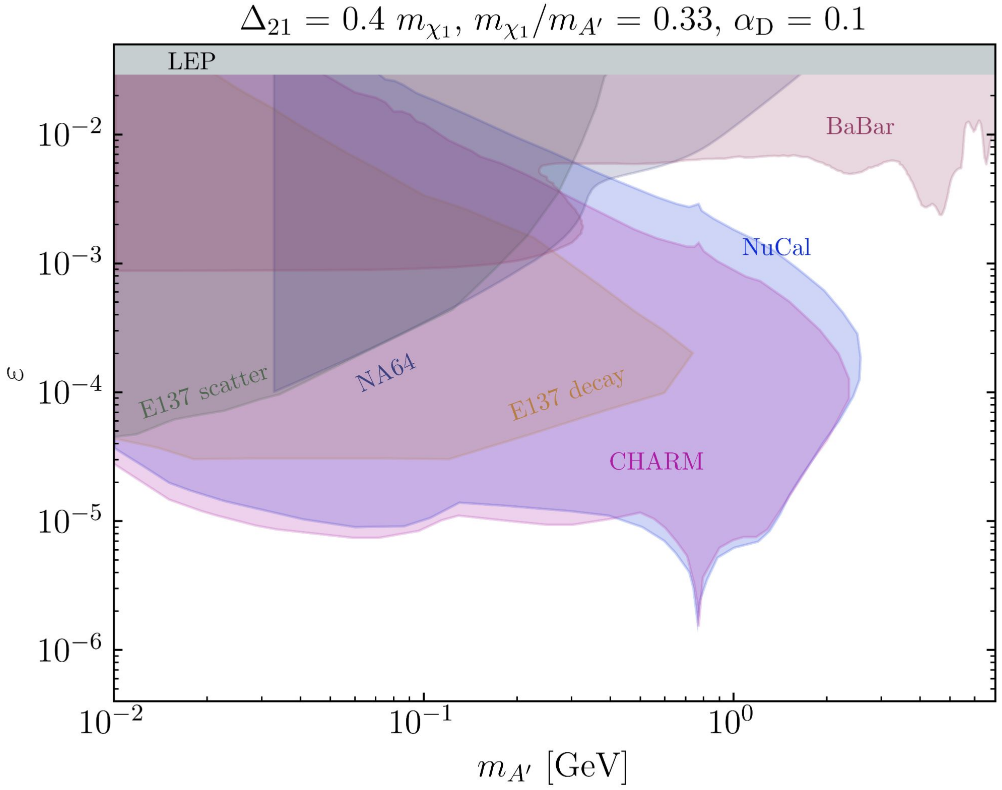
With this choice of parameters:

→ Decay of the dark photon into iDM is always kinematically allowed

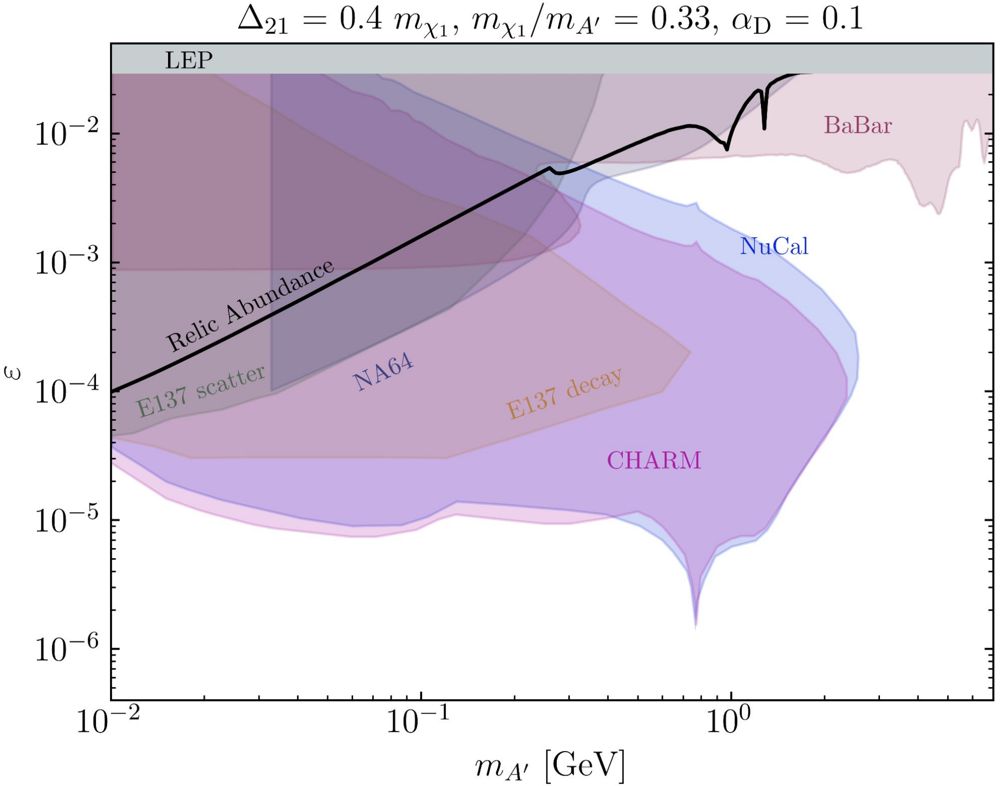
→ The heavier state can only decay through a three-body decay



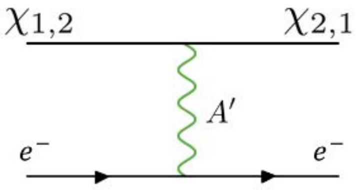
Bounds on dark photon in the iDM model

Bounds from M. Mongillo et al., Eur. Phys. J. C 83, 391 (2023)

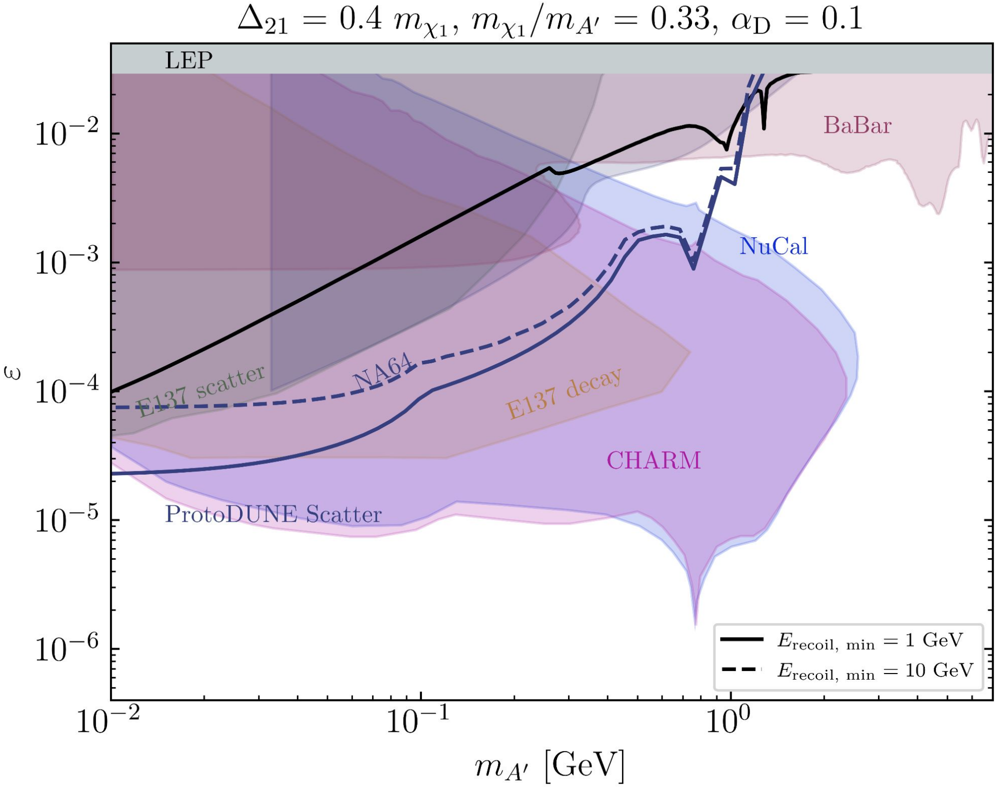
→ If the lighter state is stable, it can constitute dark matter and we have bounds from the relic abundance.



Sensitivity from ProtoDUNE: Scattering



Dark matter reaches the detector, where it scatters with the electrons inside.



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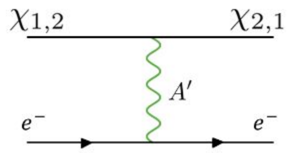


Two limits:

→ Low mass region: $m_{A'}^2 \lesssim 2m_e E_e$

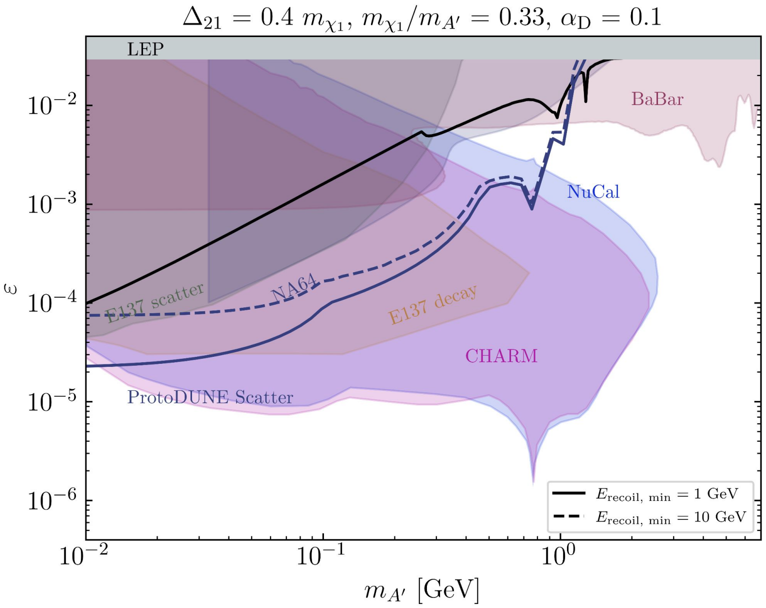
$$\frac{d\sigma}{dE_e} \approx 4\pi\varepsilon^2 \alpha_{EM}\alpha_D \frac{2E_{\chi_1}^2 m_e}{(E_{\chi_1}^2 - m_1^2)(m_{A'}^2 + 2m_e E_e)^2}$$

⋙ $\sigma \propto \frac{1}{E_{\text{recoil, min}}}$

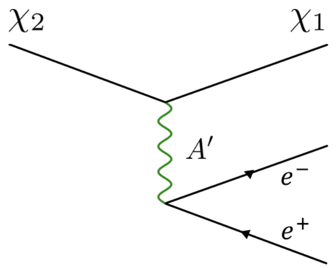
→ High mass region: $m_{A'}^2 \gg 2m_e E_e$

$$\frac{d\sigma}{dE_e} \approx 8\pi\epsilon^2 \alpha_{\text{QED}}\alpha_{\text{D}} \frac{2E_{\chi_1}^2 m_e - E_{\chi_1}(m_2^2 - m_1^2)}{E_{\chi_1}^2 m_{A'}^4}$$

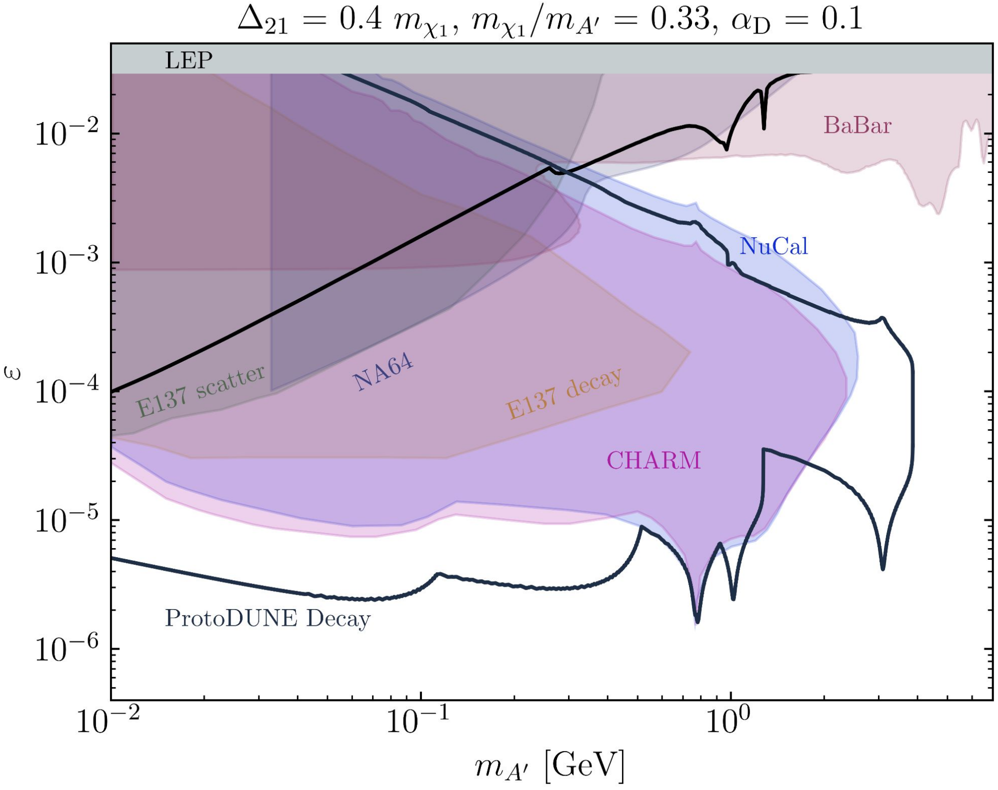
⋙ $\sigma \propto E_{\text{recoil,max}} - E_{\text{recoil,min}} \approx E_{\text{recoil,max}}$



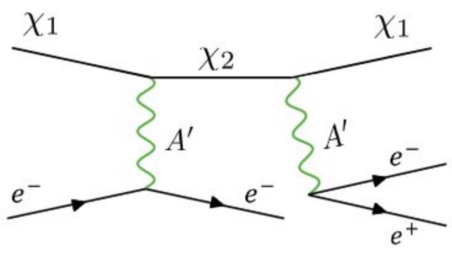
Sensitivity from ProtoDUNE: Decay



- → The **heavier iDM** state **decays** within the detector's fiducial volume.
- → Decay length must fall within a specific range to ensure the decay occurs inside the detector

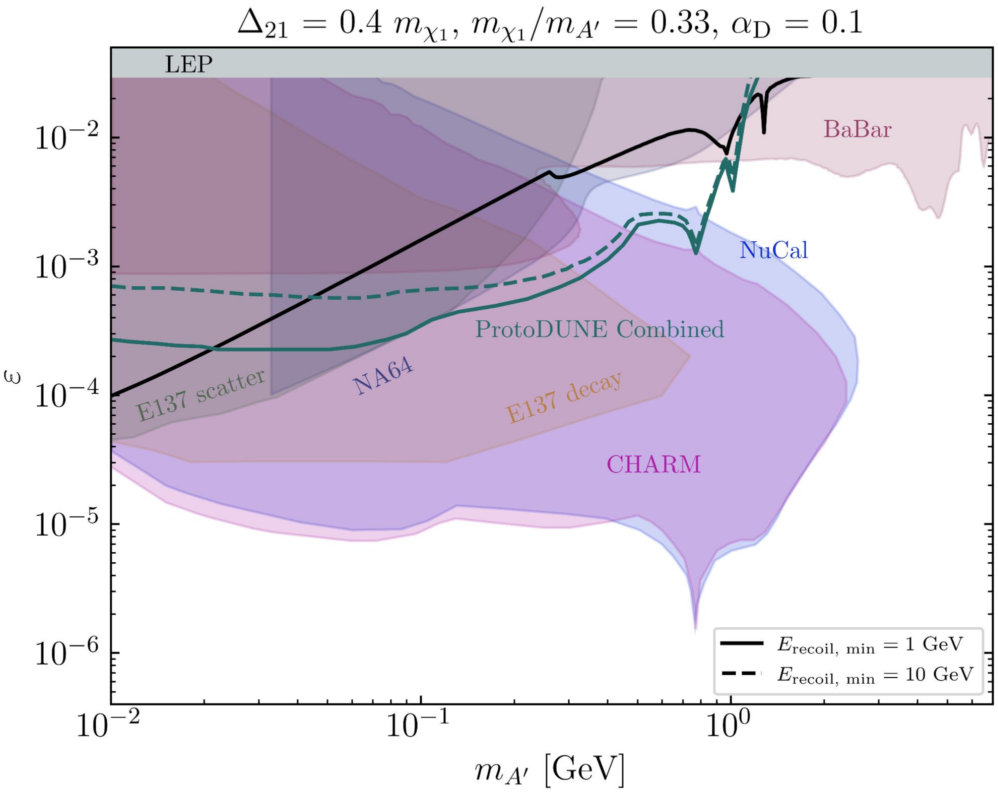


Sensitivity from ProtoDUNE: Combined signal



→ Lighter DM state up-scatters inside the detector.

→ Excited state decays *promptly*, producing a *double-bang signature*.



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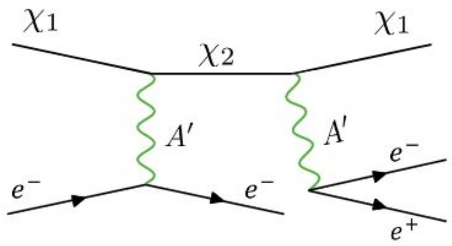
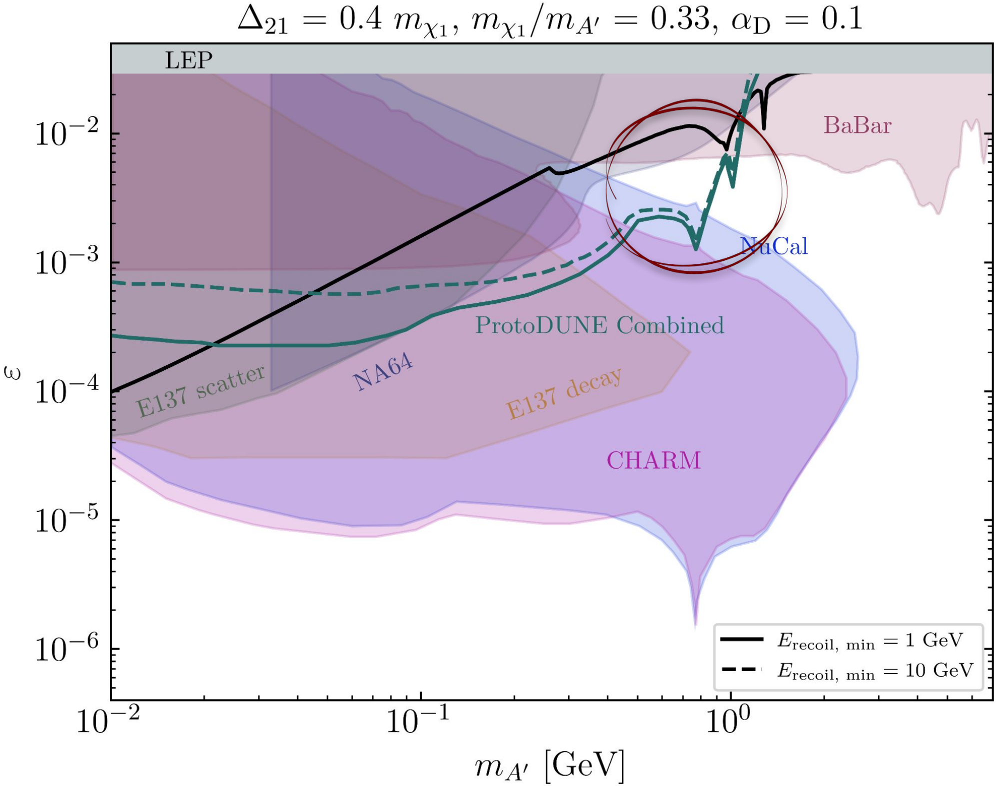




→ Lighter DM state up-scatters inside the detector.

→ Excited state decays *promptly*, producing a *double-bang signature*.

→ Probes interesting parameter space (already accessible via scattering) — **but here with no background**!

Summary and outlook

ProtoDUNE + SPS beam offer a unique setup

- Excellent imaging capabilities make it well-suited for DM particle searches

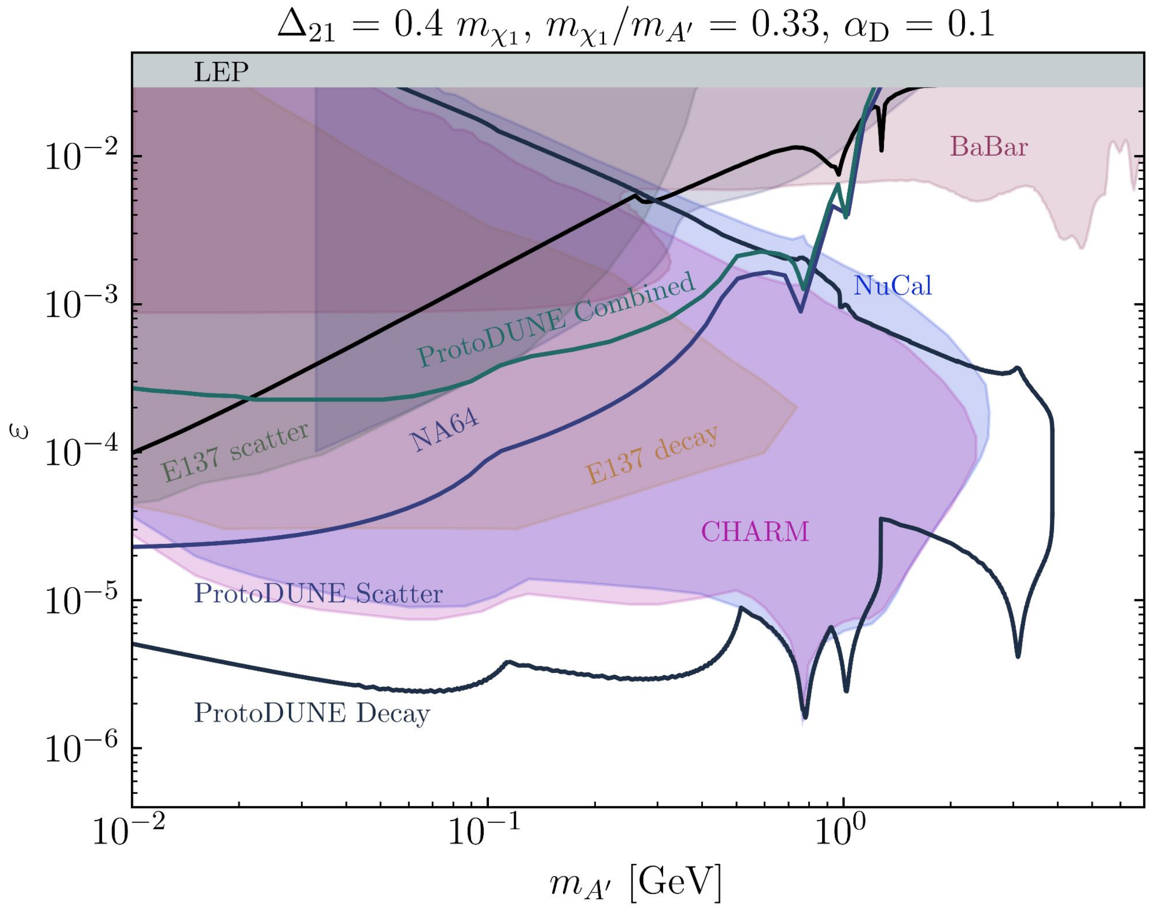
Three targeted experimental signatures for iDM

- Scattering inside the detector
- Decay inside the detector
- Scattering followed by decay

Next steps

- Detailed background analysis required to better quantify sensitivity

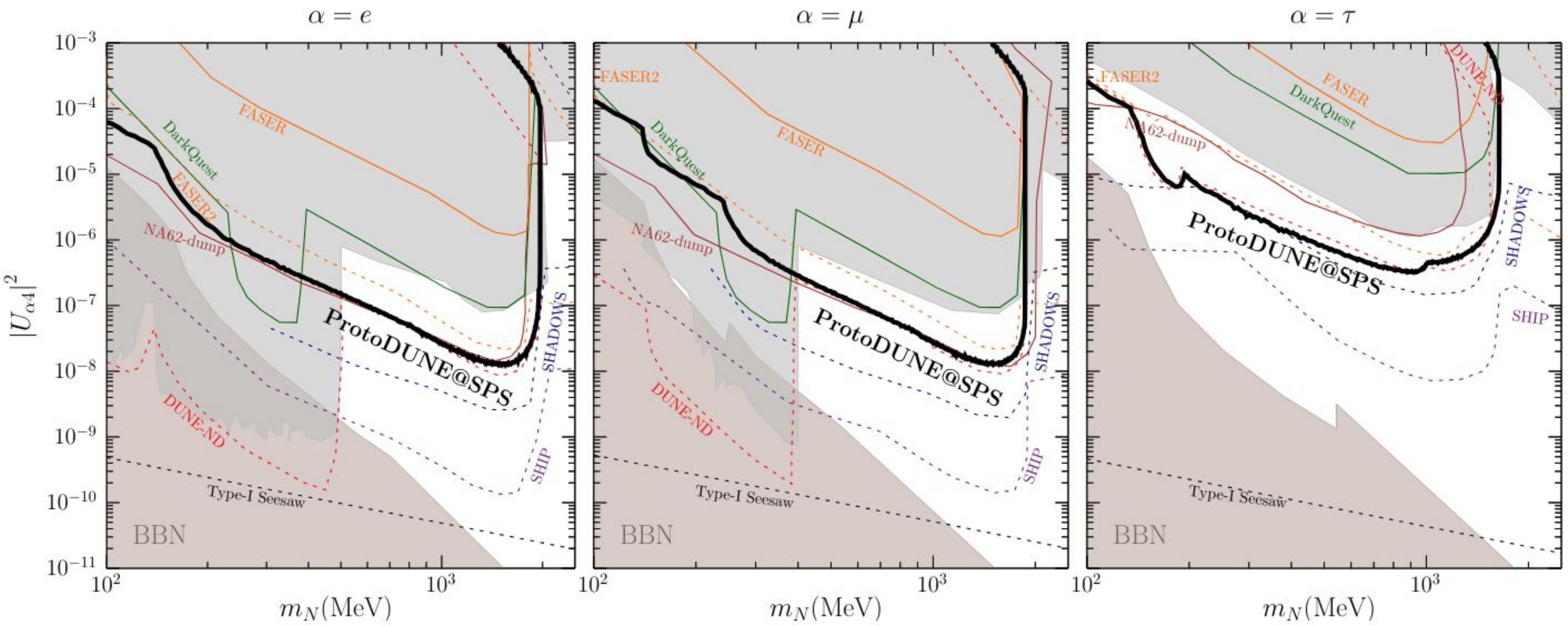
Thank you for your attention!



Backup slides

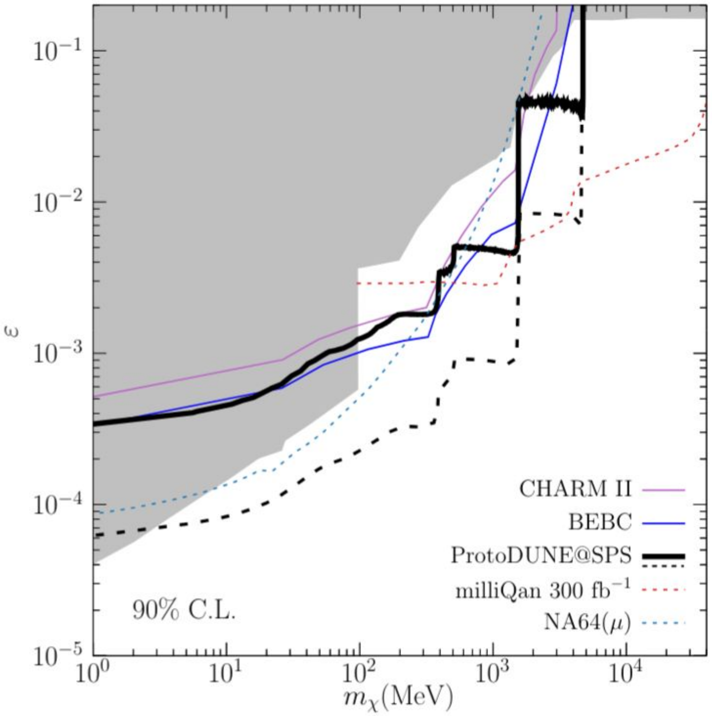
HNLs sensitivity @ProtoDUNE

P. Coloma, J. López-Pavón, L. Molina-Bueno and S. Urrea, JHEP 01 (2024), 134 doi:10.1007/JHEP01(2024)134



Millicharged Particle sensitivity @ProtoDUNE

P. Coloma, J. López-Pavón, L. Molina-Bueno and S. Urrea, JHEP 01 (2024), 134 doi:10.1007/JHEP01(2024)134

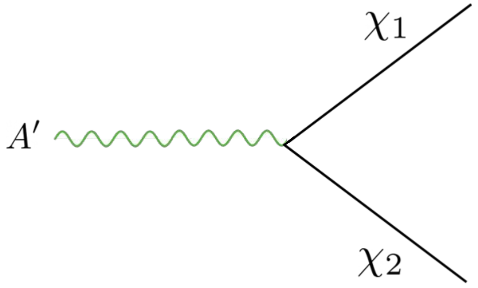


Dark Photon lifetime

For the decay inside ProtoDUNE detectors, we only consider the decay of the heavier iDM particle.

The dark photon for this choice of parameters:

- Too short-lived
- Decay mostly in dark sectors ($\alpha_{\mathrm{D}} \gg \alpha_{\mathrm{EM}}\varepsilon$).



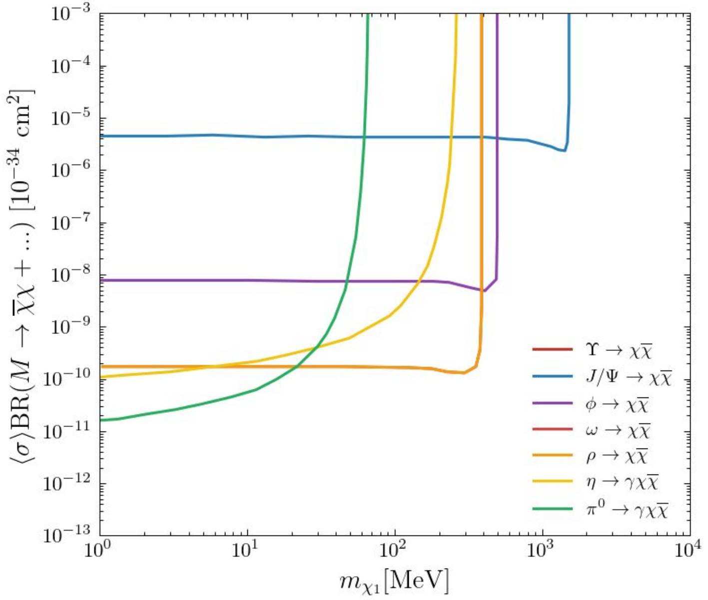
$$c\tau_{A'} \sim 10^{-13}\mathrm{m}\left(\frac{0.1\mathrm{GeV}}{m_{A'}}\right)$$

Protodune sensitivities

P. Coloma, J. López-Pavón, L. Molina-Bueno and S. Urrea, JHEP 01 (2024), 134 doi:10.1007/JHEP01(2024)134

Scattering

$$N_{ev} = \epsilon_{det}\, N_{trg}\, [\langle\sigma\rangle \cdot \mathcal{BR}]\ \mathrm{PS}\,(m_\chi, m_M)\ \frac{\Phi^\chi}{\mathrm{BR}(M \to \chi\bar{\chi}\ldots)}\, N_{\mathrm{PoT}}$$



Credits to S. Urrea

Protodune sensitivities

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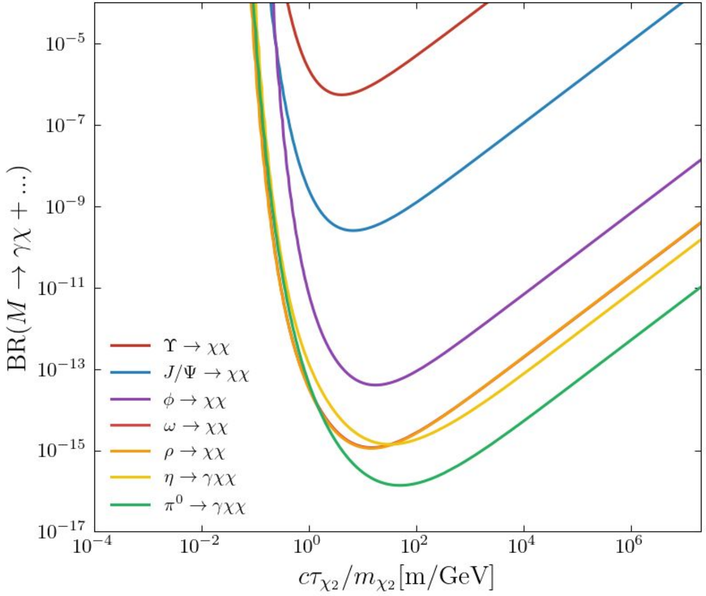
Decay

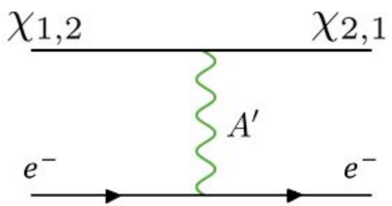
$$N^{M}_{dec} = N_{\rm PoT}\, Y_M\, {\rm BR}(M \to \Psi) \int dS \int dE_\Psi\, \mathcal{P}(c\tau_\Psi/m_\Psi, E_\Psi, \Omega_\Psi)\, \frac{dn^{M\to\Psi}}{dE_\Psi dS}$$



Credits to S. Urrea

Signature at the detector

Scattering



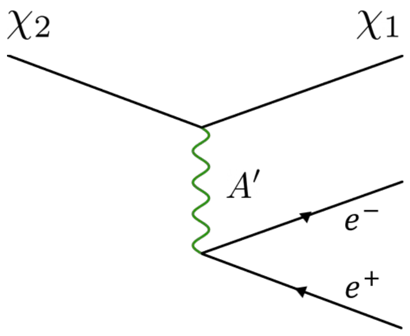
$$\frac{d\sigma}{dE_e} = 4\pi\varepsilon^2\alpha_{EM}\alpha_D \frac{2E_{\chi_1}^2 m_e + g(E_e)/2}{(E_{\chi_1}^2 - m_1^2)(m_{A'}^2 + 2m_e E_e - 2m_e^2)^2}$$

e.g. averaged over the flux from η mesons

$$\langle\sigma\rangle = \frac{1}{\Phi^{\chi_1}}\int_0^\infty dE_{\chi_1}\int_{E_{e,min}}^{E_{e,max}} dE_e \frac{d\sigma}{dE_e}(E_{\chi_1})\frac{d\Phi^{\chi_1}}{dE_{\chi_1}}$$

$$\langle\sigma\rangle \sim 3\cdot 10^{-36}\text{cm}^2\left(\frac{\varepsilon}{10^{-4}}\right)^2\left(\frac{0.1\text{GeV}}{m_{A'}}\right)^2$$

Decay



$$\Gamma(\chi_2 \to \chi_1 e^+ e^-) = K\frac{4\varepsilon^2\alpha_{EM}\alpha_D\Delta^5 m_1^5}{15\pi m_{A'}^4}$$

$$c\tau_{\chi_2} \sim 110\text{m}\left(\frac{10^{-4}}{\varepsilon}\right)^2\left(\frac{0.1\text{GeV}}{m_{A'}}\right)$$