



Inelastic Dark Matter searches at ProtoDUNE

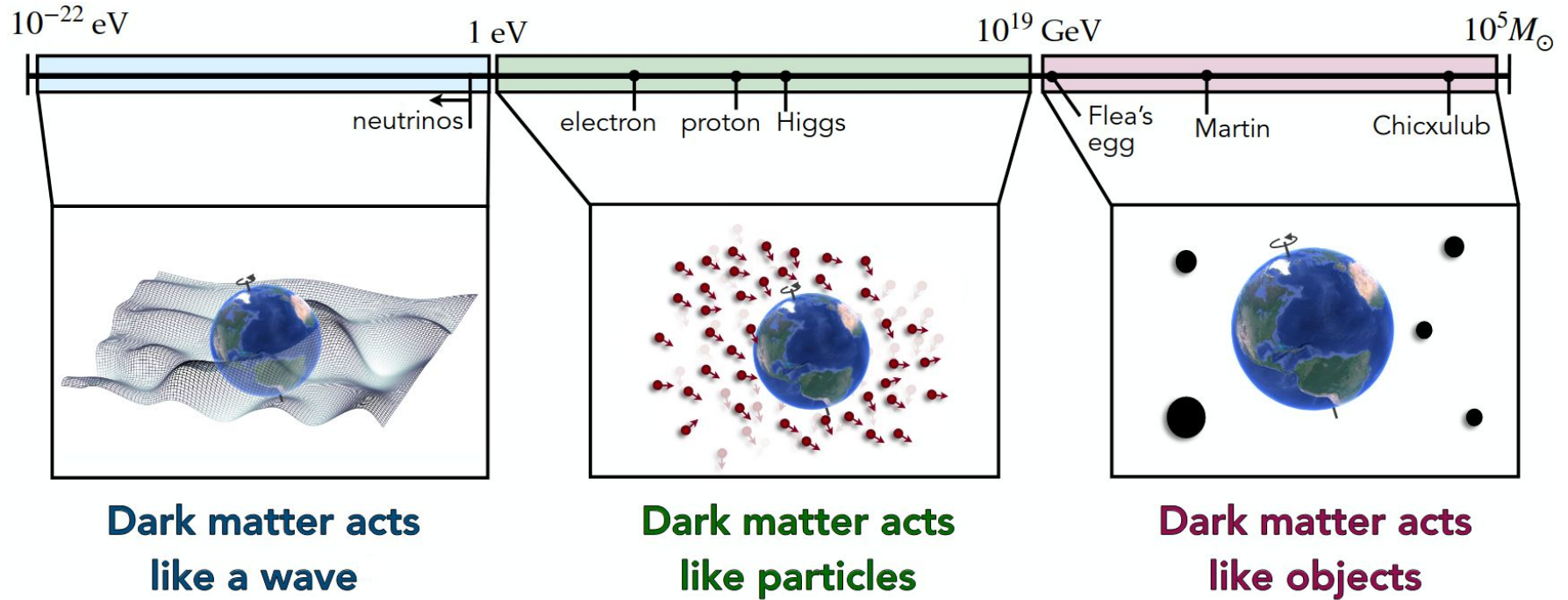
Sara Bianco (sara.bianco@desy.de)

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

Light Dark World 2025, Madrid

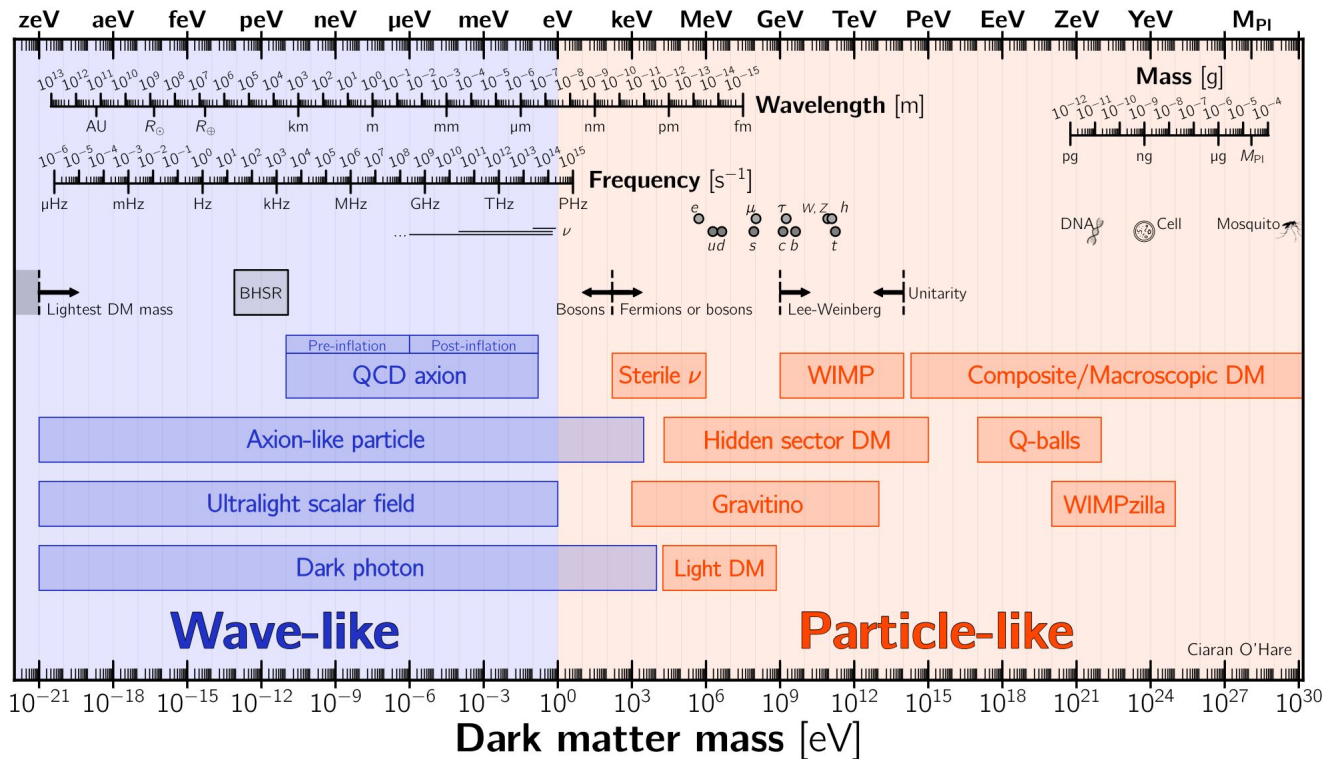
15 September 2025

Different Dark Matter candidates



Ciaran O'Hare

Different Dark Matter candidates



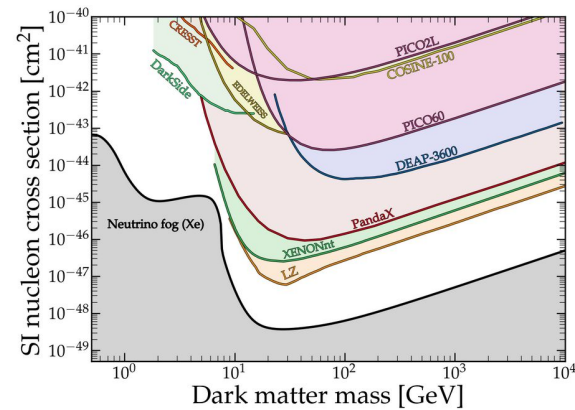
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Different Dark Matter candidates

particle dark matter

WIMP (GeV - TeV)

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



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Different Dark Matter candidates

particle dark matter

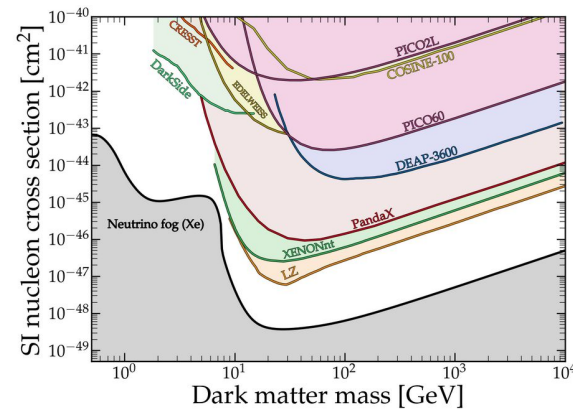
Light Dark Matter ($\text{MeV} - \text{GeV}$)

In the standard thermal WIMP story, masses $< \text{GeV}$ 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

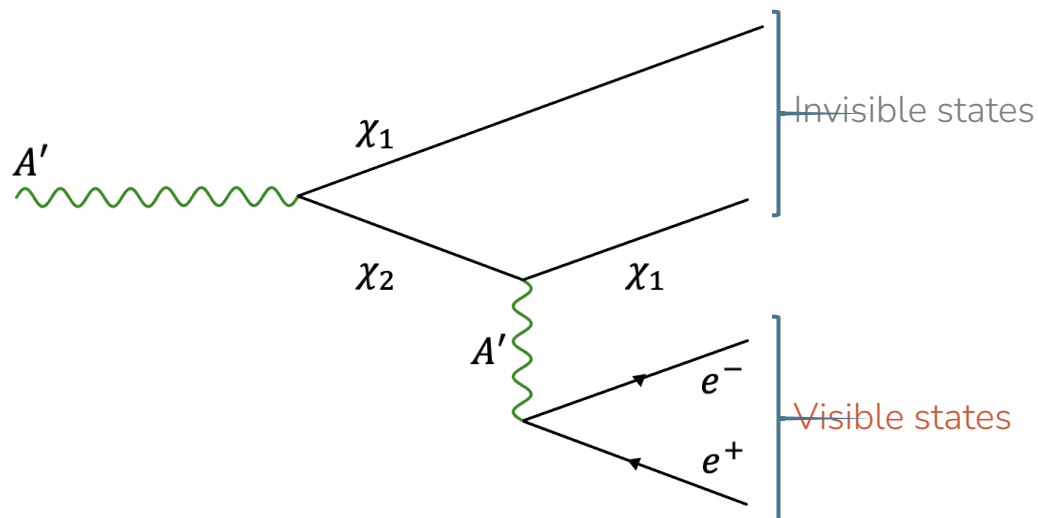
WIMP ($\text{GeV} - \text{TeV}$)

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:

$$\mathcal{L}_{int} \supset A'_\mu (g_D \mathcal{J}_D^\mu - e\varepsilon \mathcal{J}_{EM}^\mu)$$

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

$$\mathcal{J}_{iDM}^\mu = \overline{\chi}_1 \gamma^\mu \chi_2 + \text{h.c.}$$

Purely off-diagonal

ProtoDUNE experimental setup

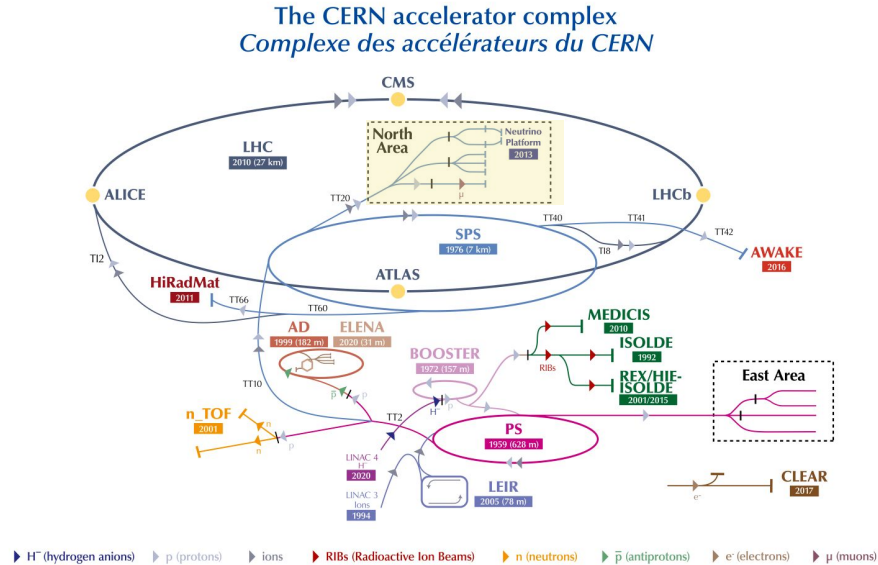


Fig.1 in 2203.09202



ProtoDUNE experimental setup

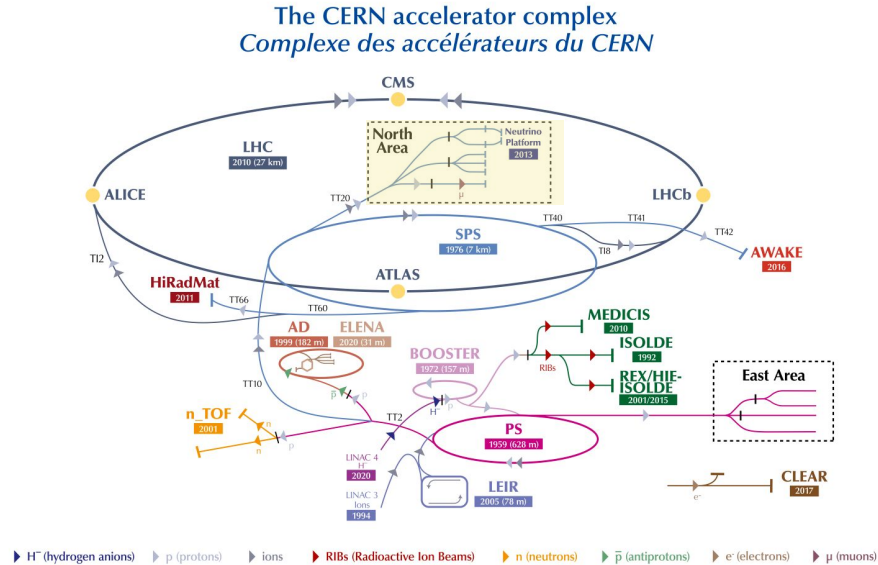
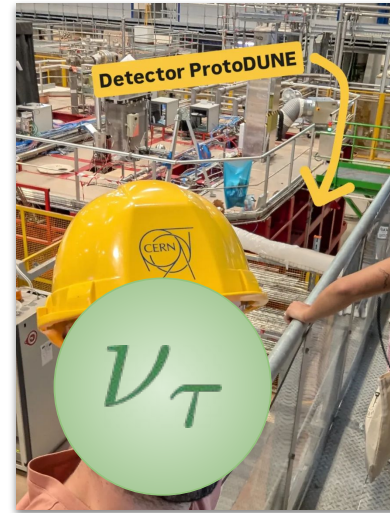


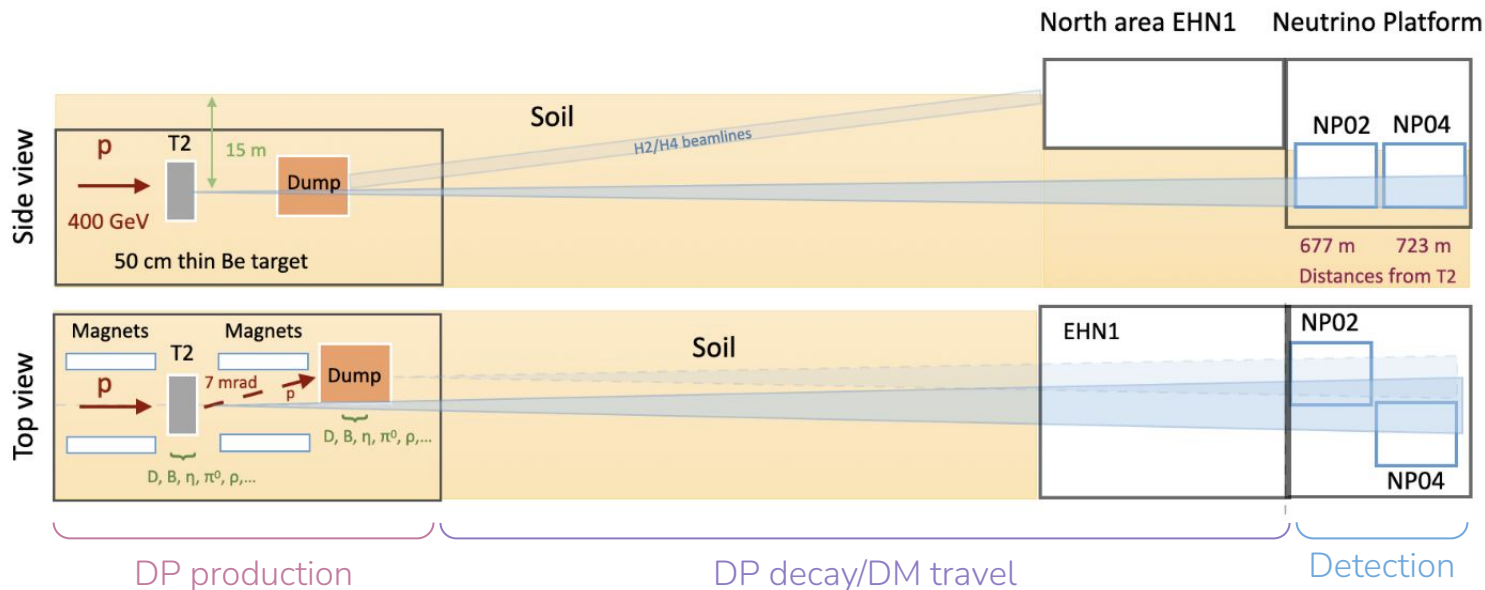
Fig.1 in 2203.09202



\rightarrow 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):

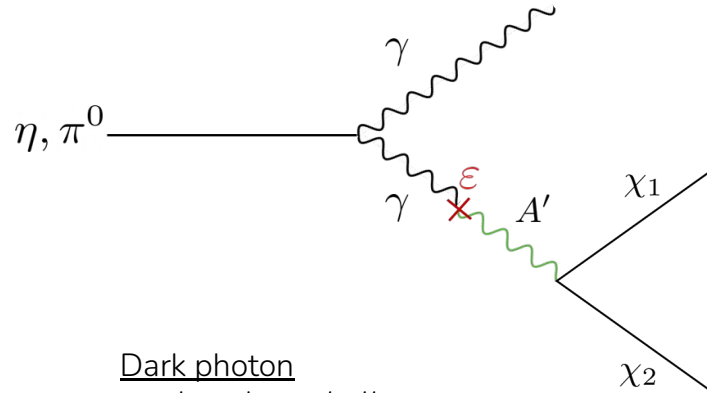
π^0	η	ρ	ω	ϕ	J/ψ	Υ
4.03	0.46	0.54	0.53	0.019	$4.4 \cdot 10^{-5}$	$2.3 \cdot 10^{-8}$

Original proposal:

- ★ HNLs
- ★ Millicharged particles

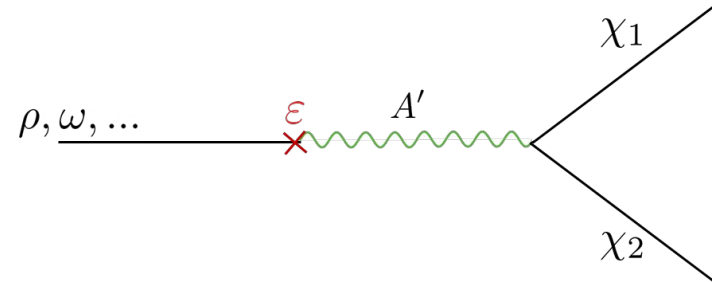
Production from meson decay

Pseudoscalar mesons:



Dark photon
produced on-shell

Vector mesons:

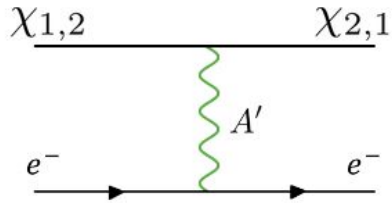


Dark photon
produced off-shell

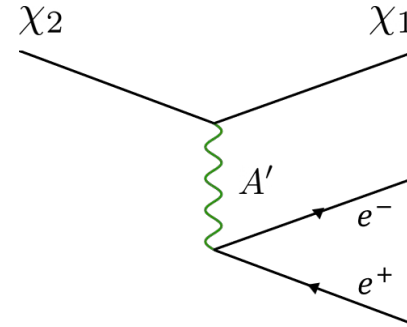
Signature at the detector

We consider three possible signatures:

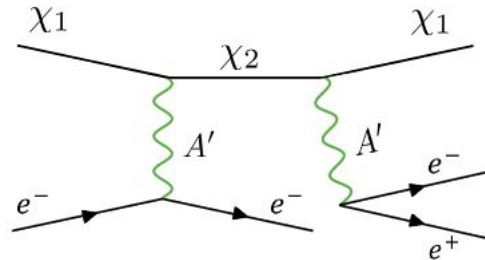
Scattering inside the detector



Decay of the heavier state

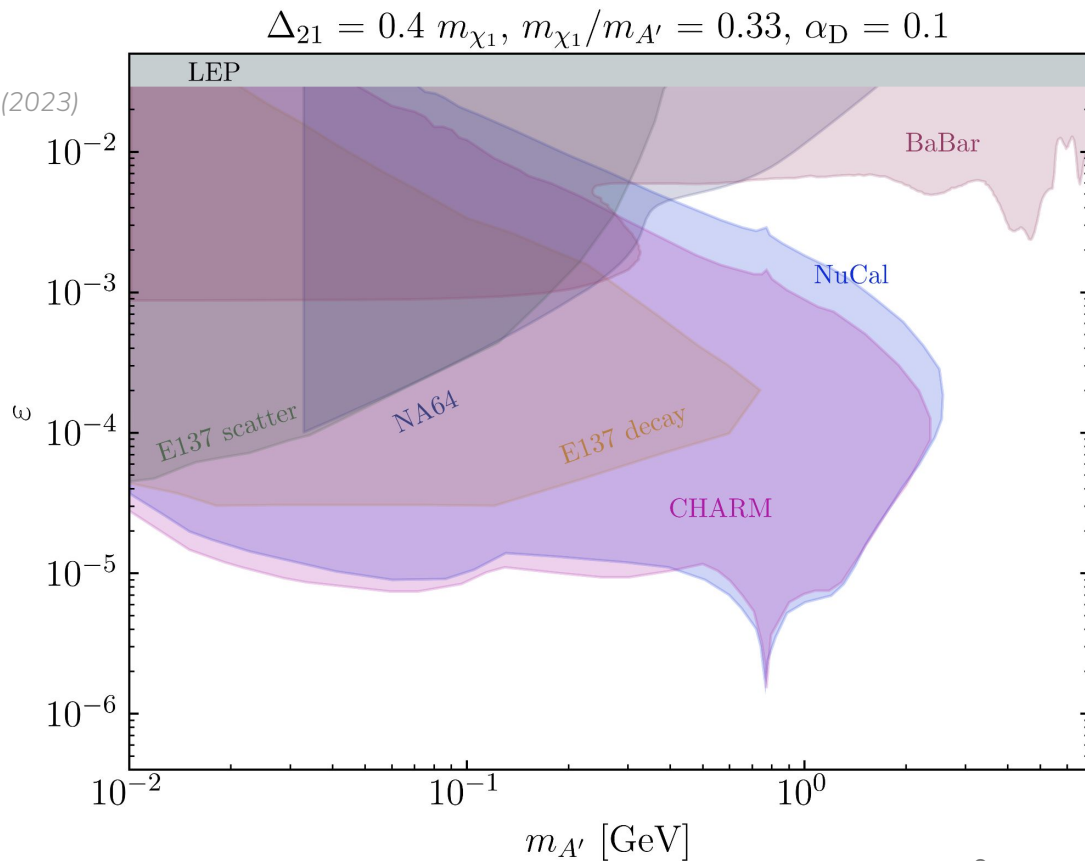


Scattering + decay (double bang)



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

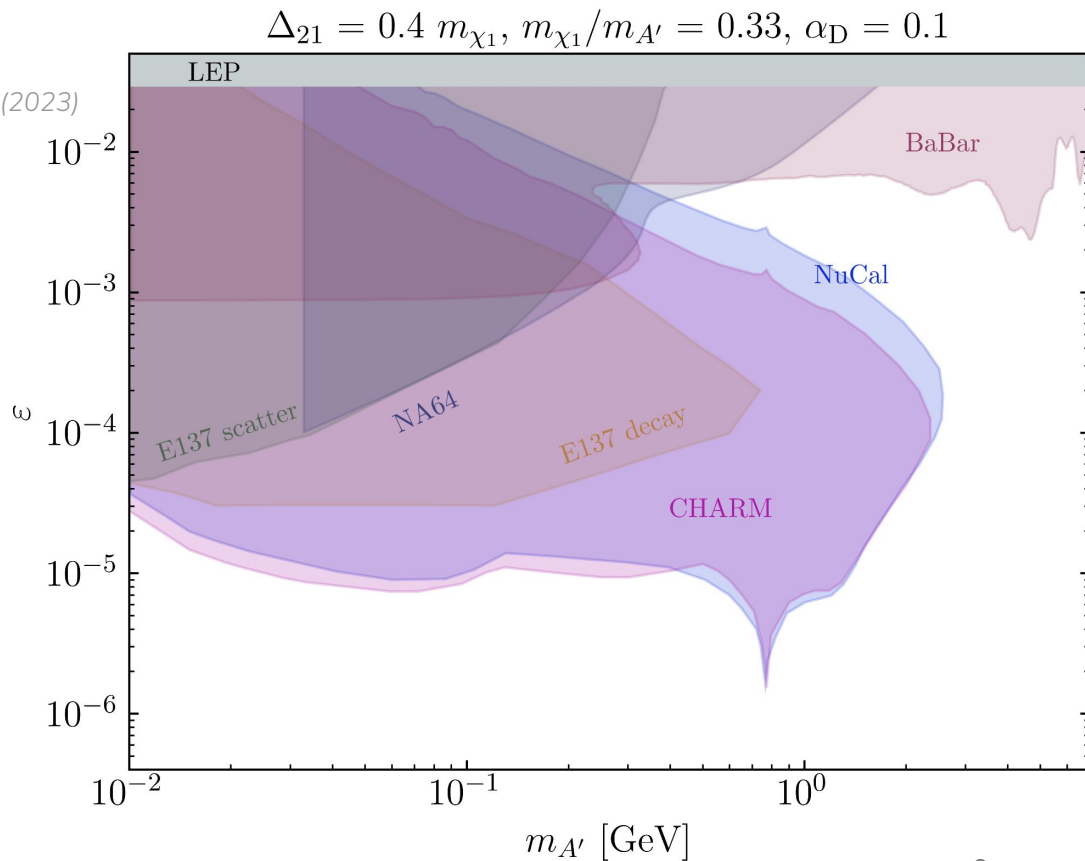
Bounds from M. Mongillo et al., *Eur. Phys. J. C* 83, 391 (2023)

Benchmark point considered:

$$r = m_{\chi_1}/m_{A'} = 1/3$$

$$\alpha_D = \frac{g_D^2}{4\pi} = 0.1$$

$$\Delta = \frac{m_{\chi_2} - m_{\chi_1}}{m_{\chi_1}} = 0.4$$



Bounds on dark photon in the iDM model

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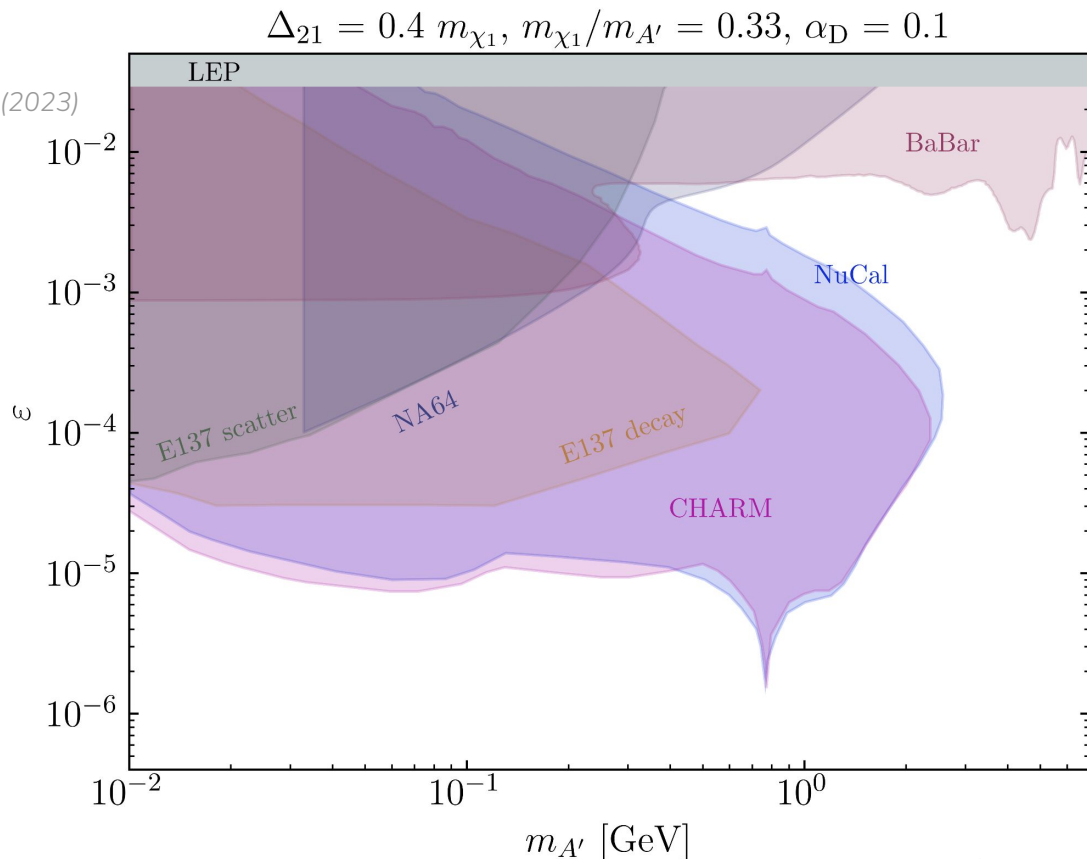
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$$\alpha_D = \frac{g_D^2}{4\pi} = 0.1$$

$$\Delta = \frac{m_{\chi_2} - m_{\chi_1}}{m_{\chi_1}} = 0.4$$

With this choice of parameters:

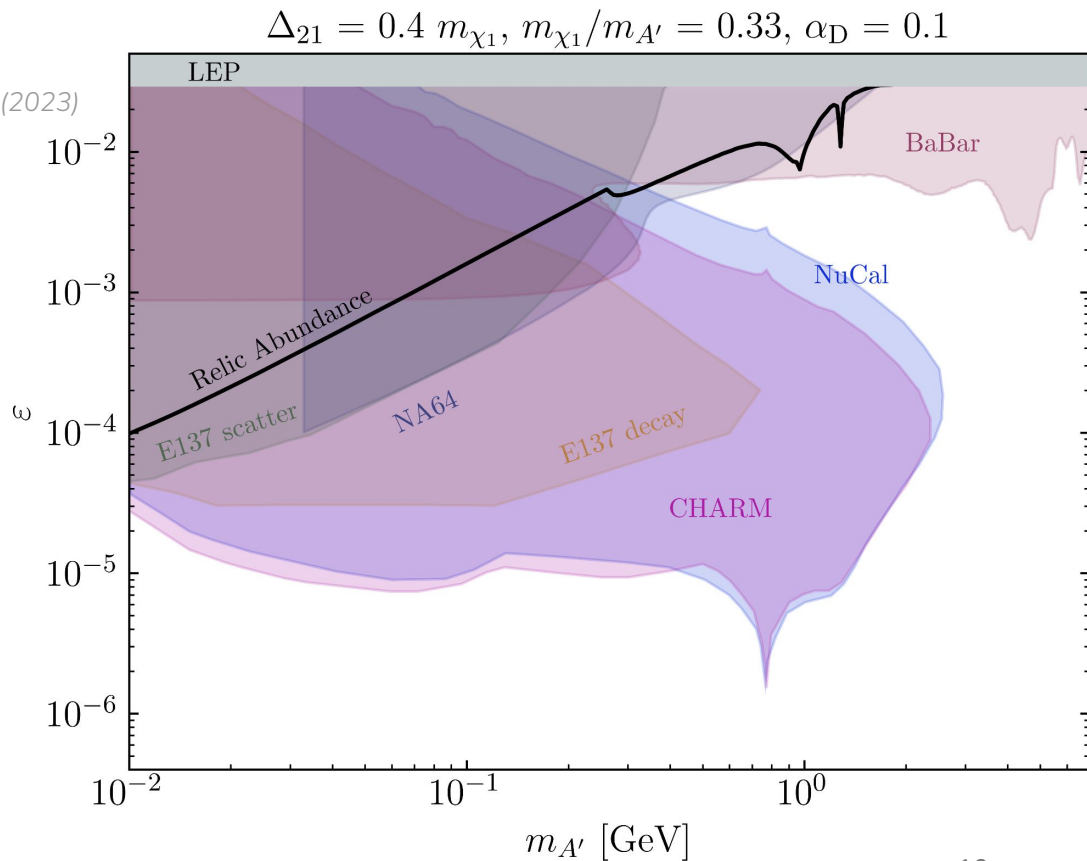
- Decay of the dark photon into iDM is always kinematically allowed
- The heavier state can only decay through a three-body decay



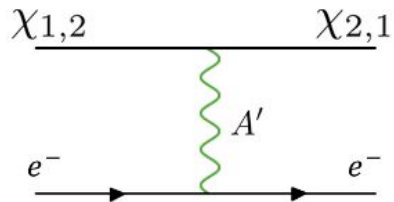
Bounds on dark photon in the iDM model

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

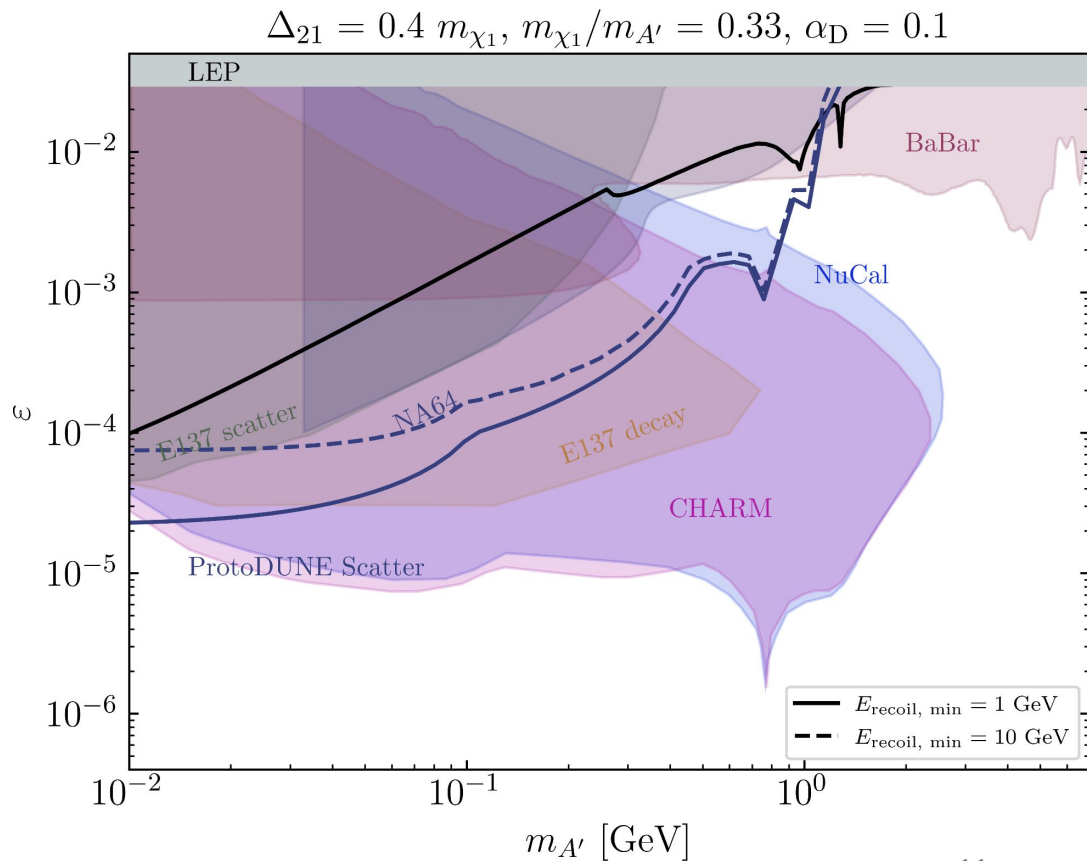
→ If the lighter state is stable, it can constitute dark matter and we have bounds from the relic abundance.



Sensitivity from ProtoDUNE: Scattering



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



Sensitivity from ProtoDUNE: Scattering

Two limits:

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

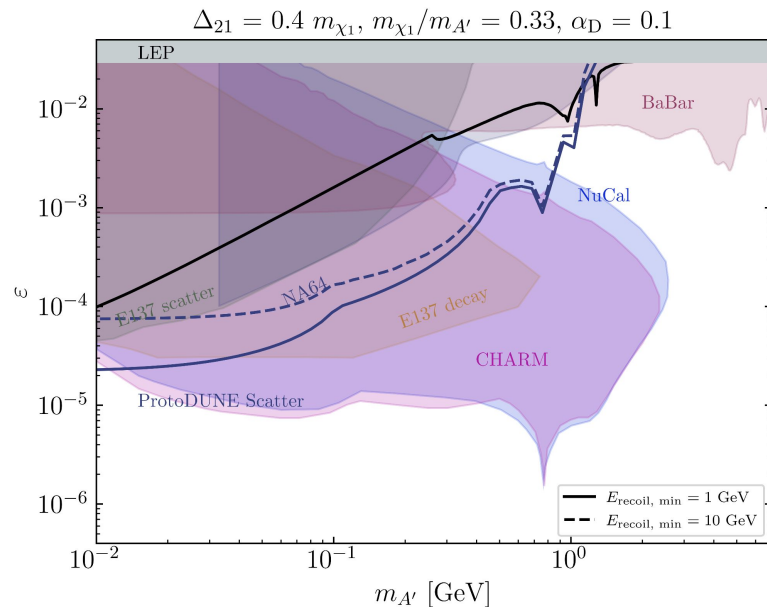
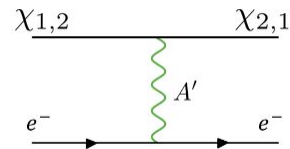
$$\frac{d\sigma}{dE_e} \approx 4\pi\epsilon^2\alpha_{EM}\alpha_D \frac{2E_{\chi_1}^2 m_e}{(E_{\chi_1}^2 - m_1^2)(m_{A'}^2 + 2m_e E_e)^2}$$

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

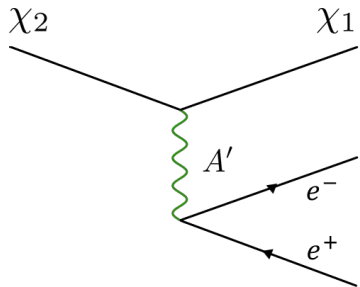
→ High mass region: $m_{A'}^2 \gg 2m_e E_e$

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

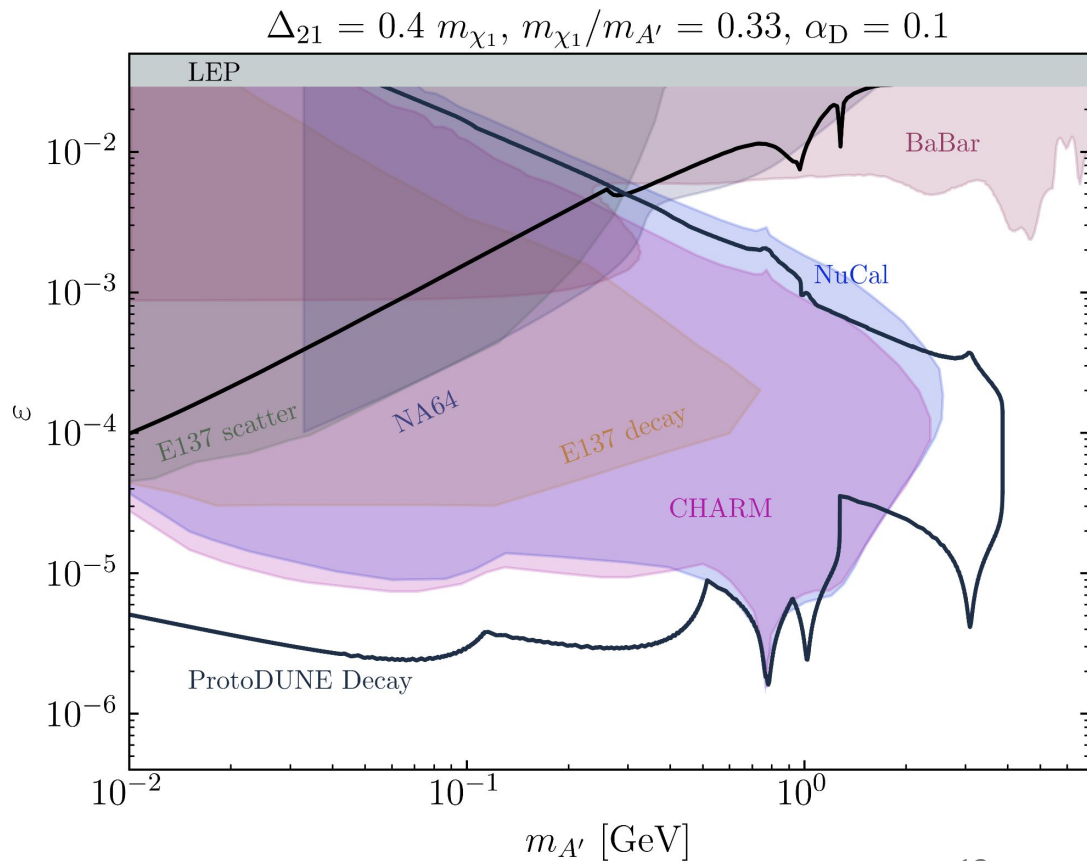
$$\gg \gg \sigma \propto E_{\text{recoil, max}} - E_{\text{recoil, min}} \approx E_{\text{recoil, max}}$$



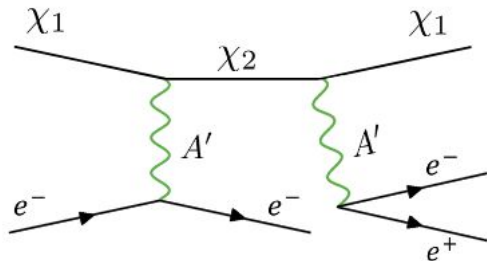
Sensitivity from ProtoDUNE: Decay



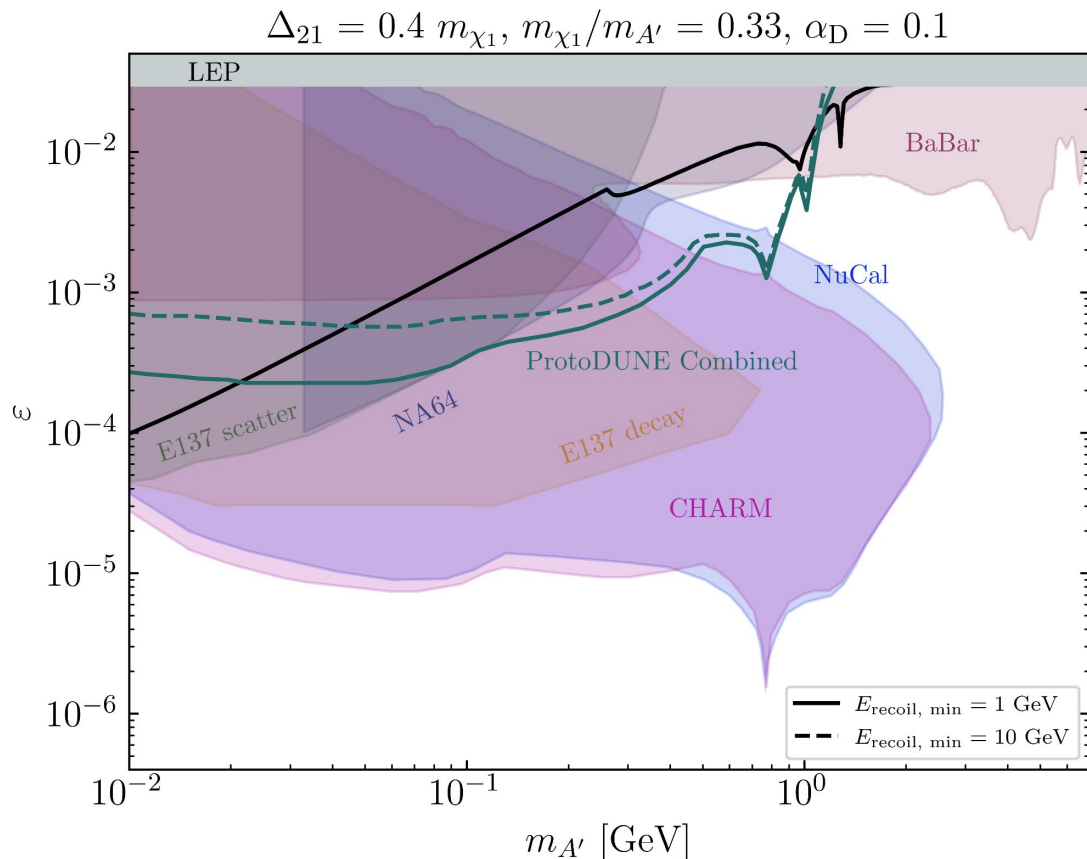
- The **heavier iDM state decays** within the detector's fiducial volume.
- Decay length must fall within a specific range to ensure the decay occurs inside the detector



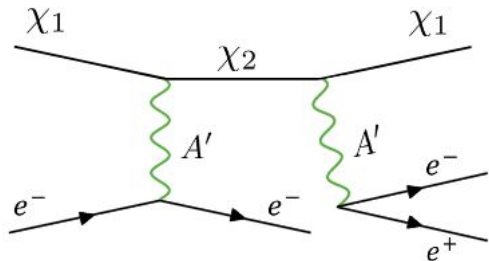
Sensitivity from ProtoDUNE: Combined signal



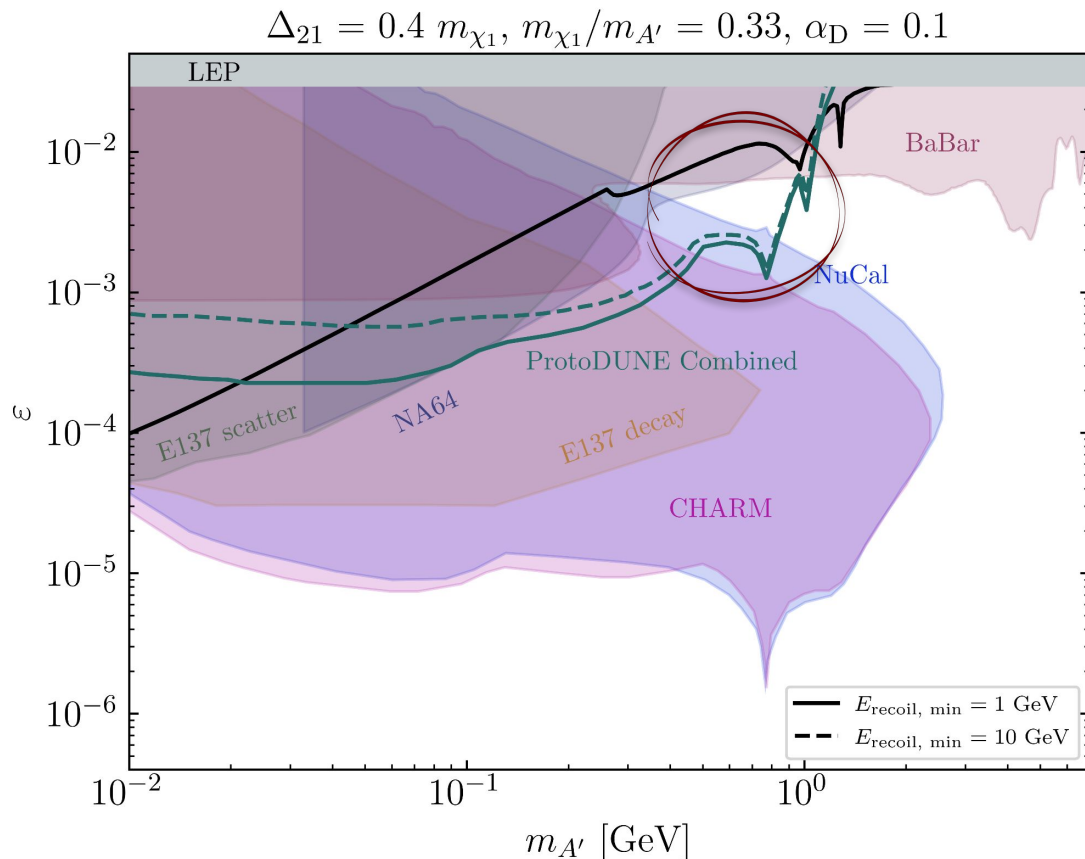
- Lighter DM state up-scatters inside the detector.
- Excited state decays *promptly*, producing a *double-bang signature*.



Sensitivity from ProtoDUNE: Combined signal



- 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

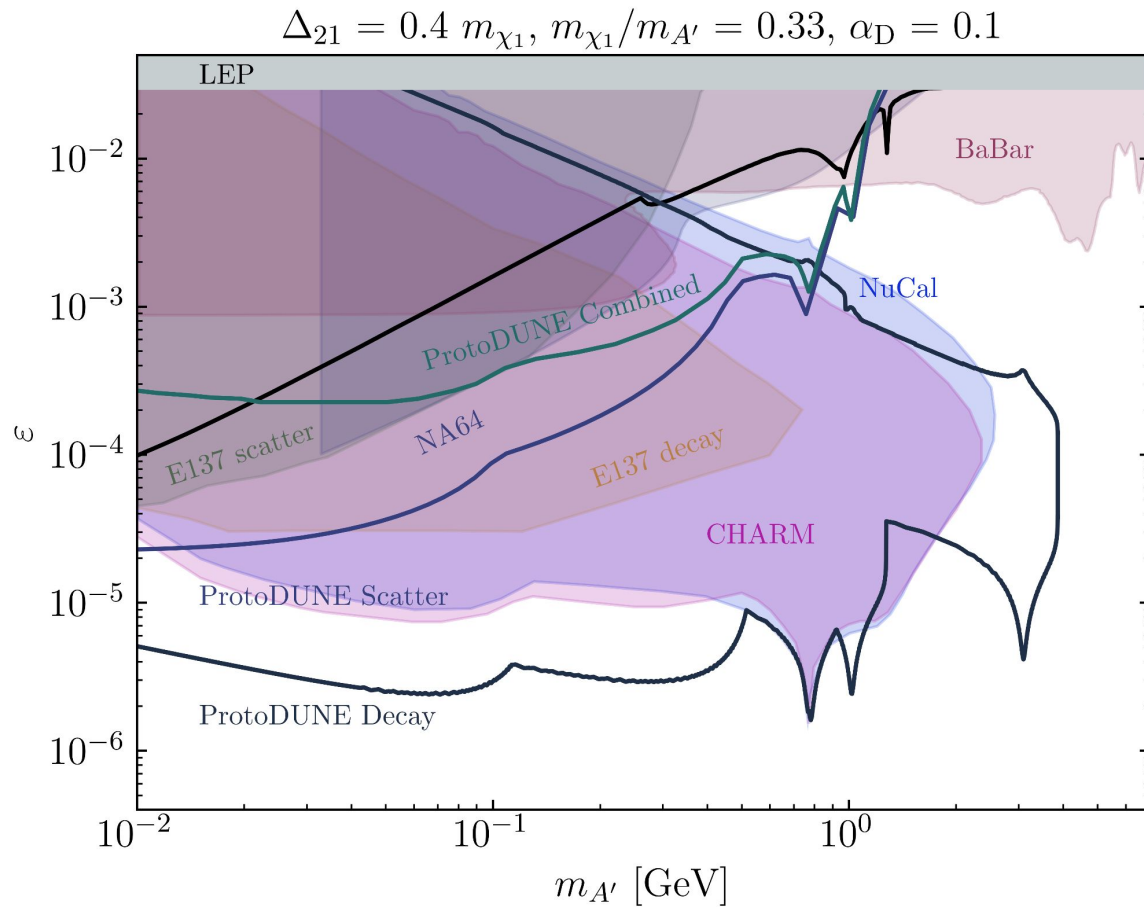
- Scattering inside the detector
- Decay inside the detector
- Scattering followed by decay

Next steps

- Detailed background analysis required to better quantify sensitivity



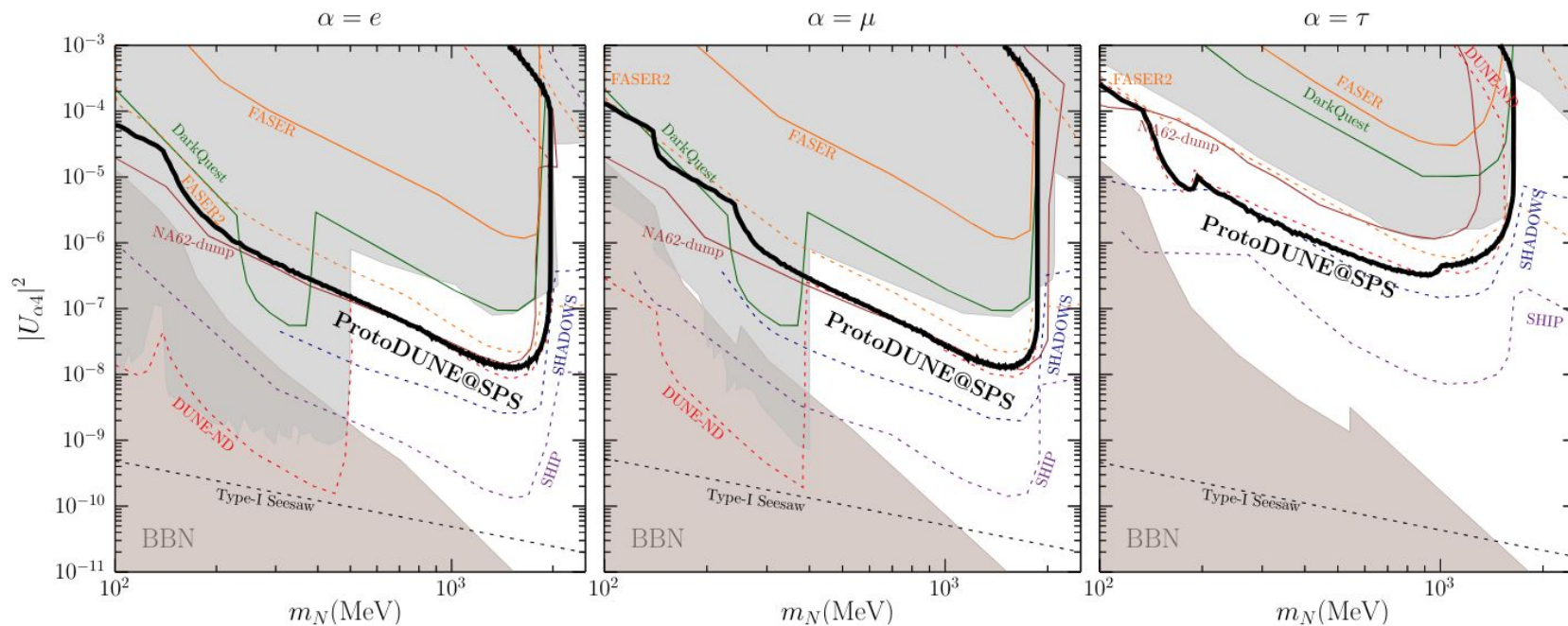
Thank you for
your attention!



Backup slides

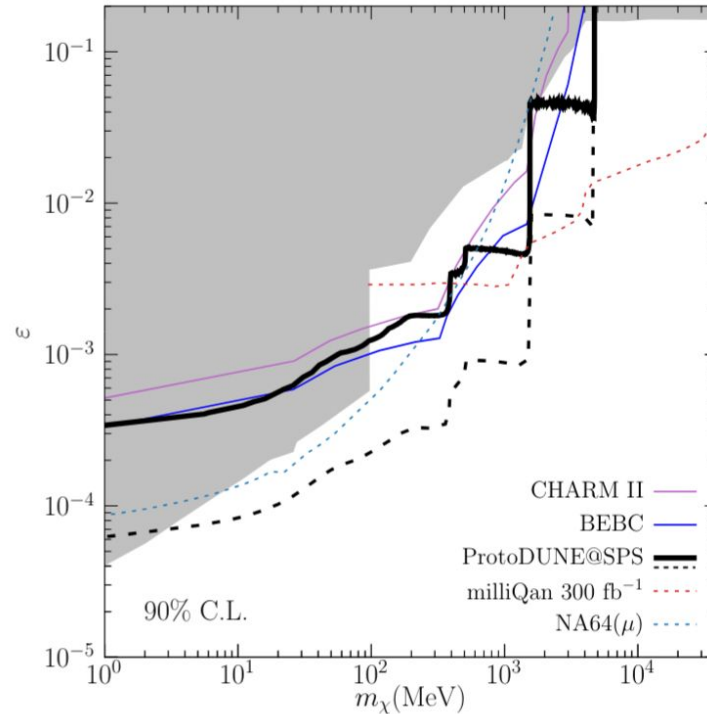
HNLs sensitivity @ProtoDUNE

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

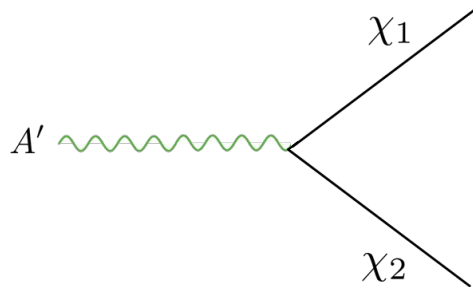


Dark Photon lifetime

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 ($\alpha_D \gg \alpha_{EM}\epsilon$).



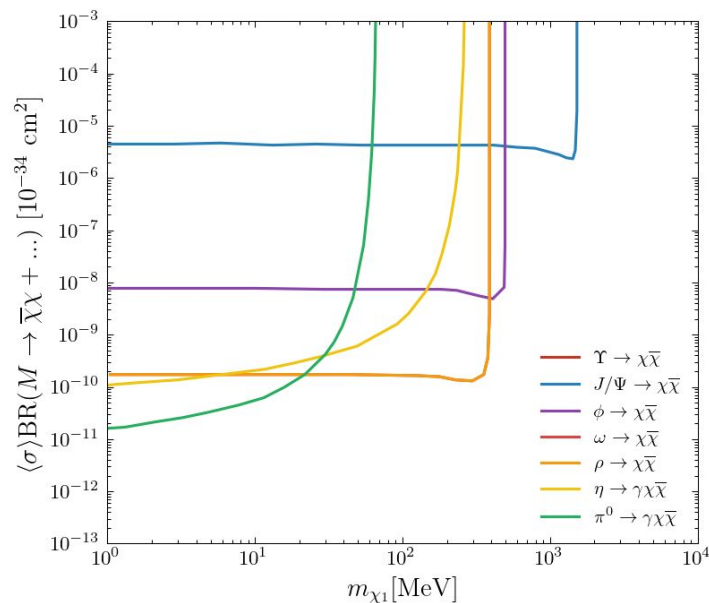
$$\ggg c\tau_{A'} \sim 10^{-13} \text{m} \left(\frac{0.1 \text{GeV}}{m_{A'}} \right)$$

Protodune sensitivities

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

Scattering

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



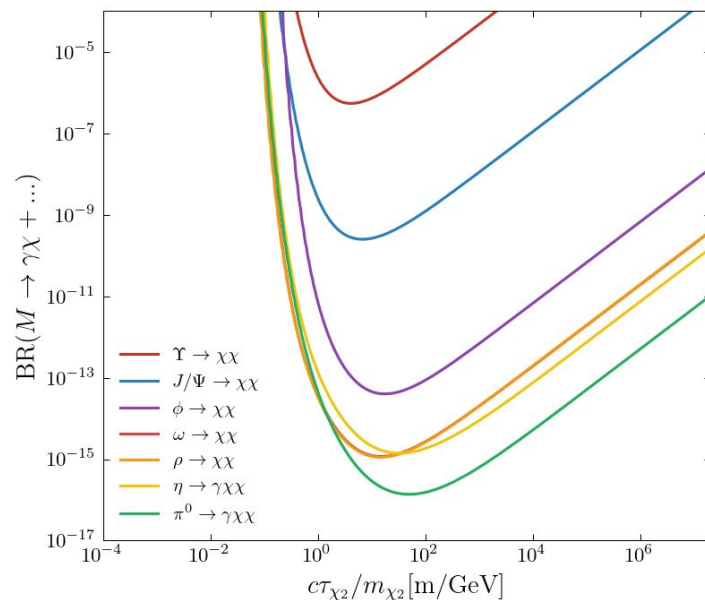
Credits to S. Urrea

Protodune sensitivities

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

Decay

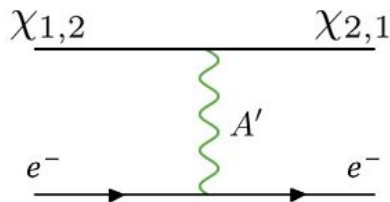
$$N_{dec}^M = N_{PoT} Y_M \text{BR}(M \rightarrow \Psi) \int dS \int dE_\Psi \mathcal{P}(c\tau_\Psi/m_\Psi, E_\Psi, \Omega_\Psi) \frac{dn^{M \rightarrow \Psi}}{dE_\Psi dS}$$



Credits to S. Urrea

Signature at the detector

Scattering



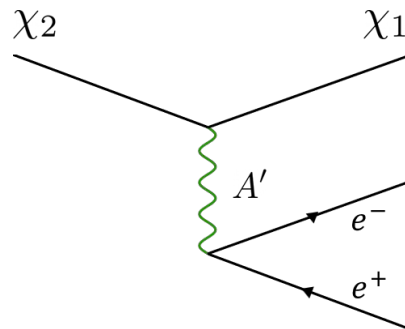
$$\frac{d\sigma}{dE_e} = 4\pi\epsilon^2\alpha_{EM}\alpha_D \frac{2E_{\chi_1}^2 m_e + g(E_e)/2}{(E_{\chi_1}^2 - m_1^2)(m_{A'}^2 + 2m_e E_e - 2m_e^2)^2}$$

e.g. averaged
over the flux
from η mesons

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

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

Decay



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

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