# MeV-Scale Features in DUNE BSM Searches

Kevin Kelly, Fermilab

Fermilab

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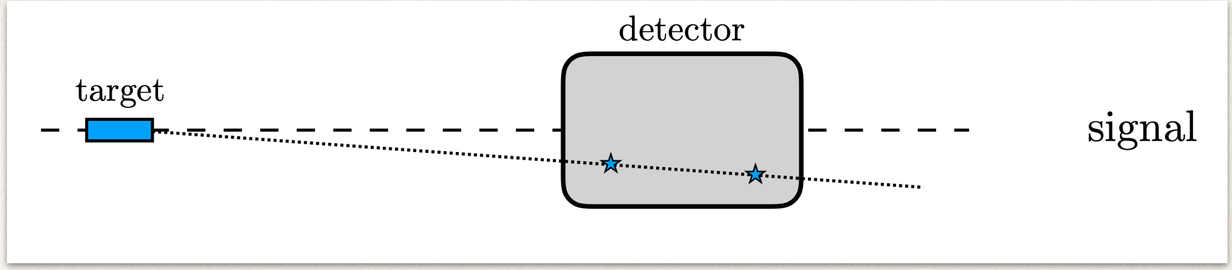
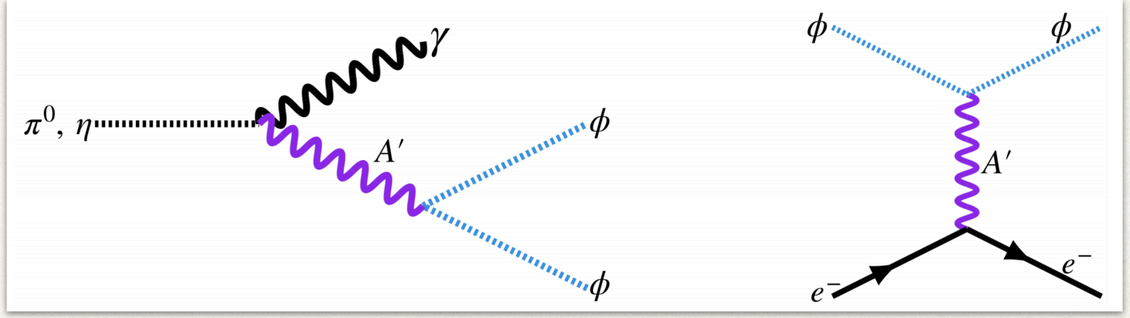
# Outline

- Millicharged Particles




Harnik, Liu, Palamara [1902.03246]

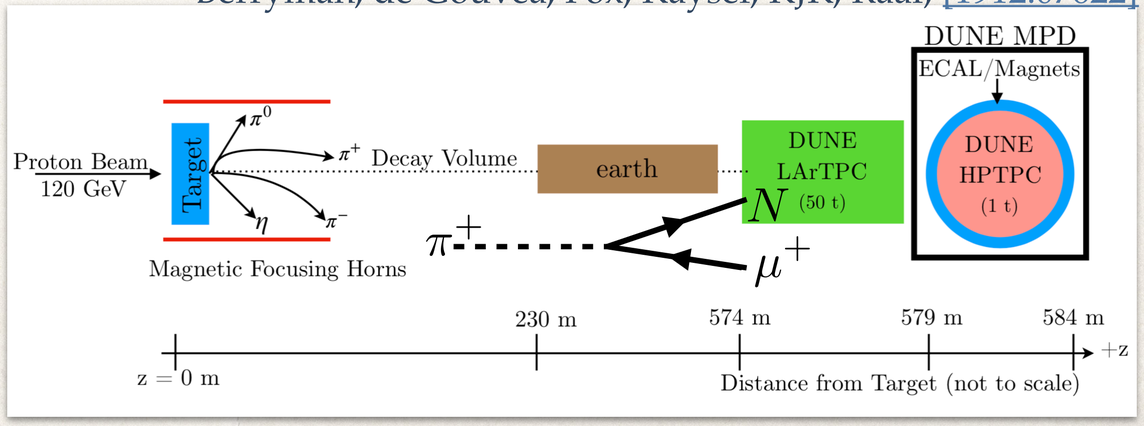
- Light Dark Matter Scattering




De Romeri, KJK, Machado [1903.10505]

- Dark Sector Mediators Decaying

Berryman, de Gouvêa, Fox, Kayser, KJK, Raaf, [1912.07622]



# Millicharged Particles

Harnik, Liu, Palamara [1902.03246]

See also Magill, Plestid, Pospelov, Tsai [1806.03310]

# MCP: The Idea

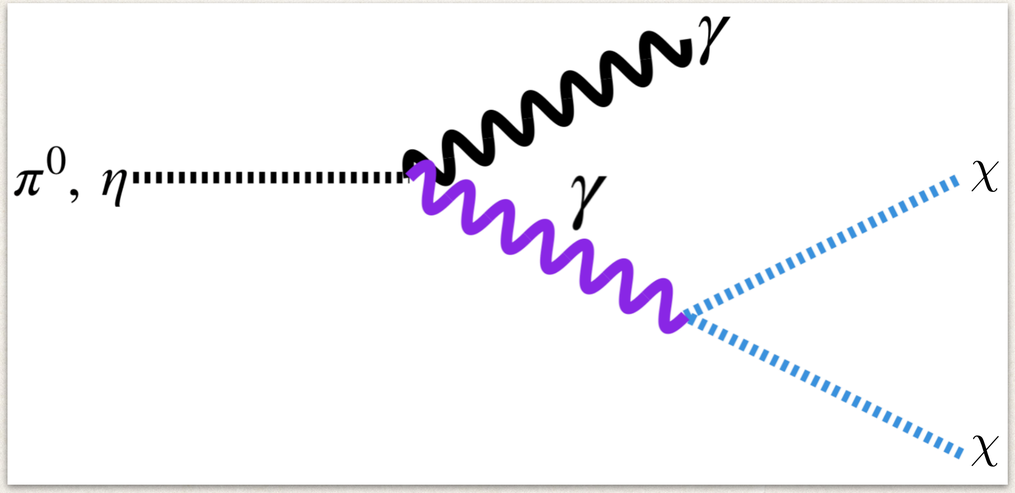
Suppose a new particle exists with a fractional charge (smaller than the quarks)

$$\epsilon \equiv \frac{Q_\chi}{e}$$

$$\frac{d\sigma}{dE_r} = \pi\alpha^2\epsilon^2 \frac{2E_\chi^2 m_e + E_r^2 m_e - E_r\left(m_\chi^2 + m_e(2E_\chi + m_e)\right)}{E_r^2(E_\chi^2 - m_\chi^2)m_e^2}$$

$$\left.\frac{d\sigma}{dE_r}\right|_{E_\chi \gg m_\chi, m_e, E_r} \simeq \frac{2\pi\alpha^2\epsilon^2}{E_r^2 m_e}$$

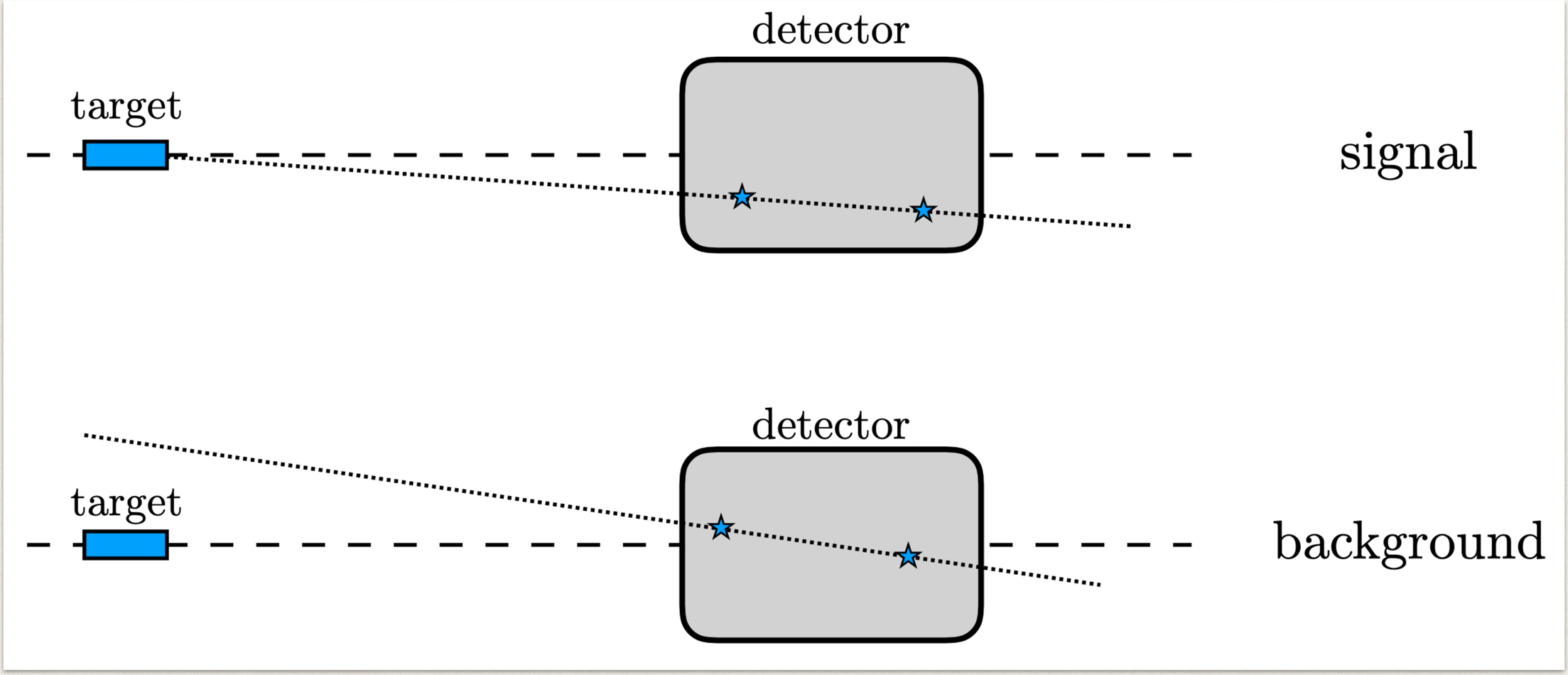
## Make Them




## See Them

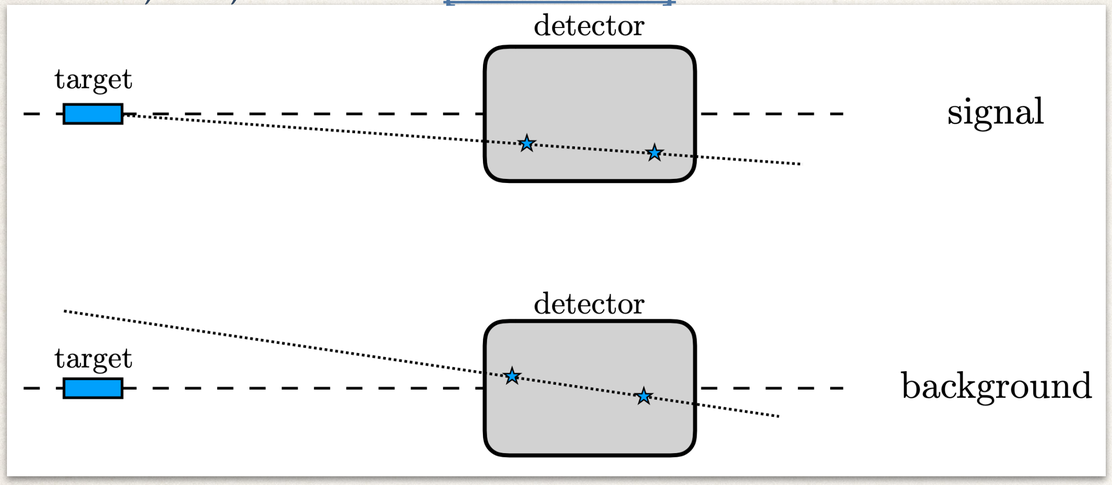
Scattering off electrons in a low-recoil detector.

# Signal vs. Background



# Double- vs. Single-hit: ArgoNeuT Test Case

Harnik, Liu, Palamara [1902.03246]




- Analyzing "empty frames", ArgoNeuT found that, on average, 12.8% of frames had MeV-scale activity. $p_{\text{hit}} = 0.128$
- From this, the number of single-hit events (signal or background) in ArgoNeuT is

$$N_{1\ \text{hit}} = N_{\text{frames}} \times \sum_n n e^{-p_{\text{hit}}} \frac{p_{\text{hit}}^n}{n!} = 4.2 \times 10^5$$

- Frames with two (or more) hits will be rarer —

$$N_{2\ \text{hit}} = N_{\text{frames}} \times \sum_n \binom{n}{2} e^{-p_{\text{hit}}} \frac{p_{\text{hit}}^n}{n!} = 2.7 \times 10^4$$

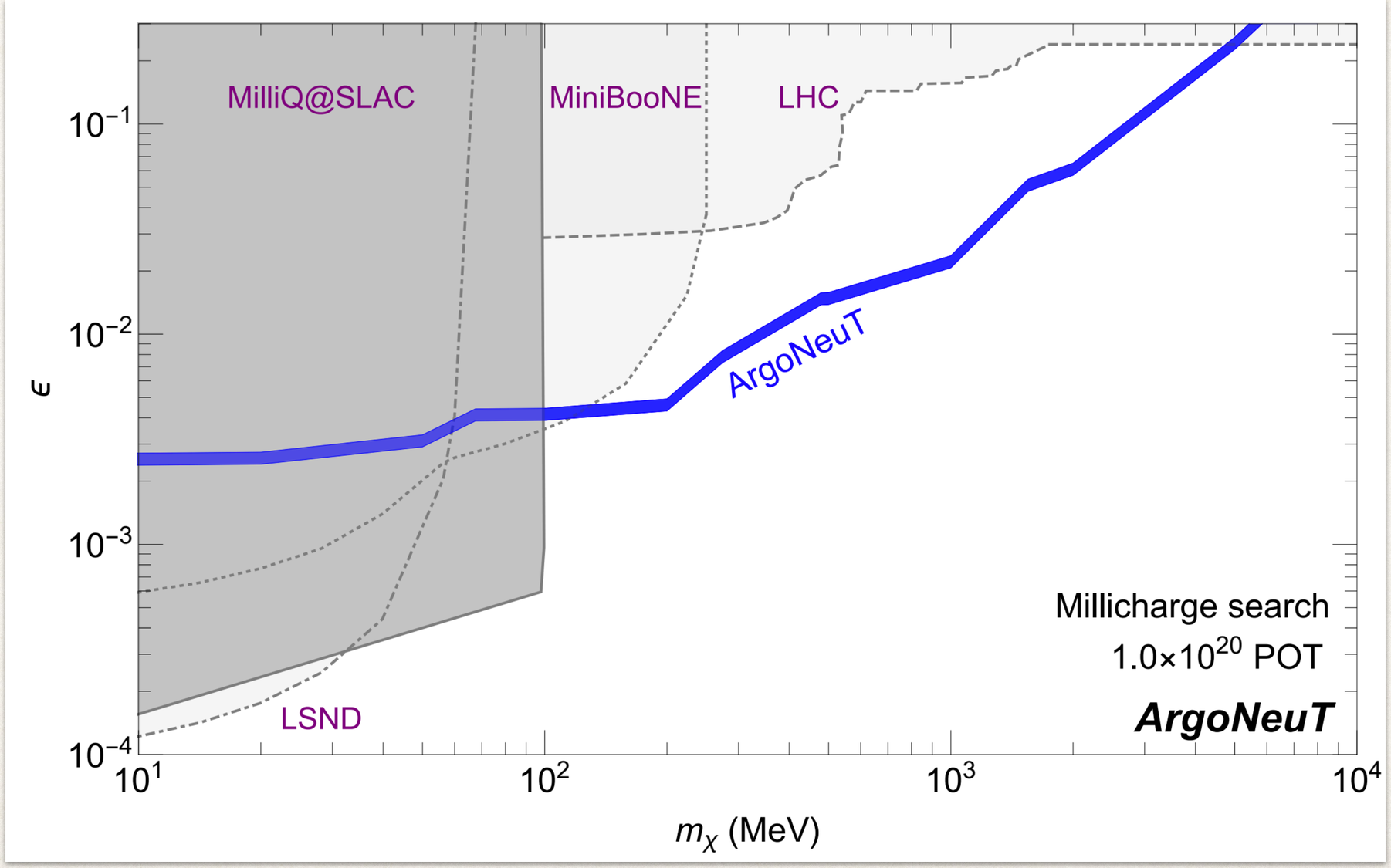
- Even rarer — frames with two hits *aligned* in the target direction

$$N_{2\ \text{hit}}^{\text{aligned}} = N_{2\ \text{hit}} \times \left( \frac{\delta x}{\Delta x} \frac{\delta y}{\Delta y} \right) = 0.24$$

Double-hit search: nearly background free!

# ArgoNeuT Limit

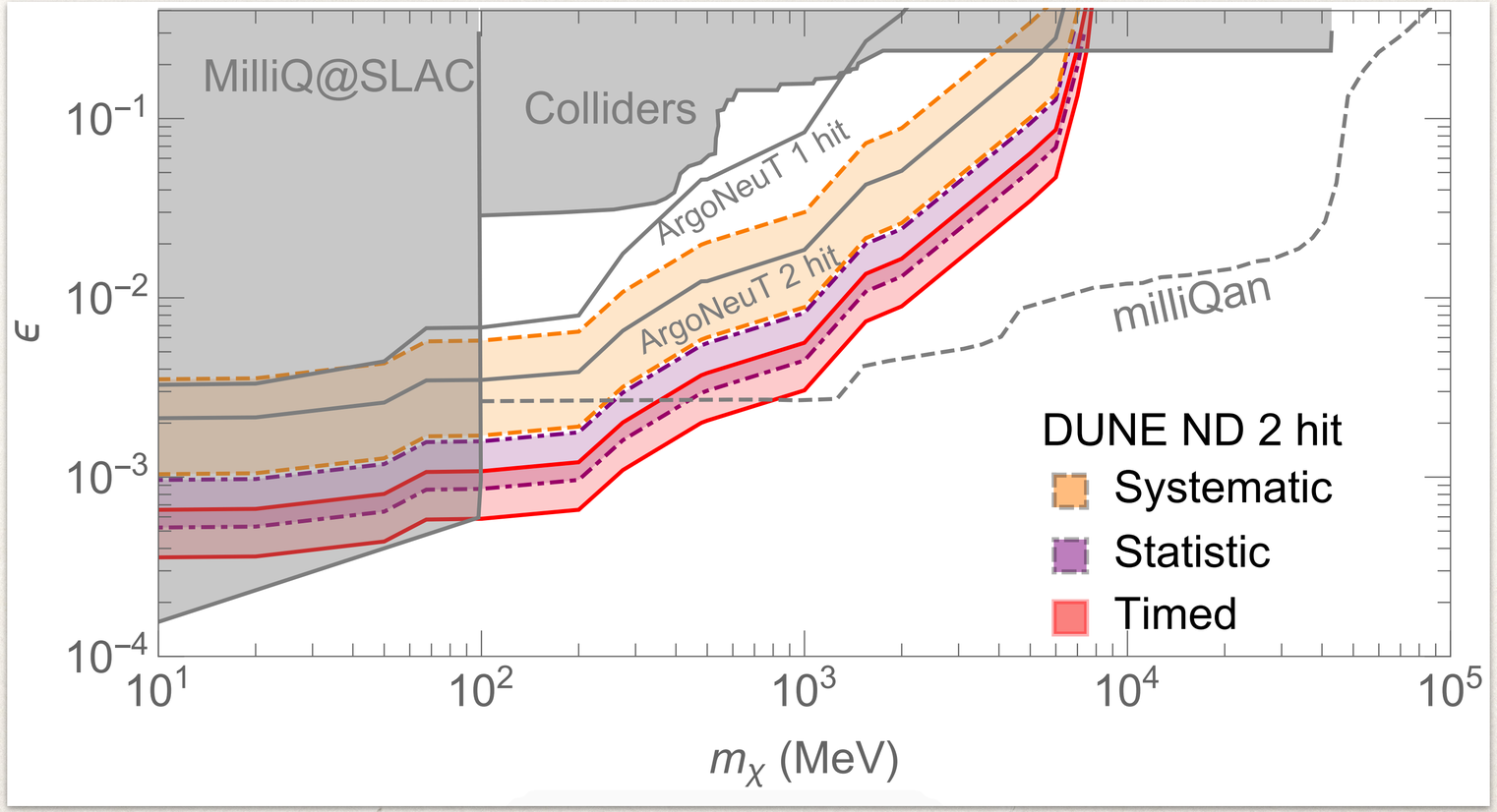
ArgoNeuT Collaboration [1911.07996]



# Challenges Going Forward

Harnik, Liu, Palamara [1902.03246]

- Given its small volume, the rate of MeV-scale energy depositions in ArgoNeuT's empty frames was relatively low (12.8%).
- Additionally, we do not know the origin of these depositions — will they scale like the detector volume going forward? The detector volume and the beam intensity?
- Even in optimistic scenarios, DUNE will see O(50) MeV-scale depositions per frame.



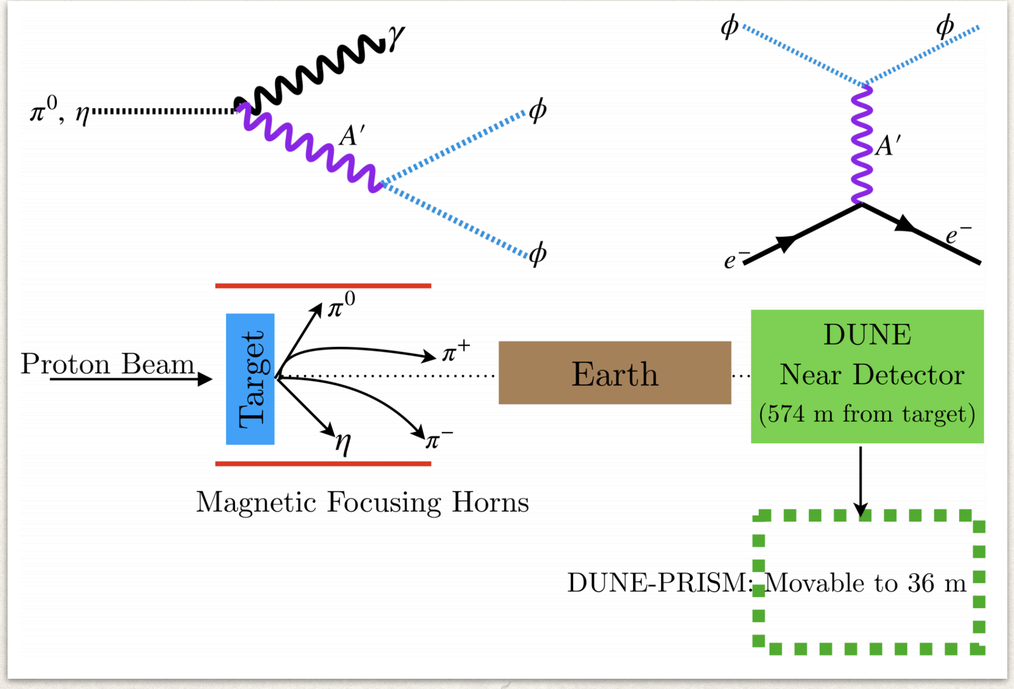
# Light Dark Matter Scattering

De Romeri, KJK, Machado [1903.10505]

# Concept

De Romeri, KJK, Machado [1903.10505]

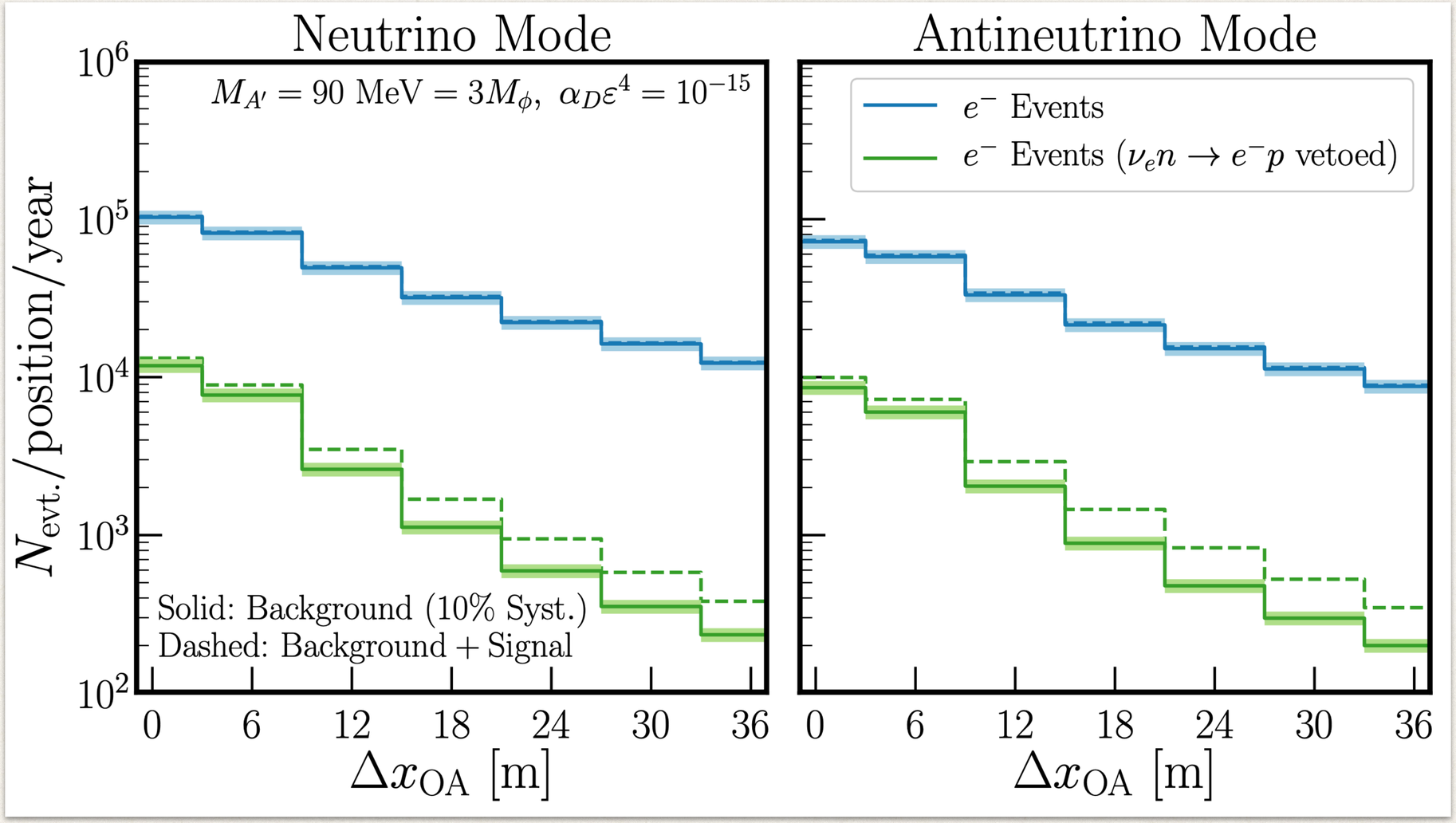
- Schematically, very similar to millicharged particle case:
  - Production via decay of neutral, pseudoscalar mesons.
  - Detection via scattering in detector (predominantly off electrons)
- Main difference: massive mediator (dark photon) instead of standard model photon.




Idea explored in the context of neutrino experiments in other works, for instance:

Batell et al [0906.5614],
deNiverville et al [1205.3499]
Coloma et al [1512.03852]

# Benefit of DUNE-PRISM: Off-Axis Data Collection

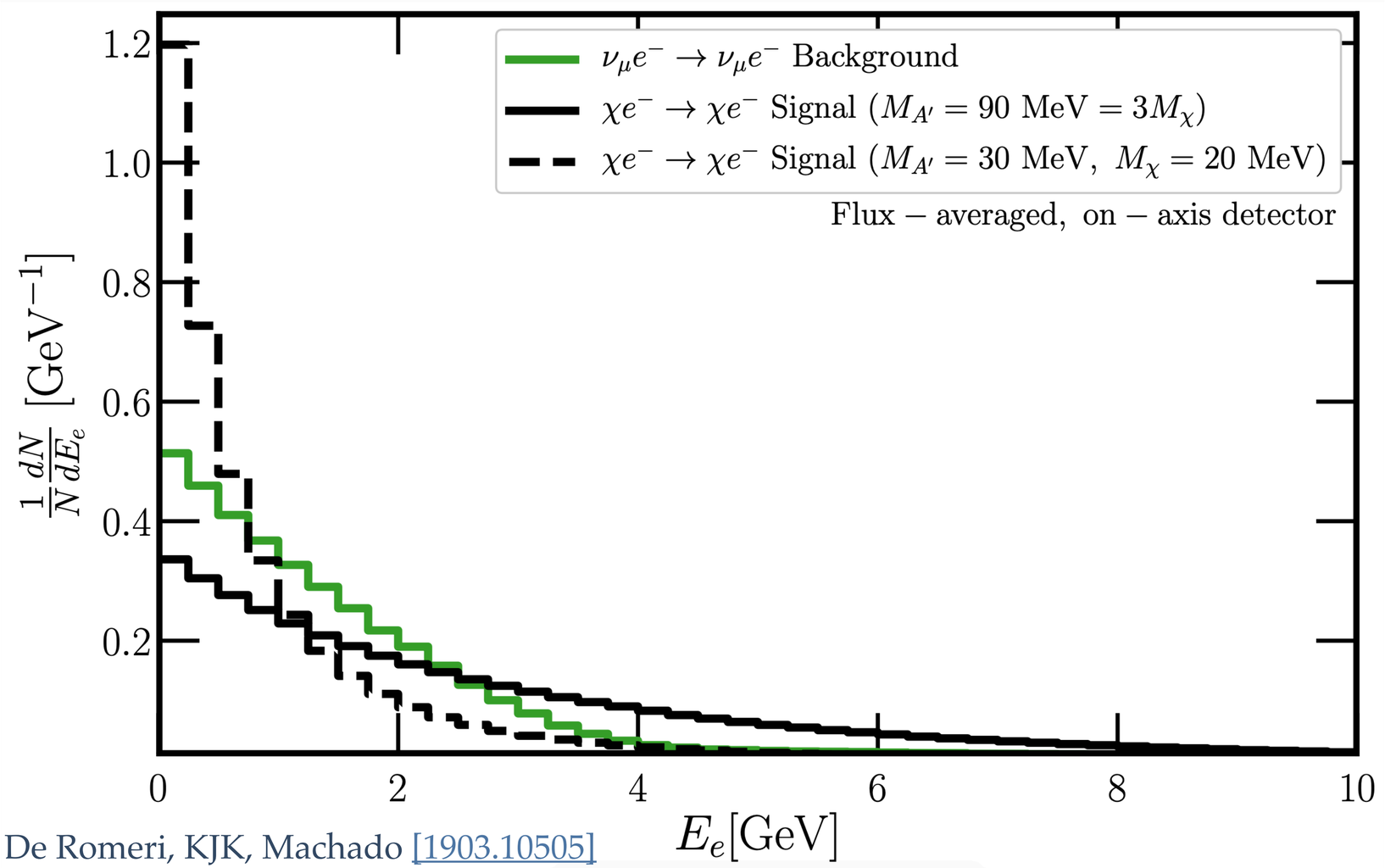



Rejection of CCQE Background: Critical!

De Romeri, KJK, Machado [1903.10505]

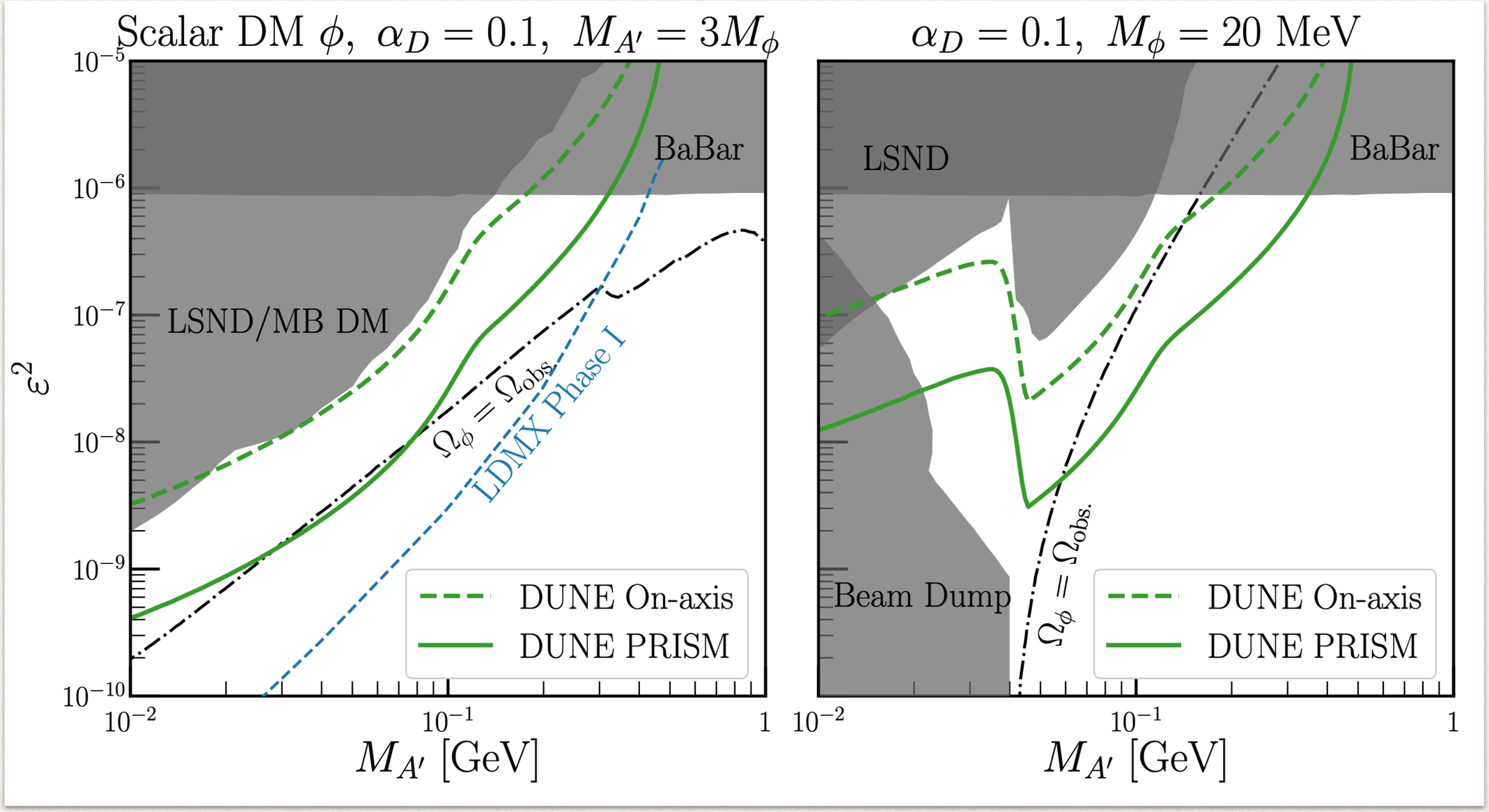
# How does Low-Energy Physics Play a Role?

- Like with the millicharged particle scenario, event rate peaks at low-electron recoil energy.
- However, this is the case as well for neutrino-electron scattering, our dominant background




De Romeri, KJK, Machado [1903.10505]

# Light Dark Matter Sensitivity with DUNE(-PRISM)



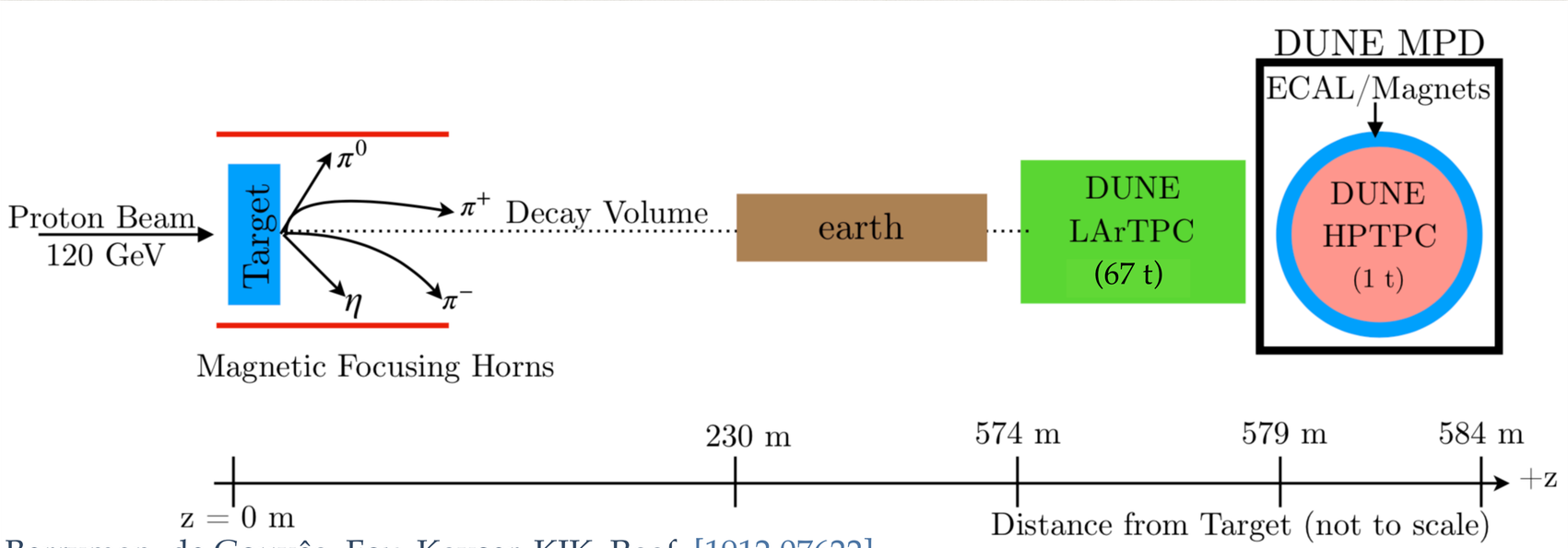

De Romeri, KJK, Machado [1903.10505]

# Decays of Dark Sector Particles

Berryman, de Gouvêa, Fox, Kayser, KJK, Raaf [1912.07622]

LEPLAr → LEPGAr

# DUNE-ND as a Beam-Dump Facility




Berryman, de Gouvêa, Fox, Kayser, KJK, Raaf, [1912.07622]

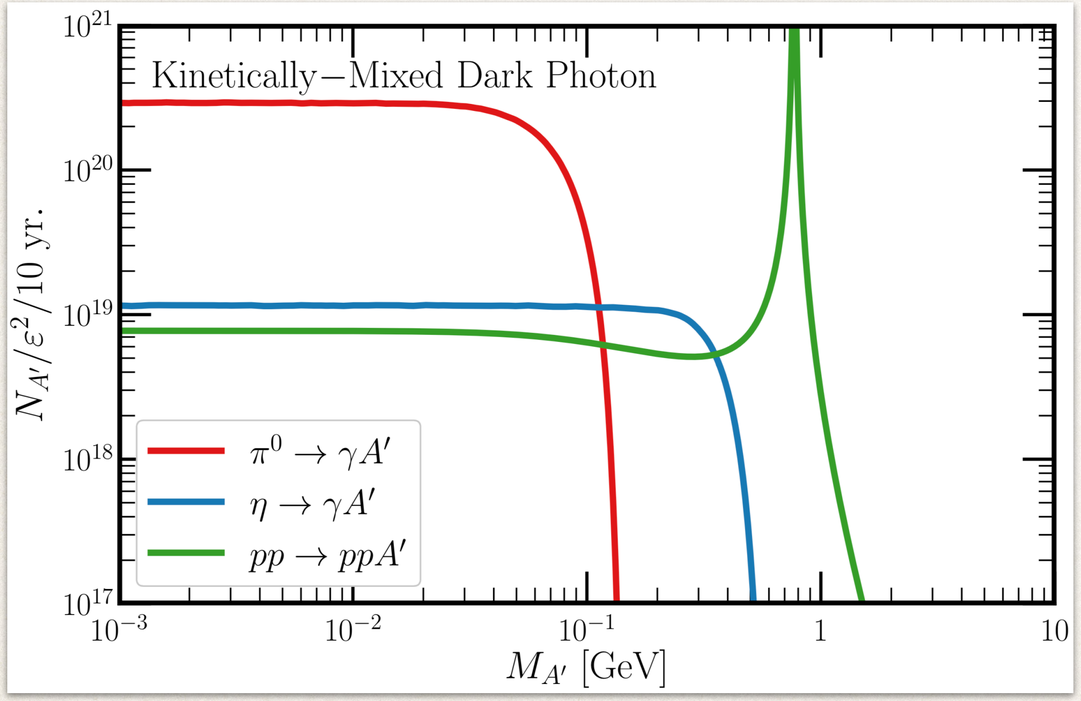
- High-intensity proton beams ($10^{21}$ or so protons on target per year), can produce copious amounts of SM mesons.
- Long-lived, charged particles can be focused/defocused by magnetic horns.
- Precision particle identification in near detectors can assist with background rejection.

# Case Study: Dark Photons

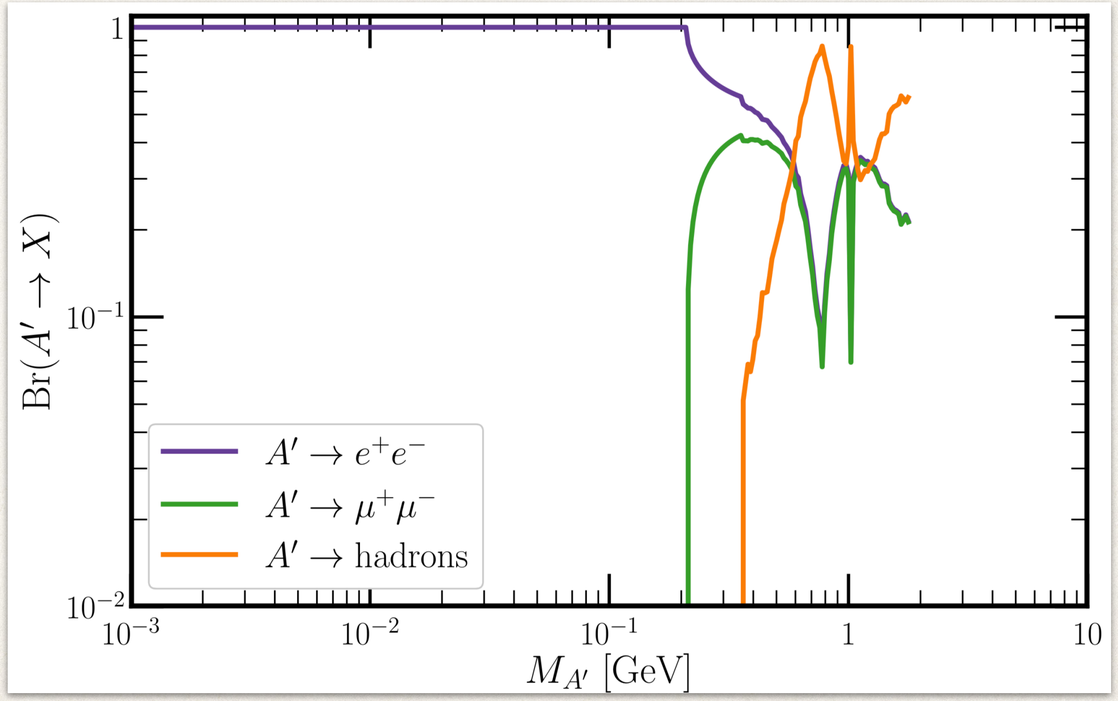
Berryman, de Gouvêa, Fox, Kayser, KJK, Raaf, [1912.07622]

Same idea as before, new U(1) kinetically mixed with the Standard Model.

Now, let's assume the dark photons can be long-lived (e.g., the distance between the DUNE target and near detector hall)




Production




Detection

# Signal vs. Background

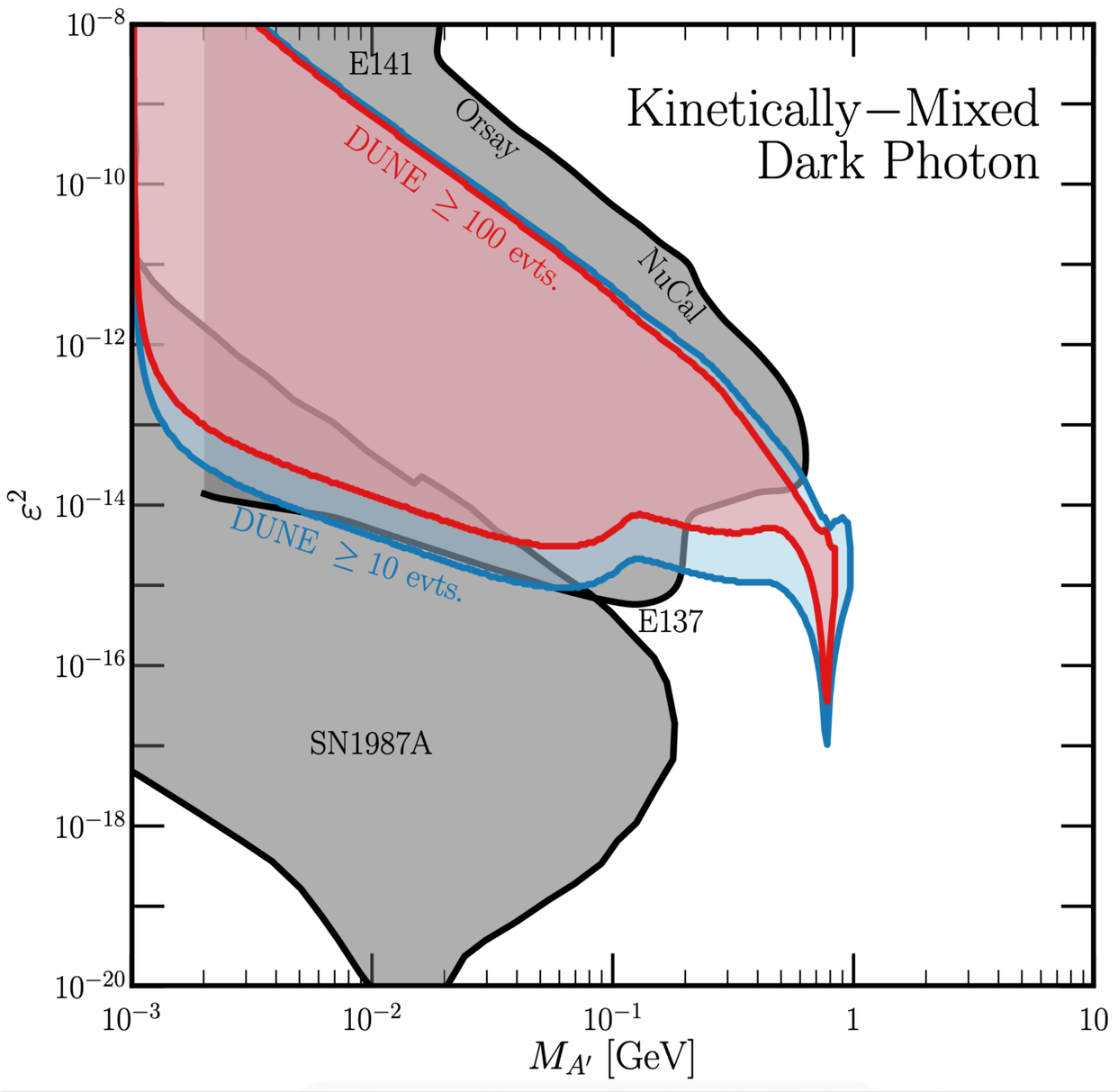
## $A' \to e^+e^-$

- Dominant background will come from neutral current pion production, where the pion decays into two photons, one is missed, and the other is misidentified as an electron.
- Identification of low-energy recoils, and understanding of photon/electron discrimination is critical for reducing this background

## $A' \to \mu^+\mu^-/\text{hadrons}$

- Backgrounds here will be mostly from charged-current single pion production, where the muon-pion system can be misidentified a pair of either muons or pions.
- Again, rejecting hadronic activity (none present in signal) will help greatly here.

# Decaying Dark Photon Sensitivity



# Conclusions

- Understanding detector capabilities at low energies, as well as lower thresholds, is key for many qualitatively different BSM searches in neutrino experiments.
- Applications vary for *how* the low-energy information is helpful:
  - Enhancing signal rates
  - Rejecting backgrounds
  - Discrimination between signal and background
- A rich program of BSM searches is viable with the next-generation of neutrino experiments!

Thank you!