Dark Matter Scattering: New Signals and Models

Bhaskar Dutta

Texas A&M University

TaoFest, May 14, 2026

I first met Tao at Fermilab in 1994 when I was a graduate student…

Long history of collaboration, discussions and friendship

Many stories….

Several papers with Tao, e.g.,

h_{an} index: 5

Leptonic Scalars at the LHC

➔*non-local:* **Sufang Shu' talk**

Leptonic scalars and collider signatures in a UV-complete model

Anomalous tau neutrino appearance from light mediators in short-baseline neutrino experiments

New physics at a neutron beam dump

Drell-Yan Production of New Particles at Fixed-Target Experiments: Heavy Neutral Lepton as a Case Study

- You are a true leader, Tao, and I am deeply thankful for everything you have been doing for the community.
- Your kindness, wisdom, and dedication have inspired so many of us over the years.
- I truly appreciate your friendship, support, and generosity.

And of course, one simply cannot properly appreciate Tao without Tao’s favorite drink!

Some friendships are built on physics, some on wisdom — ours clearly survived because of both science and good drinks.

Outline

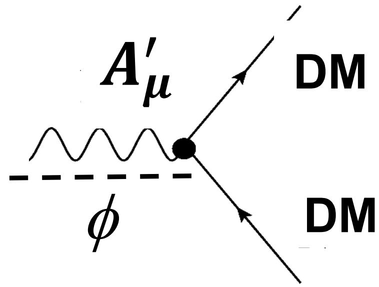
- Dark sector Models and interactions
- Extracting model interactions from the dark matter scattering
- Examples: e, μ, τ, γ etc. final states from DM scattering
  DM near detector-DM produced at the lab
  GCE excess-Ambient DM ,
  MiniBooNE anomaly-DM produced at the Lab
  Ambient DM at DUNE –far detector

Introduction

- Origin of dark matter, neutrino mass and mixing are still unknown
- Where is the new physics scale? new models?
- Many experiments are probing new physics scales:
  DM direct and indirect detections, LHC,
  neutrino experiments, proton/electron beam dump experiments,
  rare decays, etc.
- We will explore sub-GeV scale for DM
- We will utilize the DM scattering-based signals to probe
  dark sector models

Models of Light DM: A', Higgs

Models of light gauge mediators:
$L_\mu - L_\tau$, $U(1)_B$, $U(1)_L$, $U(1)_{T3R}$, $U(1)_{B\text{-}L}$, $U(1)_A$ etc.



Battel, Niverville, Pospelov, Ritz, 2014, Kaplan, Luty, Zurek, 2009, Bi, He. Yuan, 2009, Park Kim Park, 2016, Foldenauer, 2019, Dutta, Ghosh, Kumar, 2019; Dutta, Karthikeyan, Mohapatra, 2026

- These light mediators can decay into DM and various SM particles, leptons, quarks etc.

- Models also possess light scalar (associated with SSB)➔ leads to interesting phenomenology, e.g., DM, g-2, MiniBooNE anomaly etc.

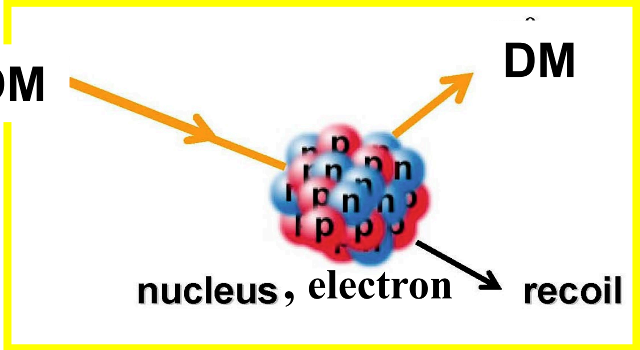
  Dutta, Ghosh, Kumar, 2019

  - The models interact with DM and SM fermions via Yukawa type couplings

➢ All these models have constraints from beam dump, low energy accelerators, g-2, astrophysics and cosmology

❑ Can the DM scattering-based signals discriminate these models?

Low mass DM



- ❑ How do we probe low-mass DM (1 MeV to 1 GeV)?

- ➢ Ambient and Laboratory produced dark matter

- • Electron/nucleus scattering, Cosmic Boosted, Migdal etc.

- ○ <u>Detectors</u> Liquid: Ar, Xe; Semiconductors: Ge, Si, SiC; Scintillators: CsI, NaI, GaAs
  [Also, Levitated sphere, polar materials, superconductors,
  superfluid helium, Dirac materials, Molecular gases etc.]

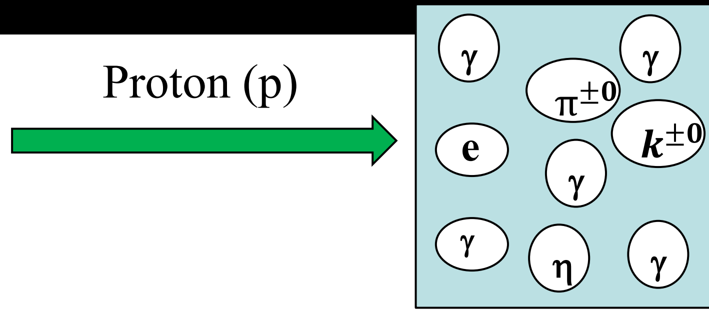
- ➢ Electron beam dump experiments: NA64e/μ, LDMX (future) etc

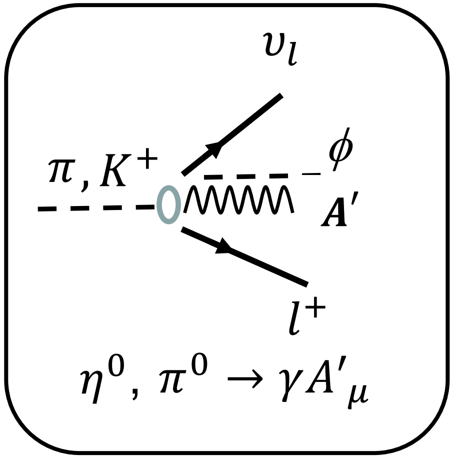
- ➢ Proton beam dump based neutrino experiments
  CEνNS (CCM, COHERENT, JSNS2); SBN (Fermilab); DarkQuest;
  DUNE (future) , SHiP (future)

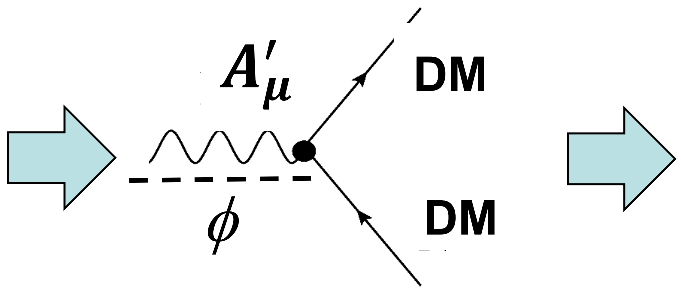
- ❑ This talk utilizes some of these facilities invoking new scattering-based signals

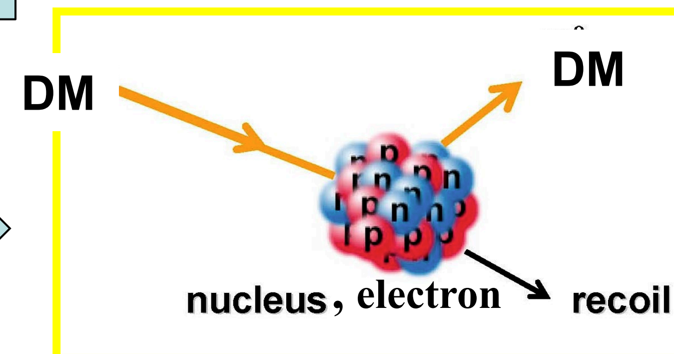
Productions of Low mass

1. Meson decays









2. Proton bremsstrahlung *3. Muon bremsstrahlung* *4. Drell-Yan Production*

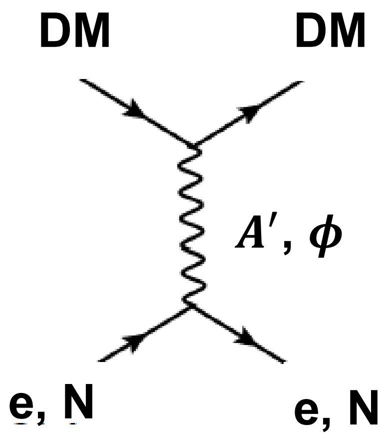
Dev, Dutta, Karthikeyan, Rai, Tabrizi, to appear

Burk, Dev, Dutta, Karthikeyan, Kim, Han, 2601.18874
Frances Burk's talk at PHENO 2026

5. The neutrons produced at the target can also be a source of new particle production

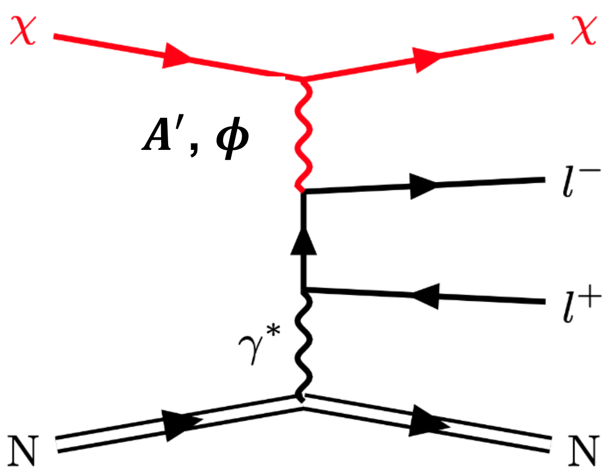
Dev, Dutta, Han, Kim, Karthikeyan, Phys.Rev.D 110 (2024) 5, L051703

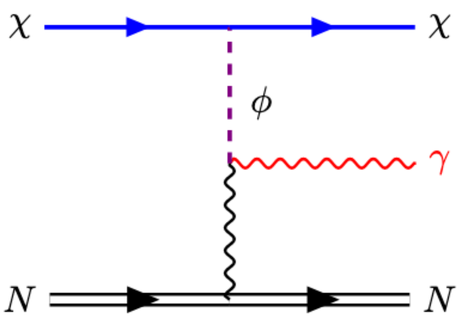
DM detection



- Standard DM detection: DM-electron/nucleon elastic scattering
- Threshold: serious issue
- Background: due to SM neutrino interactions
- Cannot probe any other lepton flavors

➢ *We introduce 2-4, 2-3 processes with both scalar and vector mediators*

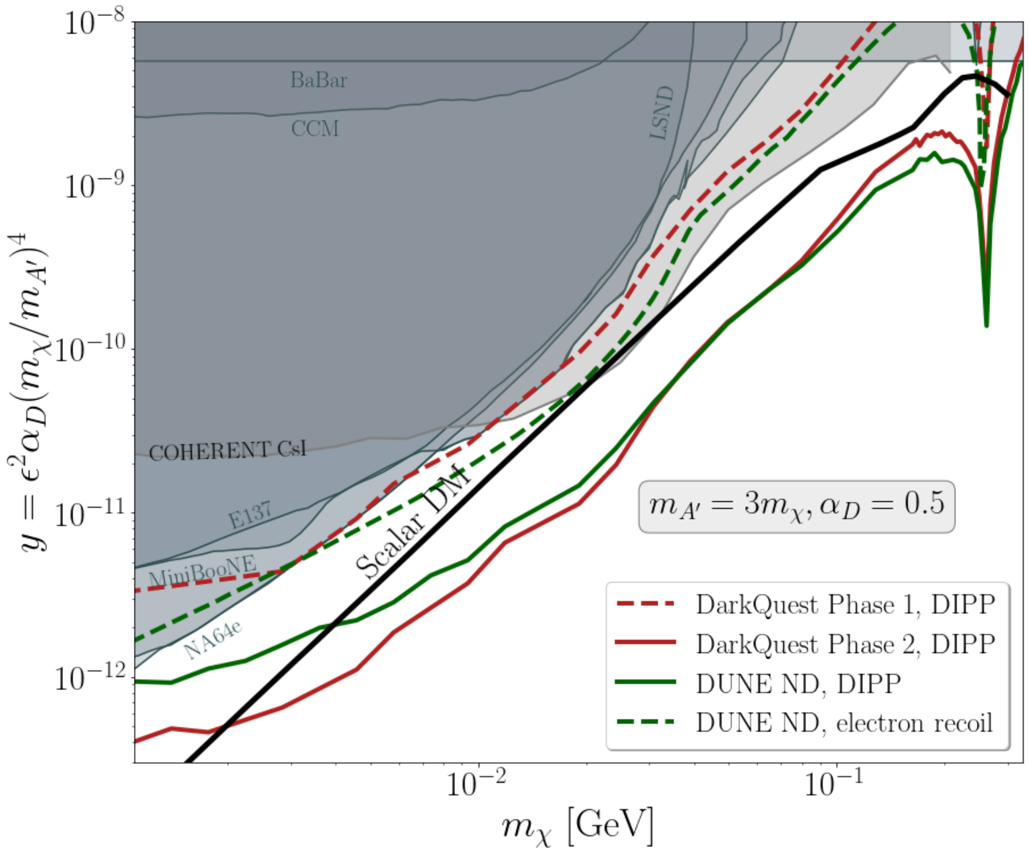


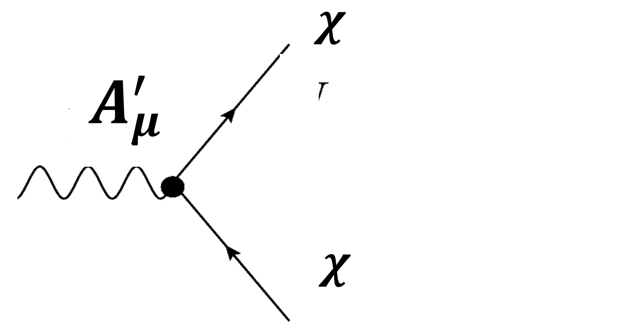


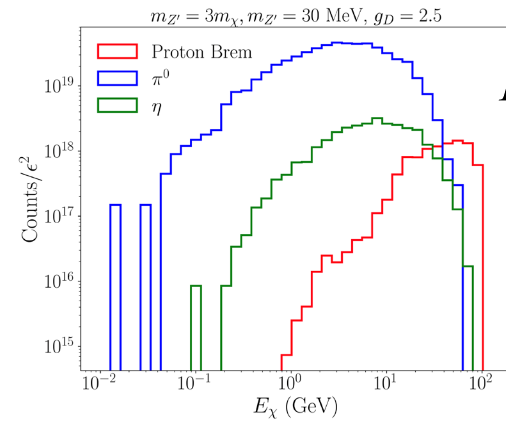
- DM induced internal bremsstrahlung (DIPP)

A new channel for DM: Vector Mediator

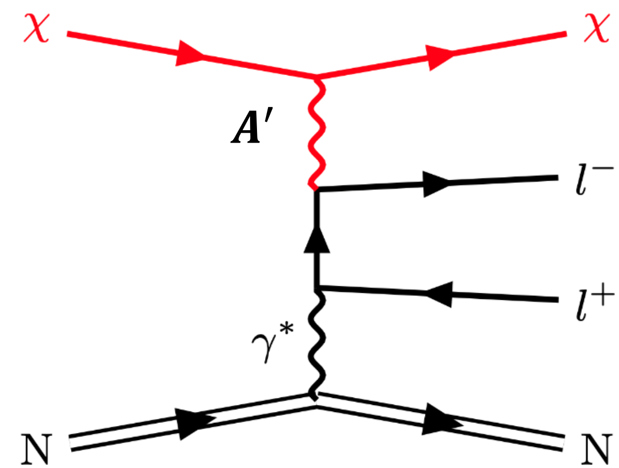
- DIPP-dark photon







DM energy

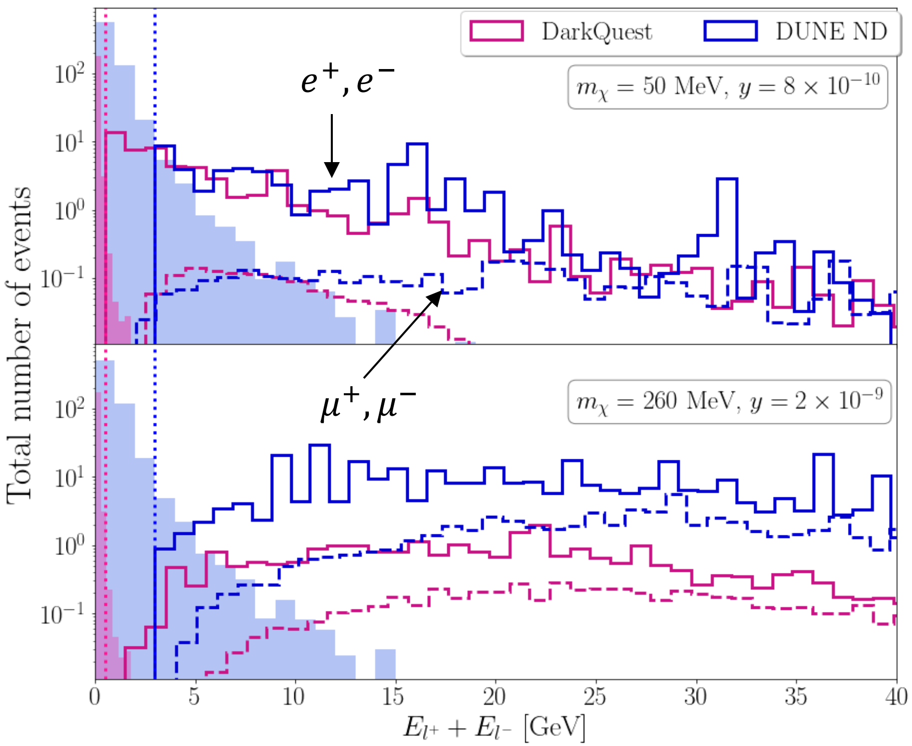


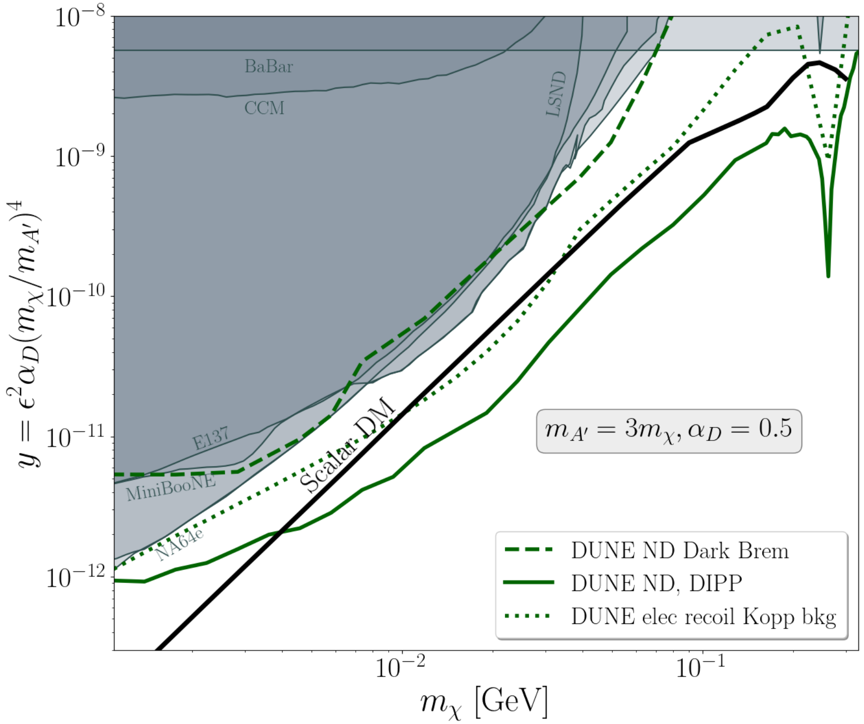
$$\mathscr{L} \supset \epsilon e \sum_f Q_f^{\rm em} \bar{f} \gamma^\mu f A'_\mu + g_D \bar{\chi} \gamma^\mu \chi A'_\mu$$

Better sensitivity: $l^+ l^-$ final states with higher energy

Dutta, Kim, Karthikeya, Rai, Phys.Rev.Lett. 135 (2025) 1, 1

A new channel for DM: Vector Mediator





- Energy distributions of the final state electron-positron pair along with the SM background (mostly from ν_μ-NCπ^0)
- Sensitivity of the DIPP channel in comparison with the DM-e scattering

A new channel for DM: Vector Mediator

- DIPP Sensitivity - Muon-Quark philic model

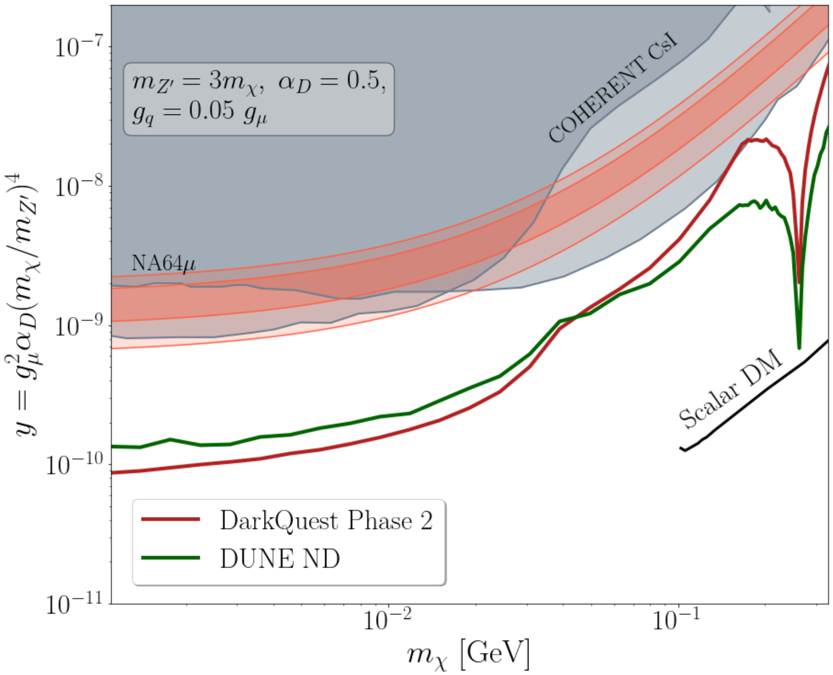
$$\mathscr{L} \supset g_q \bar{q}\gamma^\nu q Z'_\nu + g_\mu \bar{\mu}\gamma^\nu \mu Z'_\nu + g_D \bar{\chi}\gamma^\nu \chi Z'_\nu$$

- DIPP probes the combination: $g_q^2 g_\mu^2$
- Complementary:

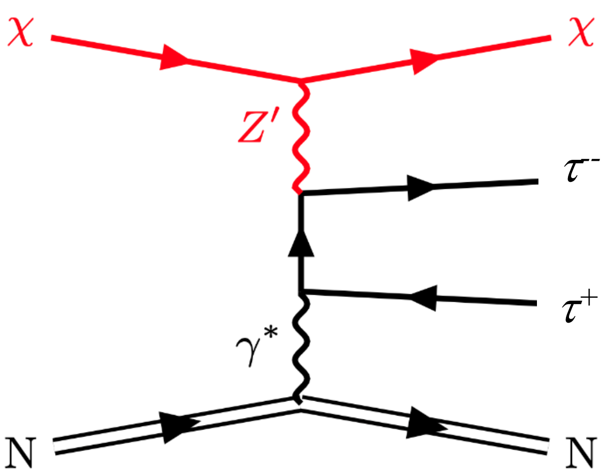
➢ NA64 probes (missing energy) g_μ^2

➢ COHERENT probes g_q^4

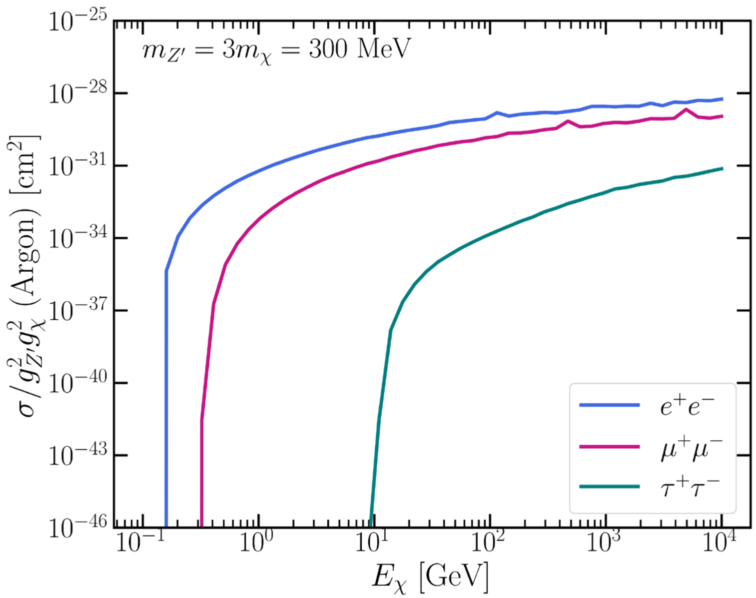
❑ Probes dark sector model interactions



τ s in the final state



Tao and ant-Tao: pros and cons, Carlos Wagner's talk

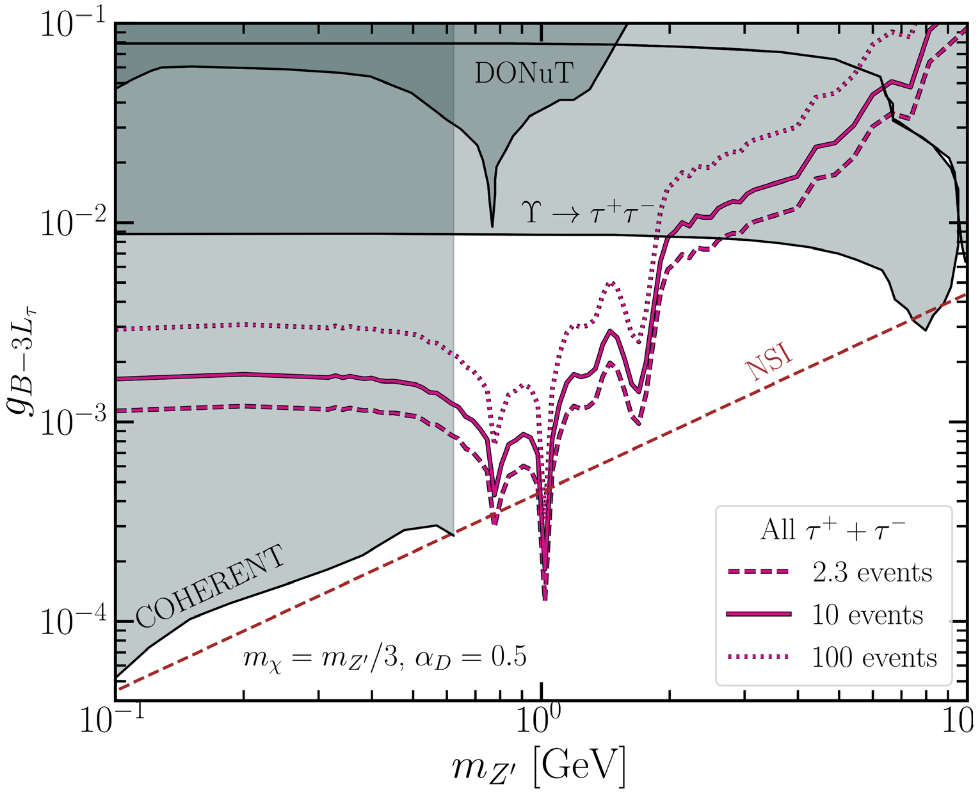


- DIPP with τs
- New mechanism to produce τ at the near detector at DUNE
- Proton bremsstrahlung production of energetic DM allows the production of di-tau final states
- DM from meson decays does not have enough energy to produce diatu final states
- τ leptons can be detected via hadronic (mesons), leptonic final states (e, μ etc.)

τ decay modes

Decay mode	Branching ratio (%)
$\pi^- \pi^0 \nu_\tau$	25.49
$e^- \bar{\nu}_e \nu_\tau$	17.82
$\mu^- \bar{\nu}_\mu \nu_\tau$	17.39
$\pi^- \nu_\tau$	10.82
$\pi^- 2\pi^0 \nu_\tau$	9.26

τ s in the final state



- SM processes for production τ at the detector: ν_τ induced charged current

➤ Negligible number of ν_τ

- *$\nu_\mu \to \nu_\tau$ oscillation*
- *D mesons decays:* $B(D^+ \to \tau^+ \nu_\tau) = (1.2 \pm 0.24) \times 10^{-3}$

- Here, the NSI line is model-dependent
- U(1)$_{T3R}$ model does not have the NSI line
- Similar sensitivity plots can also be obtained for scalar mediators

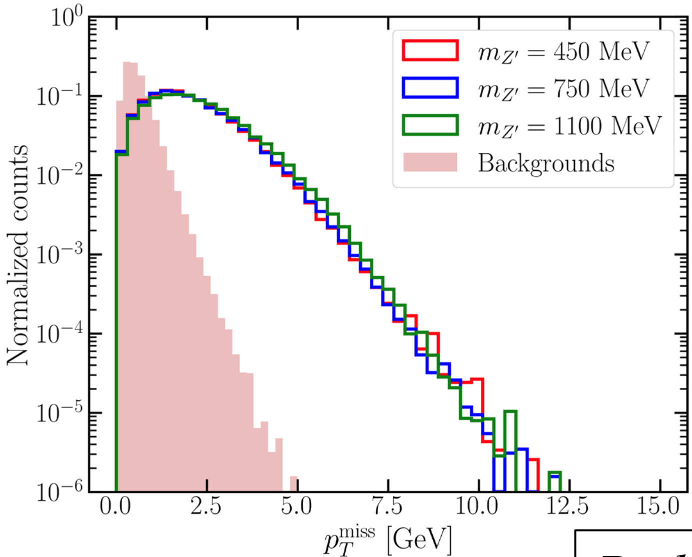
Dev, Dutta, Goswami, Karthikeyan, Kim, To appear

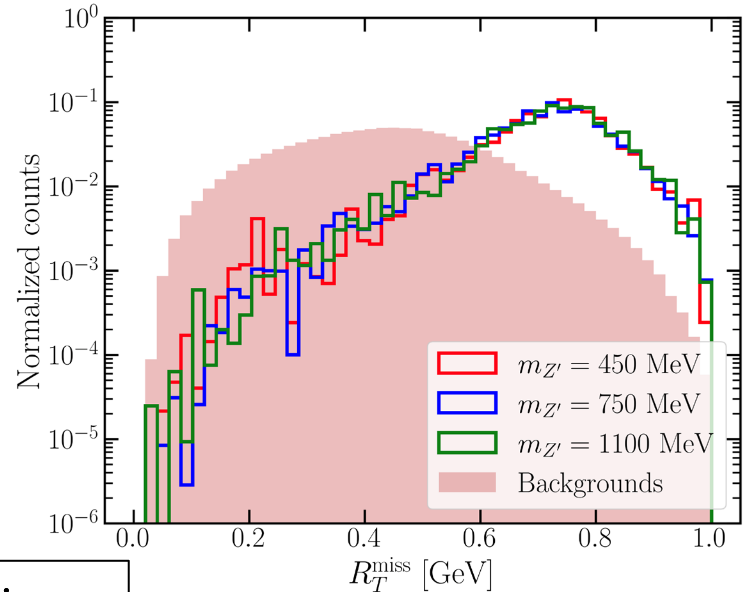
- Z' decays into a pair of ν_τ can produce τ final states

Dev, Dutta, Han, Kim, Phys.Lett.B 850 (2024) 138500

τ s in the final state

- Hadronic final states: background due to neutral current
- Leptonic final states: charged current
  - Using muon +hadrons final state [Sousa et al.2023]





Preliminary

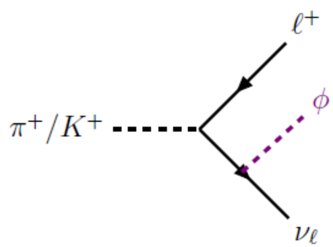
$$R_T^{miss} = \frac{P_T^{miss}}{P_T^{miss} + P_T^{\mu}}$$

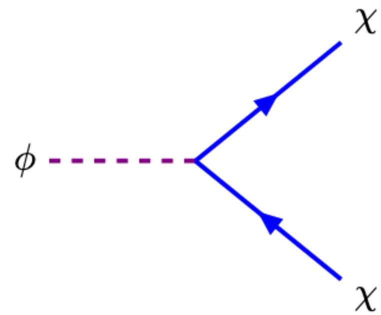
- Energy spectra of the hadrons

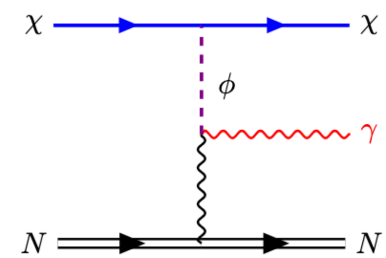
- The background can be removed with a few handles

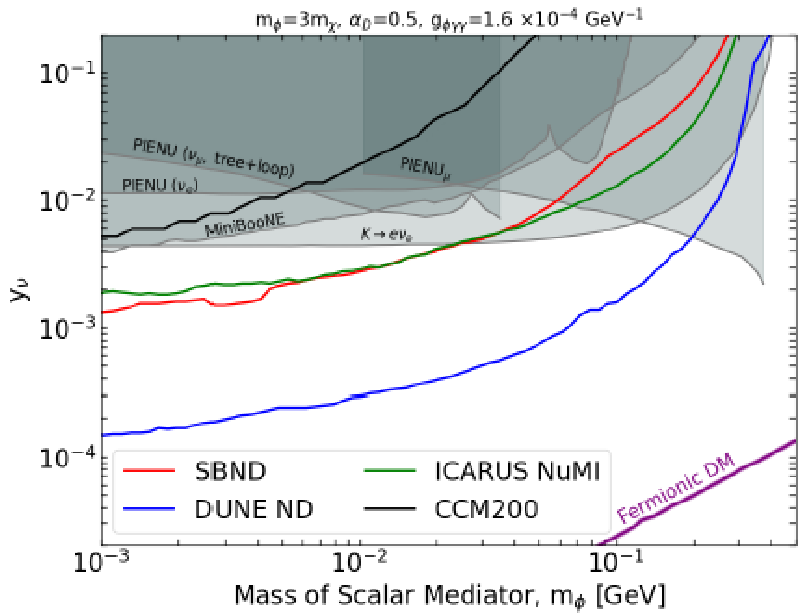
Scalar mediator and DM

$$\mathcal{L} \supset i g_D \bar{\chi}\chi\phi + \frac{1}{2} i g_{\phi\gamma\gamma}\phi F^{\mu\nu}F_{\mu\nu} + i y_f \bar{f} f \phi$$







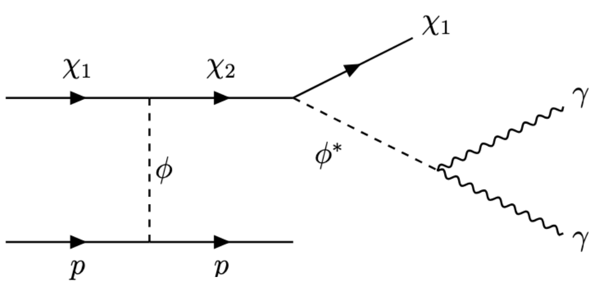


γ in the final state in a DM scattering leads to many interesting possibilities

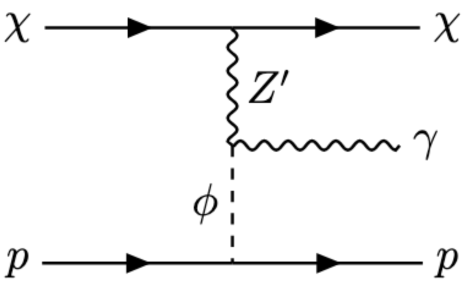
Dutta, Goswami, Karthikeyan, JHEP 02 (2026) 142

DM scattering –models and signals

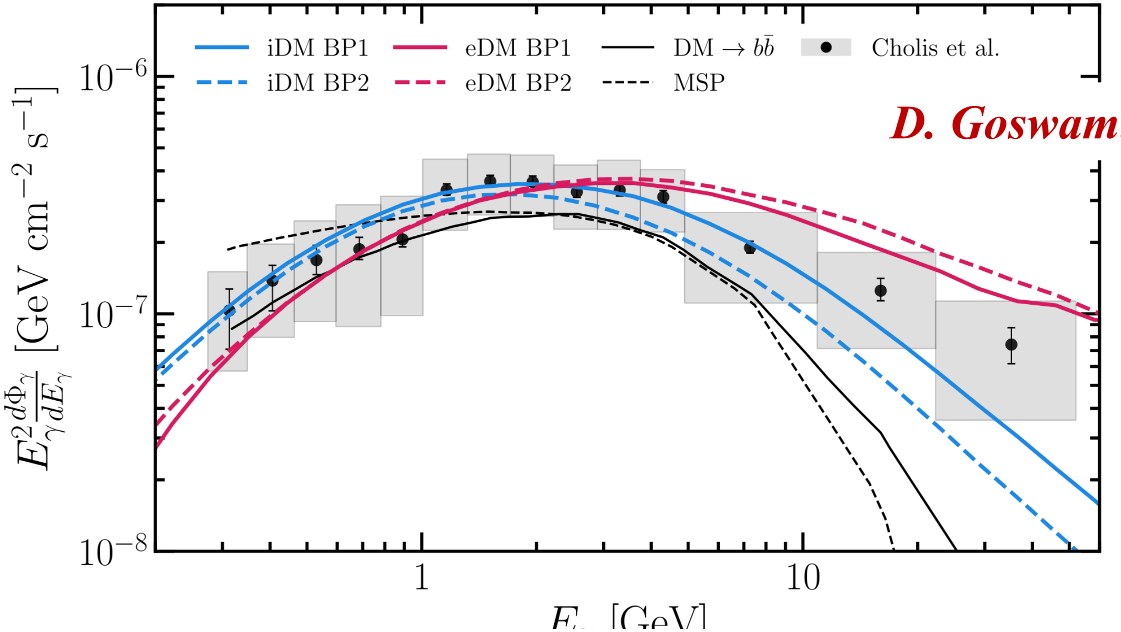
- Sub-GeV DM scattering with cosmic-ray protons can explain the GCE excess



iDM



eDM



D. Goswami's talk; PHENO 2026

Dutta, Goswami, Kumar, Rai, Sathyan, 2605.08010

DM scattering –models and signals

- MiniBooNE Excess: 560.6 119.6 (neutrino), 77.4 28.5 (antineutrino)

  - *4.8 σ excess: electron-like event*

Ross-Lonergan's talk, PHENO 2026

- MicroBooNE also observed similar low energy excess:
  560.6 ± 119.6 (neutrino mode) [2025]
  LAr based detector (94 ton at 468.5 m from the target), 8 GeV BNB

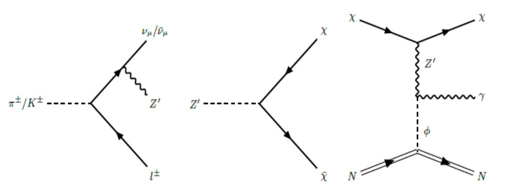
  - *2.2 σ excess: 1γ final state*

- These low energy excess events do not have any hadronic activity

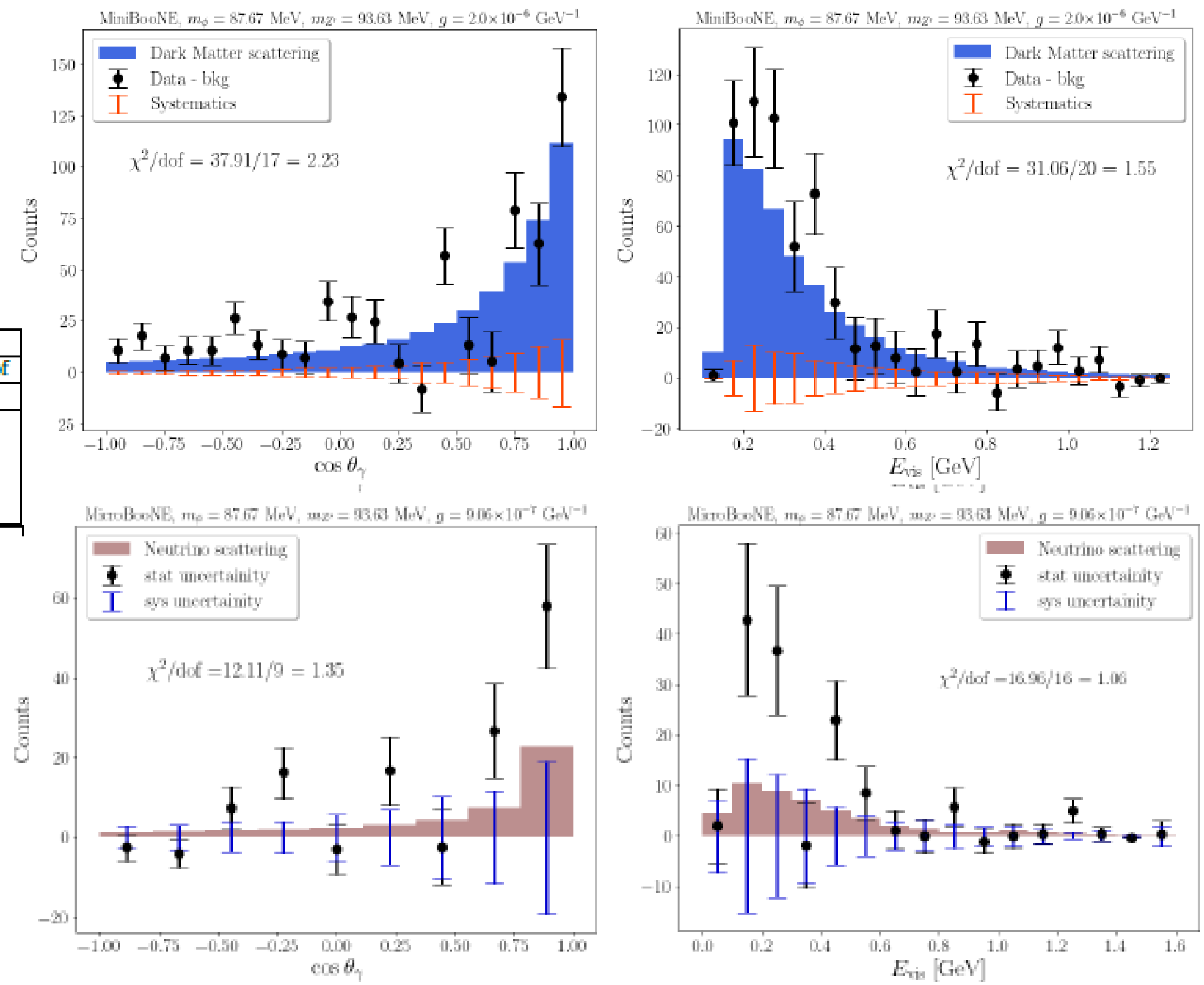
- New physics is needed

- SBND, ICARUS, CCM are ongoing where the explanations can be checked

DM solution?



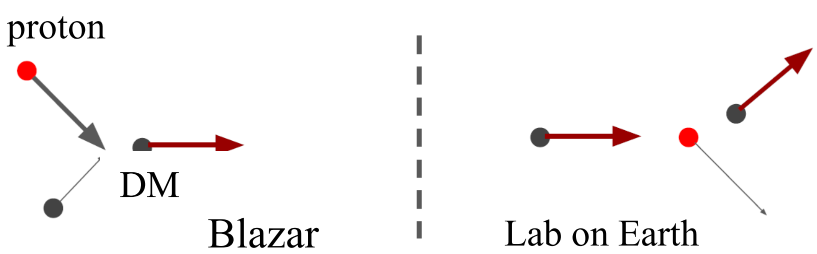
Dark matter fits ($\alpha_\chi = 0.5$)				
No	$(m_\phi, m_{Z'}, m_\chi)$ [MeV]	$g_{\phi Z'\gamma} y_\phi$ [GeV^{-1}]	Average χ^2/dof ν-MB	μB
①	(45.41, 48.49, 16.17)	2×10^{-4}	2.20	1.28
②	(87.67, 93.63, 31.21)	5×10^{-4}	1.89	1.27
③	(119.08, 114.06, 38.02)	7×10^{-4}	2.21	1.34
④	(193.07, 138.95, 46.31)	1×10^{-3}	1.79	1.41



Dutta, Goswami, Karthikeyan, Kim, Thompson, Van de Water, Phys.Rev.D 113 (2026) 1, 015029

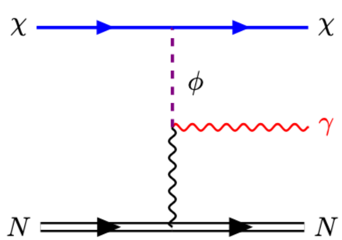
DUNE –FD and DM models

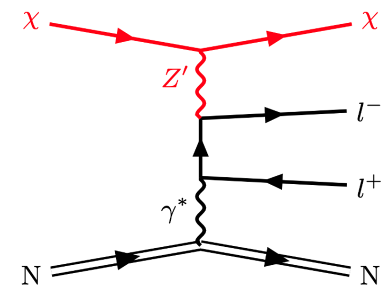
- The light DM particles can produce detectable leptonic signals from DM scattering at DUNE FD
- To detect sub-GeV DM at DUNE , we need boosting from cosmic rays
- High-energy proton jets from Blazars are useful to boost ambient DM

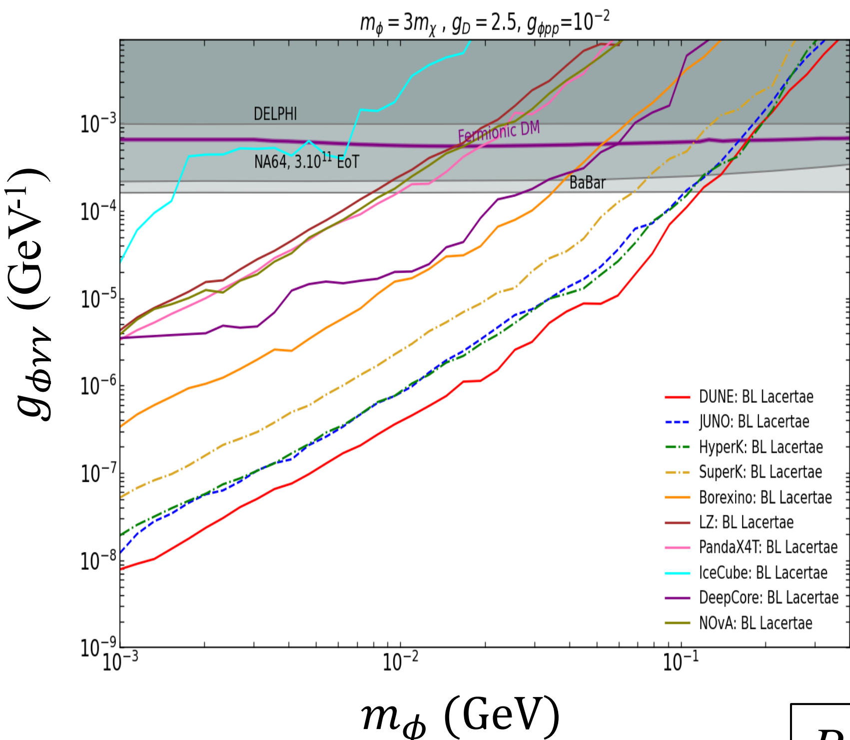


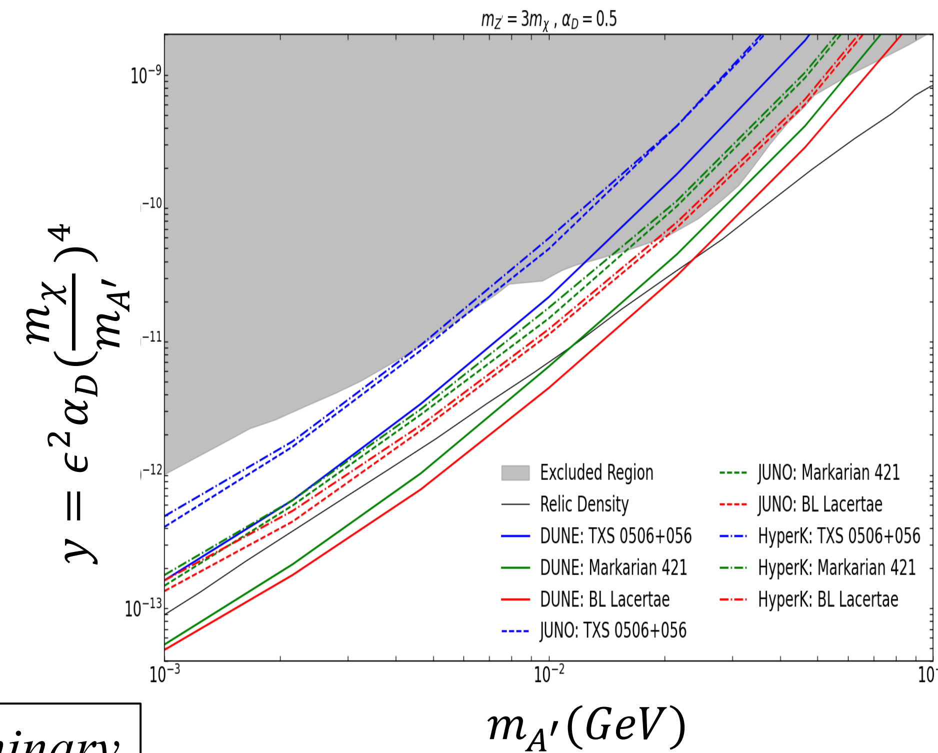
- Neutrinos from Blazars have been observed at IceCube
- Use these blazars to boost DM **E.g., De Marchi, Granelli, Nava, Sala, JHEP 12 (2025) 136**
- Along with electron and nuclear recoil, 2→3,4 scattering processing provides additional handles on models

DUNE -FD and DM models









Preliminary

Cappiello, Dent, Dev, Dutta, Goswami, Karthikeyan, To appear

Outlook

- Many dark sector models explain the DM abundance
- DM scattering via nuclear/electron recoils may not probe the details of a model
- DM scattering with multiple scattering can probe more final states, ee, $\mu\mu$,$\tau\tau$, γ etc. via 2→3, 4 scattering
- These scattering processes can probe new parameter space and final states with kinematics different from the SM background at DUNE near and far detectors
- These scattering processes can also explain the Galactic Center Excess, MiniBooNE excess etc. with new perspectives

HAPPY 70th Tao!