Dark Matter Scattering: New possibilities

Bhaskar Dutta

Texas A&M University

Based on 2410.07624 (to appear in PRL), 2504.08071, 2505.22754

Phenomenology at the Frontiers, University of Wisconsin, Madison

June 6, 2025

Introduction

- New Physics: Dark Matter (DM), Neutrino masses and mixing, Matter-antimatter asymmetry, Anomalies, e.g., MiniBooNE/MicroBooNE, KM3NeT, Atomki etc.

- Where is the new physics scale?

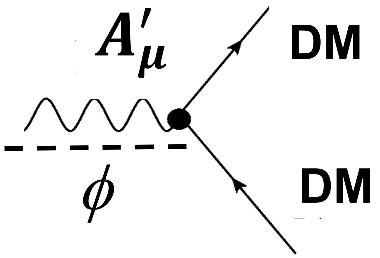
- Many experiments are probing new physics scales: DM direct and indirect detections, LHC, neutrino experiments, beam dump experiments, rare decays, etc.

➢ This talk investigates mostly light DM

- A few new possibilities to investigate more parameter space and address some of these anomalies

Models of Light Mediators, DM

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



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

- These light mediators can decay into DM and various SM particles

- Models also possess light scalar (associated with SSB)➔ leads to interesting phenomenology, e.g., DM, g-2, etc. **Dutta, Ghosh, Kumar, 2019**

- One can utilize the Higgs- sector based new physics to have a light scalar (sub-GeV)

- Higgs sector is extended (No additional gauge symmetry) by a doublet, triplet, and a singlet, e.g., $\phi_1{:}\left(2,\frac{1}{2}\right)$, $\phi_2{:}\left(2,\frac{1}{2}\right)$, $\phi_s{:}\,(1,0)$, $\Delta{:}\,(3,1)$,

- Minimize the Higgs potential➔ In addition to the light scalar, one can have a light scalar/pseudoscalar +Higgs+heavier scalar

**Dutta, Ghosh, Li, Thompson, Verma,
JHEP 03 (2023) 163, Phys.Rev.D 100 (2019) 11, 115006**

Low mass DM

- ❑ How do we probe low-mass DM (sub GeV)?

- ➢ Ambient and Laboratory produced dark matter

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

- o Detectors Liquid: Ar, Xe; Semiconductors: Ge, Si; Scintillators: CsI, NaI, GaAs
  [Also, optical trapping, polar materials, superconductors,
  superfluid helium, Dirac materials, Molecular gases etc.]

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

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

This talk utilizes new DM scattering diagrams to

- Investigate new DM parameter space (proton beam-dump based experiments)
- Applications: Address the MiniBooNE/MicroBooNE anomaly, KM3NeT event from the scattering

These diagrams can be used to explore new parameter space in various other experiments

Low mass DM at ν experiments

- Proton beam dump-based neutrino experiments provide a great opportunity to probe light DM

- High-intensity proton beam ($10^{20\text{-}23}$ POT) ➔ A large number of dark matter particles

Many experiments: E.g., O(1) GeV at COHERENT, CCM, $JSNS^2$, 8 GeV at SBND, MicroBooNE, ICARUS, MiniBooNE, 120 GeV at ICARUS , DUNE, DarkQuest etc.

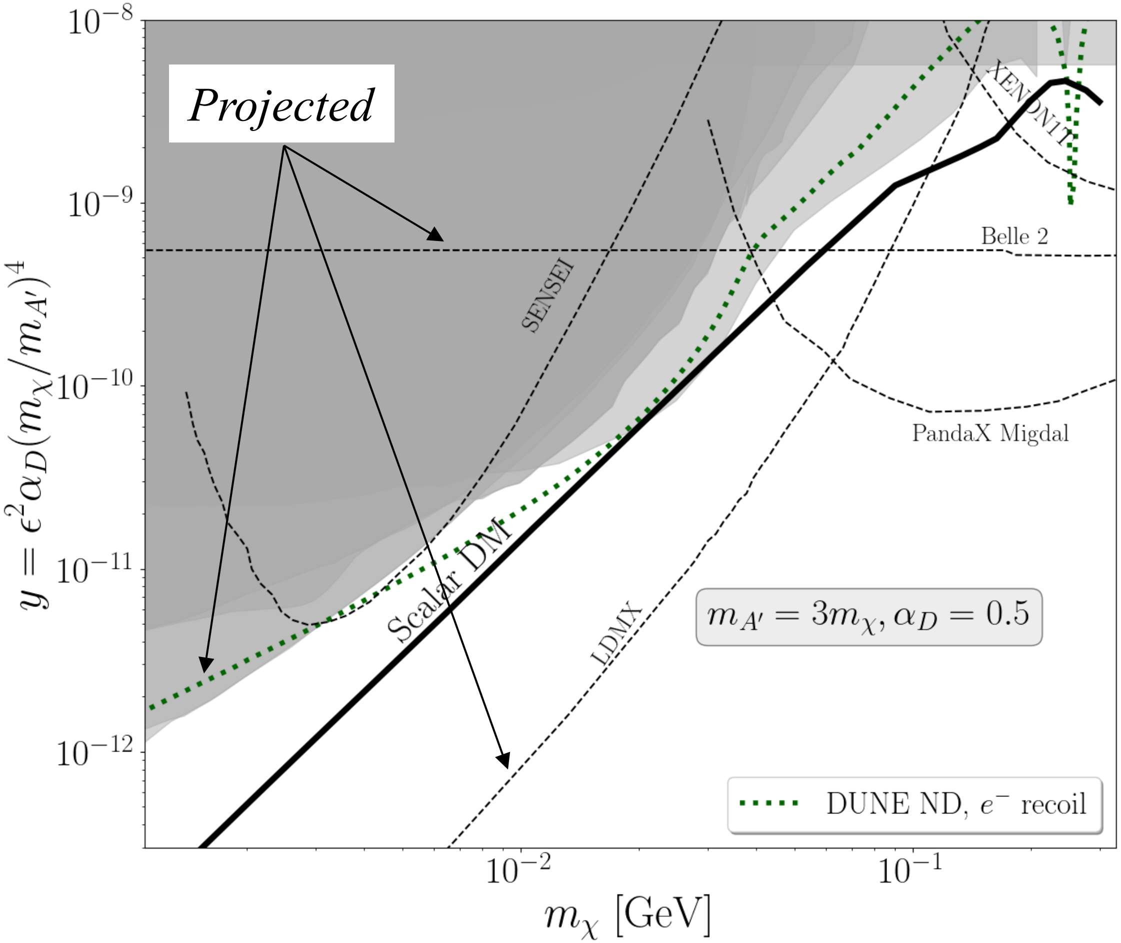
- Dark matter particles are produced at higher energy

- Large-size detectors

- Various kinds of detectors, e.g., LAr, CsI, NaI, D_20, Ge etc.

==> Best constraint on the existing parameter space

Low mass DM at ν experiments



Direct detection constraints:
XENON, PANDAX:
electron coupling
(electron recoil): g_e^2
Quark couplings (Migdal): g_q^2

LDMX, Belle 2:
electron coupling: g_e^2

Proton-beam based ν experiment $g_e^2 * g_q^2$, g_q^4

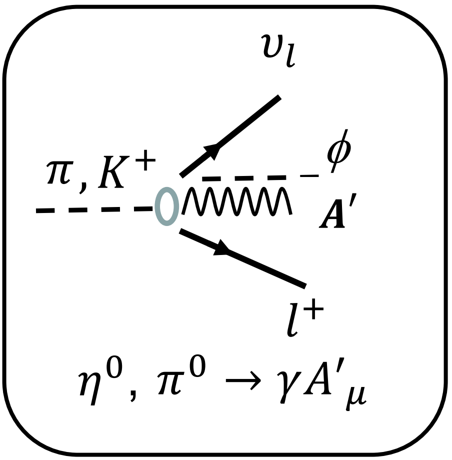
Shaded regions: $\underbrace{\text{COHERENT, LSND}}_{\sim \textit{GeV beam}}$, MiniBooNE, NA64e **(Current constraints)**

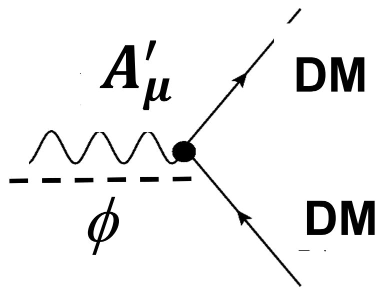
~ GeV beam   *8 GeV beam*

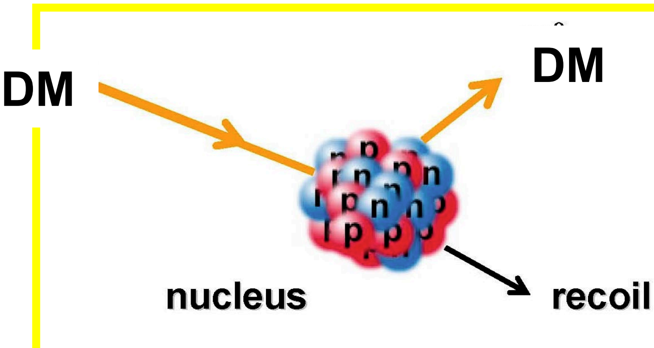
Low mass DM at ν experiments

Dark matter particles can be produced in the lab

➔ Dark gauge bosons, scalars decay into dark matter: Mediators with shorter lifetime



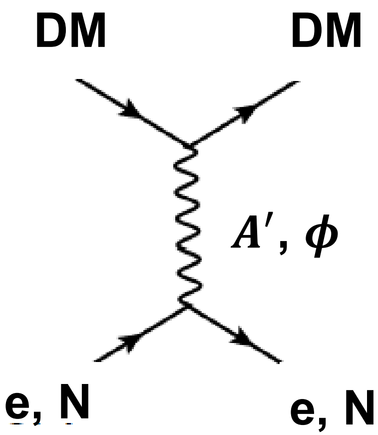




Nuclear and electron recoil

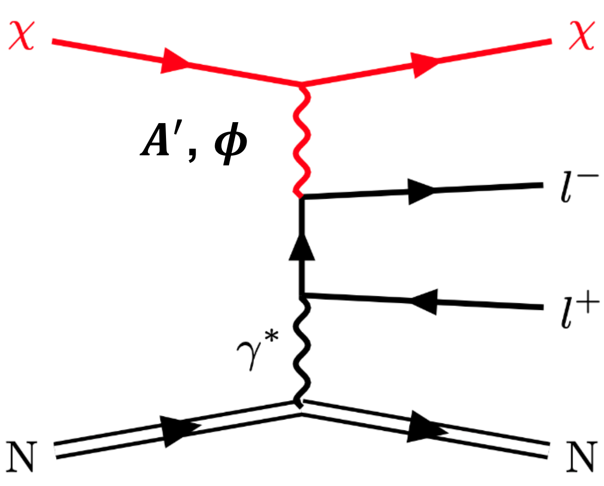
- Lower threshold detectors would be useful
- Lot more dark matter particles compared to direct detection experiments
- Problem: Neutrinos also produce the same signals ➔ Neutrino floor?

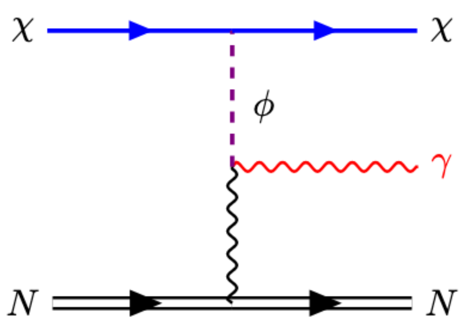
DM : New detection Channel



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

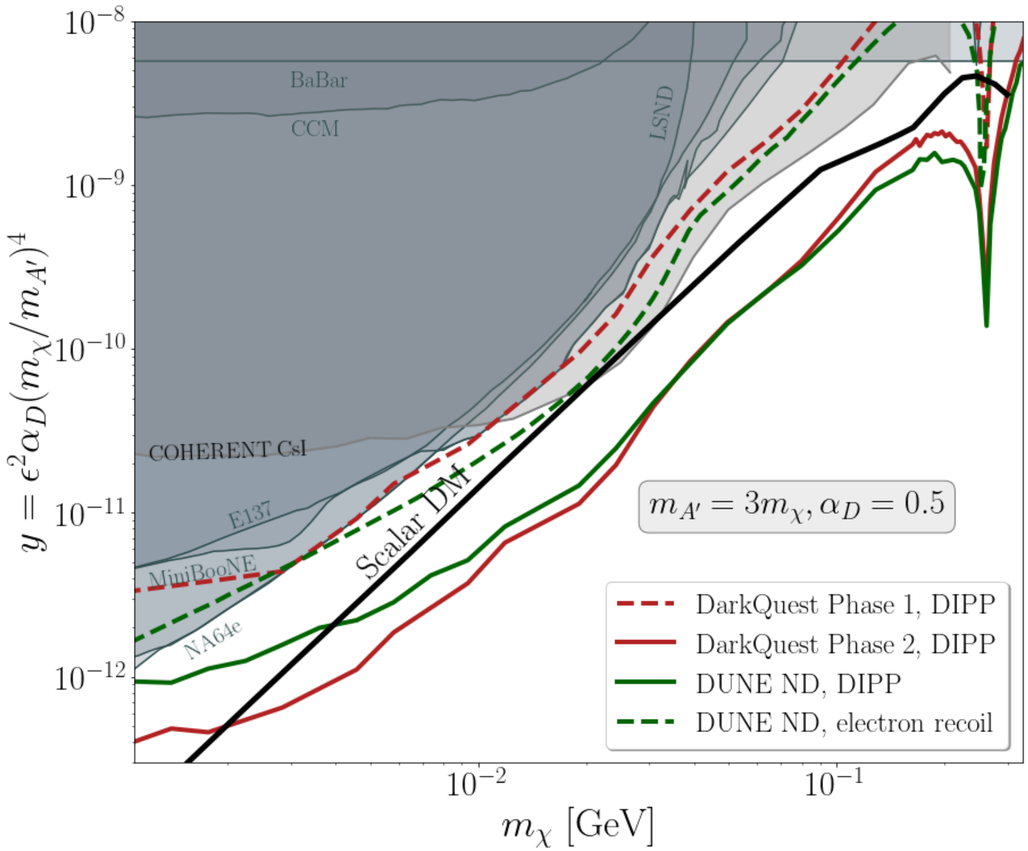
➢ *We introduce 2-4, 2-3 processes with both scalar and vector mediators*



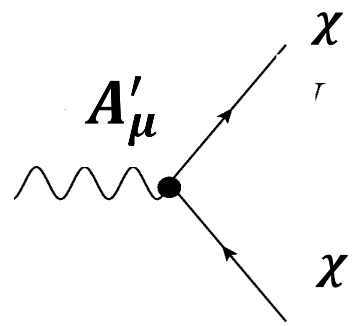


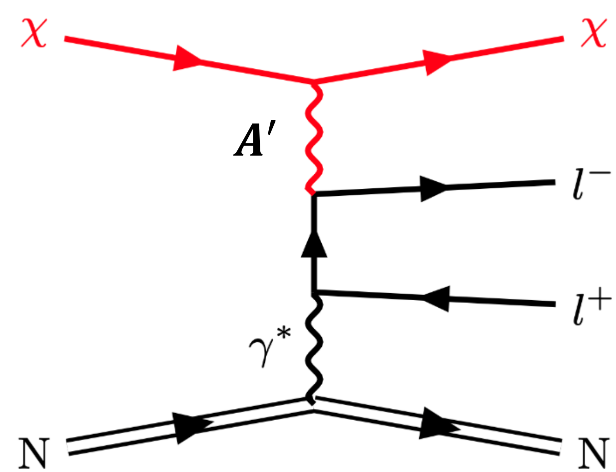
…

A new channel for DM: Vector Mediator



$\eta^0,\ \pi^0 \to \gamma A'_\mu$

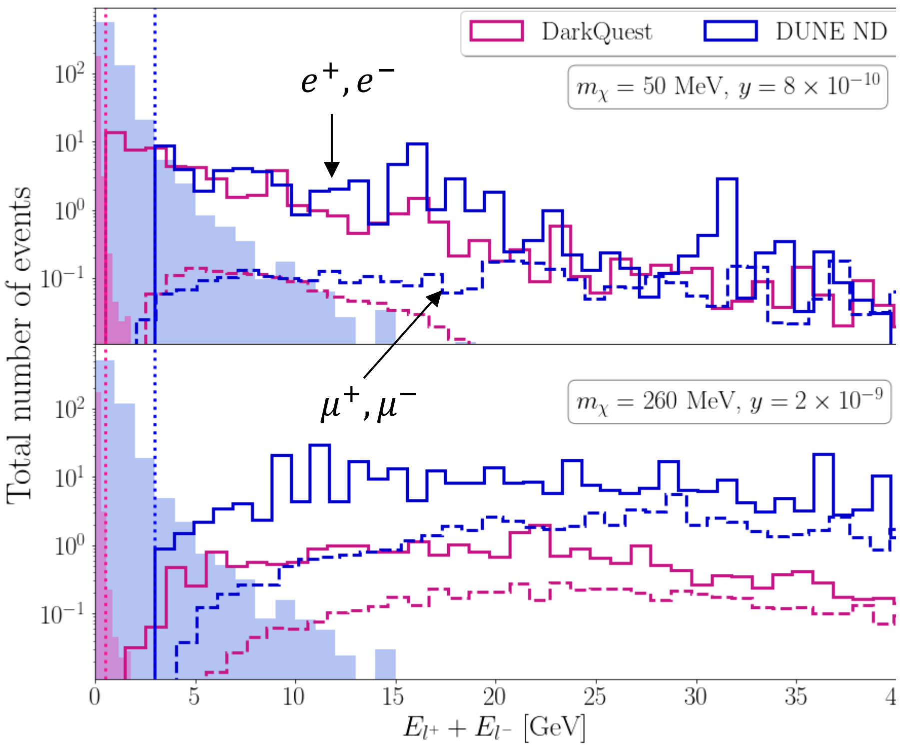


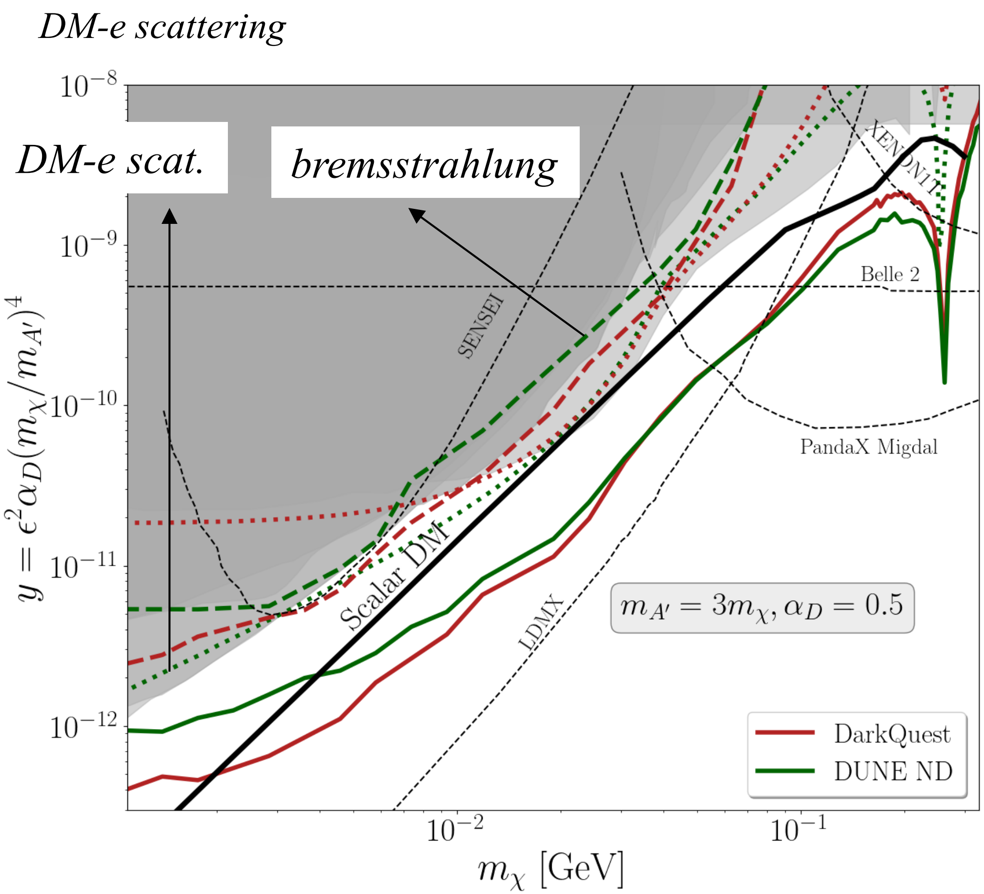


Better sensitivity: l^+l^- final states with higher energy

Dutta, H. Kim, Karthikeya, Rai, 2410.07624 (to appear in PRL)

A new channel for DM: Vector Mediator



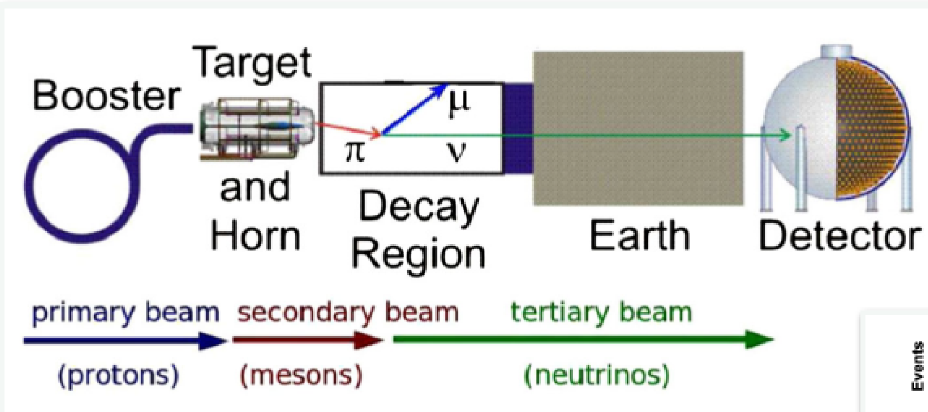


Energy distributions of the final state electron-positron pair along with the SM background (mostly from ν_μ-NCπ^0)

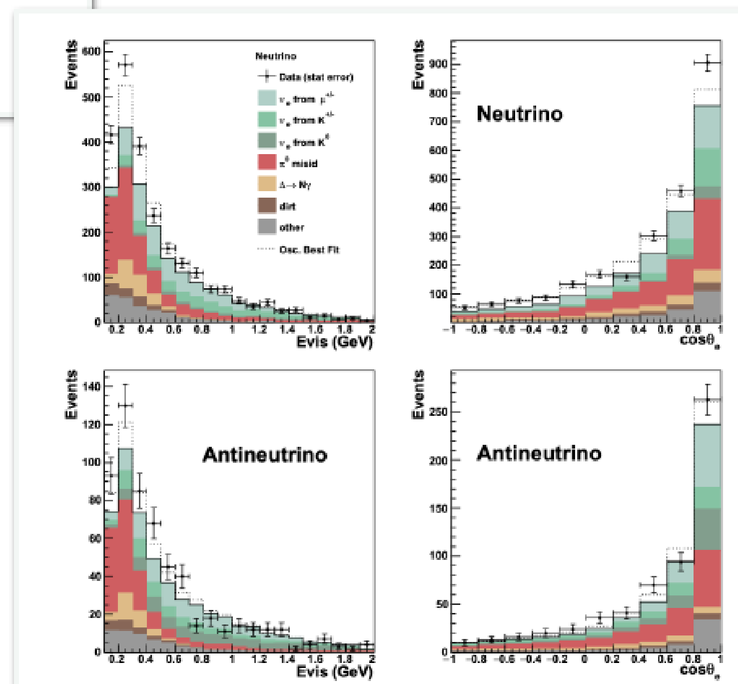
Sensitivity of the DIPP channel in comparison with the DM-e scattering

1. MiniBooNE/MIcroBooNE anomaly

MiniBooNE Anomaly



- MiniBooNE, 2021 [2006.16883]
- MiniBooNE, 2019 [1807.06137]
- MiniBooNE, 2018 [1805.12028]



- 8 GeV proton beam on Be target
- Magnetic horns focus charged meson decays for neutrino production
- 12m diameter, 818 tonne mineral oil (CH2) detector
- 489m downstream from dump

MiniBooNE/MIcroBooNE anomaly

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

  - *4.8σ excess: electron-like event*

- MicroBooNE also observed similar low energy excess:

  93 ± 22(stat.) ± 35 (syst.) (neutrino mode) [2025]

  LAr based detector (94 ton at 468.5 m from the target), 8 GeV BNB

  - *2.2σ 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

Existing solutions

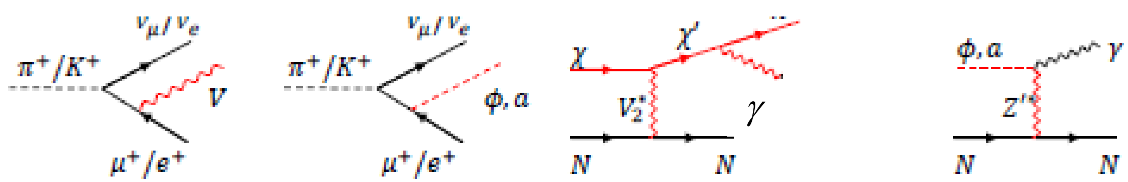
Model	U. Signature
3+1	Oscillations
(3+1) + inv-ν decay	Damped oscillations
(3+1) + NSI	Modified matter effects
Anomalous matter	Resonant appearance
Large extra dim	Osc with related freqs.
LNV in μ decays	$\mu^+ \rightarrow$ anti-ν_e
Lorentz violation	Sidereal time variation
Dark neutrinos	Upscattering to $N \rightarrow \nu\, e^+e^-$
Dipole portal	Upscattering to $N \rightarrow \nu\, \gamma$
(3+1) + vis-ν decay	DIF of $\nu_s \rightarrow \nu_e$
(3+1) + vis decay	DIF of $N \rightarrow \nu\, \gamma$
Dark sectors: dark matter	Upscattering to $\chi' \rightarrow \chi\, e^+e^-$
Dark sectors: (pseudo)-scalar	Forward scattering to γ

Existing Neutrino Based solution requires extra species

Dark Matter based solution need inelastic dark matter

1 γ + 0 p solutions:

- Neutrino upscattering, $\bar{\nu}\sigma_{\mu\nu}NF^{\mu\nu}$
- dark matter upscattering, $\bar{\chi}\sigma_{\mu\nu}\chi' F^{\mu\nu}$
- longer lived mediator



Dutta, Kim,Thompson,Thornton,Van de Water, PRL 129 (2022) 11, 111803

- Can we have solutions involving DM and active neutrino elastic scattering?

Anomaly: New physics

MiniBooNE		Excess	POT	Charged Mesons Focused?
Target Mode	*Neutrino Mode*	560.6±119.6	1.875E+21	π^+, K^+
	Anti-neutrino Mode	77.4±28.5	1.127E+21	π^-, K^-
Dump Mode		None	1.86E+20	Isotropic

- When a proton beam hits a target, a lot of charged and neutral mesons are Produced about one pion/POT, 0.1 kaon/POT
- Almost all the charged pions, and kaons are horn focused on the direction of the detector (the neutral mesons fraction is smaller)

Solutions:

- Most of the solutions which are proposed are neutrino-based new physics
- Dark sector attempts to use π^0 decay are ruled out by the dump mode data

Jordan, Kahn, Moschell, Krnjaic, Spttz, Phys.Rev.Lett. **122 (2019) 8, 081801**

$$\pi^0 \to X + \gamma$$

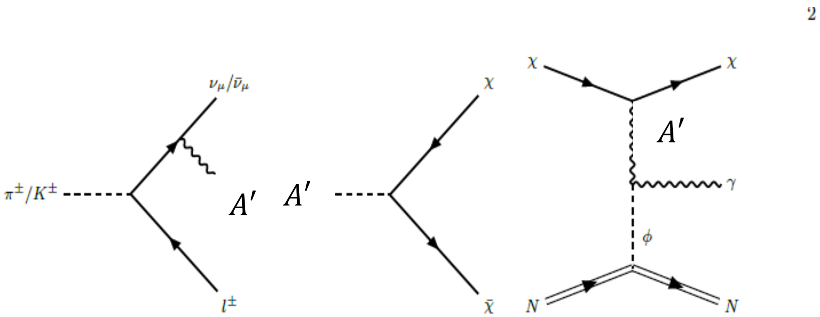
- We can use the charged pion decays for the dark sector based solution

Dutta, Kim,Thompson,Thornton,Van de Water, PRL 129 (2022) 11, 111803

- Neutrino-anti-neutrino mode excess difference can be accommodated
- in the charged pion-based solutions

DM solution?

- Can DM solve this excess?



$\propto g_\nu \, g_{\phi A'\gamma} g_q$

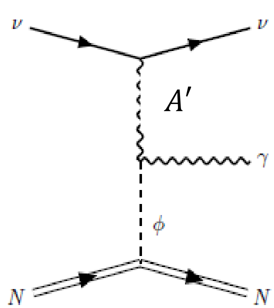
α_D=0.5

A', ϕ can be replaced by single, multiple ϕ's

$$\mathcal{L}_{\text{int}} \supset g_\nu(\bar{\nu}_\mu\gamma^\alpha\nu_\mu + \bar{\nu}_e\gamma^\alpha\nu_e)A'_\alpha + g_\chi\bar{\chi}\gamma^\mu\chi A'_\mu - \frac{g_{\phi A'\gamma}}{2}F_{\mu\nu}A'^{\mu\nu} + g_q\bar{q}q\phi$$

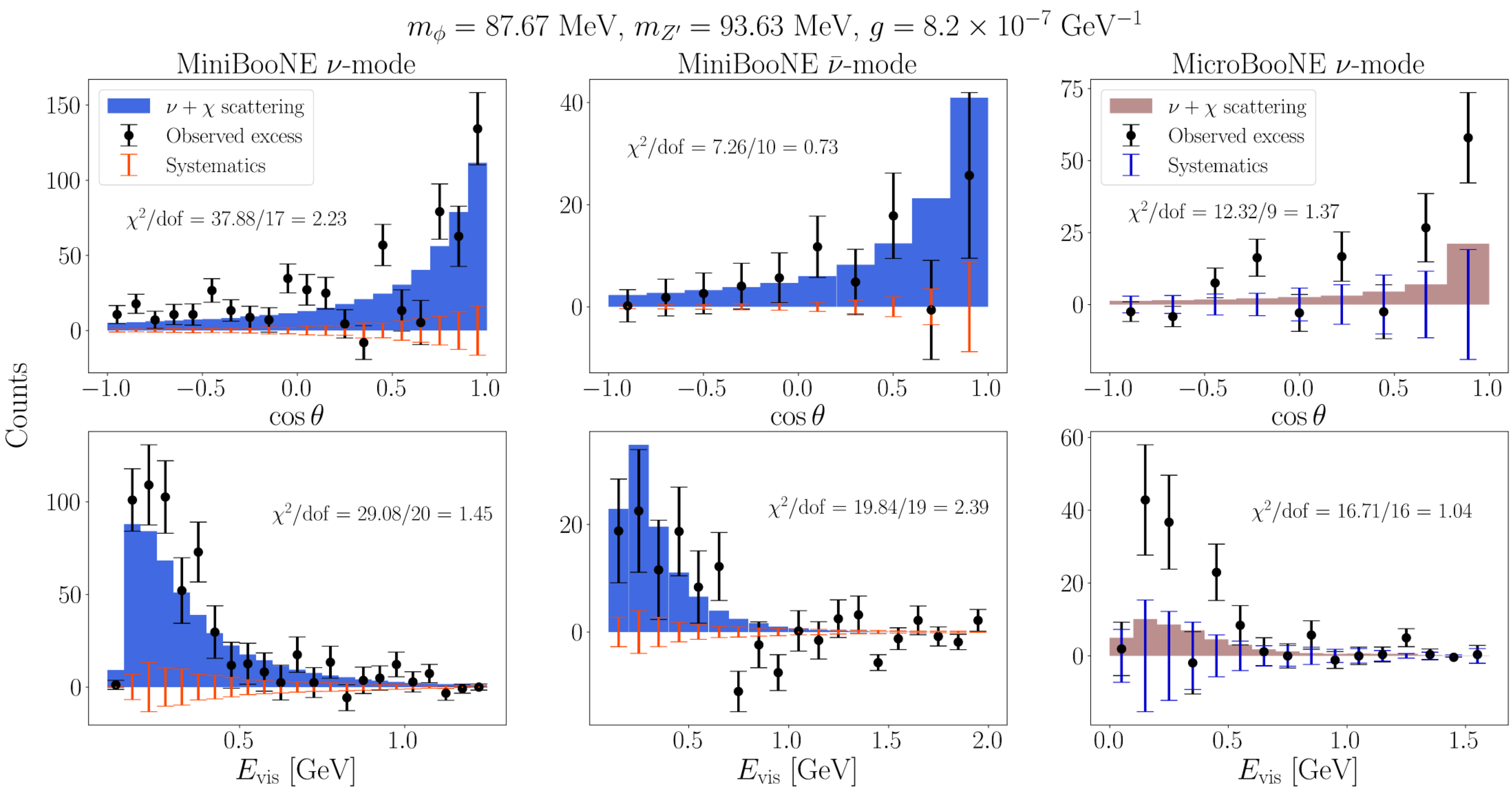
- Dark matter shares a large amount of energy with γ

- Can ν solve this excess?

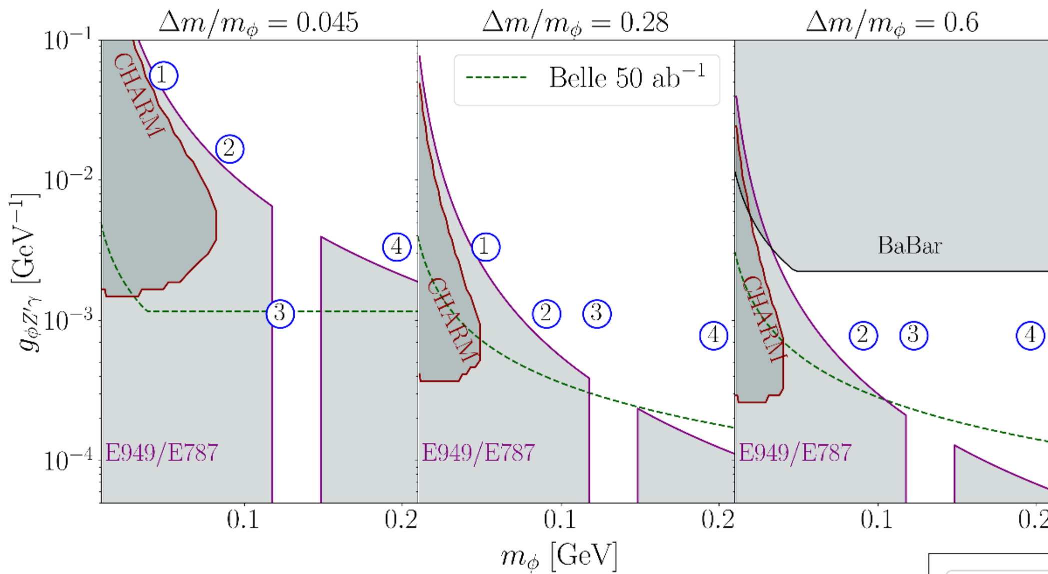


Dutta, Karthikeyan, D. Kim, Thompson, Van de Water, 2504.08071

DM/ν solution?



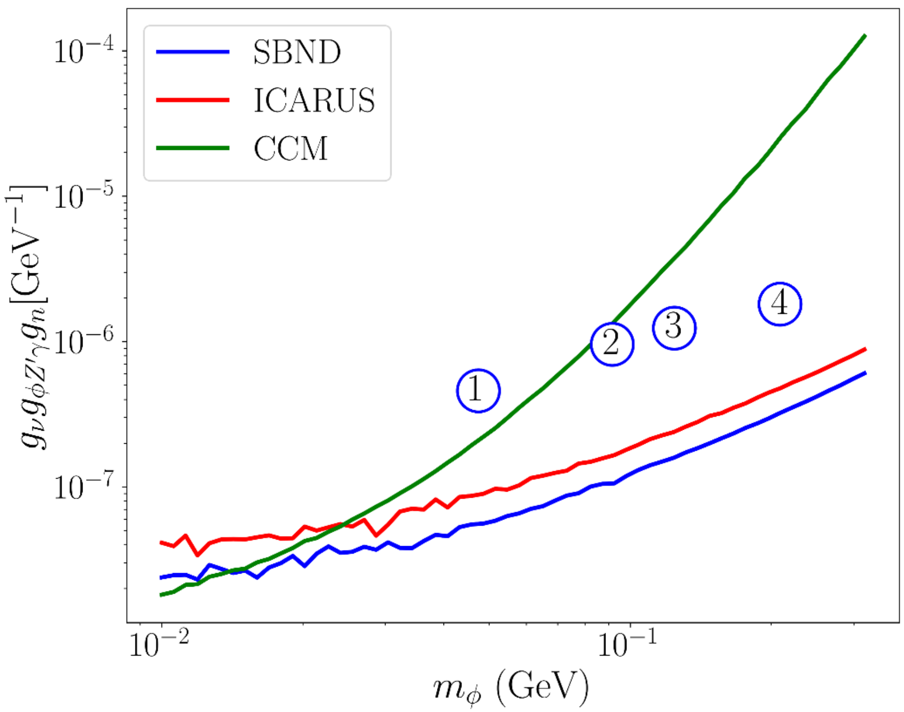
DM/ν solution?



Mono-photon search at Belle2, Babar, CHARM: depends on the mass gap of $m_\phi - 2m_\chi$

E787/949: $K^+ \to \pi^+ \phi$

Neutrino + dark matter fits					
			Average χ^2/dof		
No	$(m_\phi, m_{Z'})$ [MeV]	g [GeV^{-1}]	ν-MB	$\bar{\nu}$-MB	μB
1	(45.41, 48.49)	3.93×10^{-7}	2.02	1.49	1.13
2	(87.67, 93.63)	8.20×10^{-7}	1.76	1.56	1.20
3	(119.08, 114.06)	1.06×10^{-6}	1.76	1.58	1.28
4	(193.07, 138.95)	1.55×10^{-6}	1.76	1.66	1.35

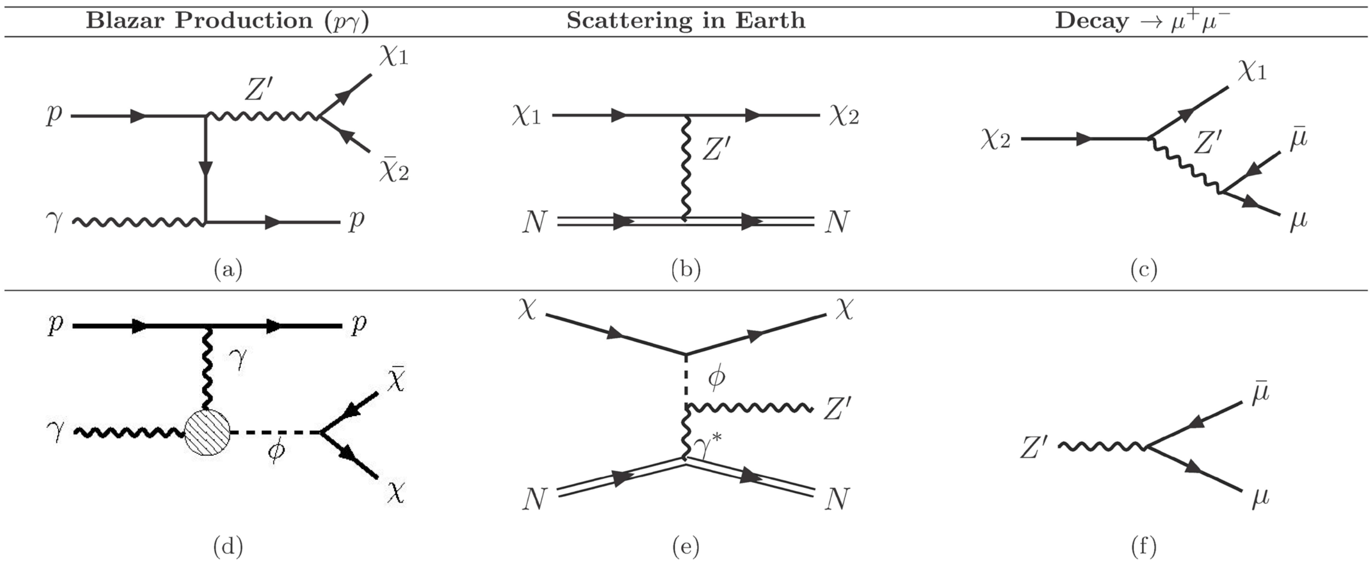


2. KM3NeT event: DM scattering

- Detected a throughgoing muon in 335 days of live data from ARCA with 0.15 km^3 instrumented volume. 3672 PMTs (35% of the active PMTs) triggered.
- Estimated muon energy: 120^{+110}_{-60} PeV.
- Event direction is 0.6^0 above horizon (with 1.5^0 uncertainty at 68% CL) at an azimuth of 259.8^0.
- In equatorial coordinates, RA=94.3^0, dec.=-7.8^0 (far from GC).
- A few potential blazar sources pinpointed (at 68% CL).
- Best-fit neutrino flux: 2.25-3σ tension with IceCube
  O. Adriani et al. (KM3NeT), 2502.08173; Li, Machado, Naredo-Tuero, Schwemberger, 2502.04508
- Any solution needs to address why this KM3NeT observation is not shown up at IceCube

KM3NeT and IceCube

- We produce dark matter using pp, pγ interactions in the blazar
- The dark matter scatters inside the Earth and shares energy with the mediator
- The mediator decays into a muon pair

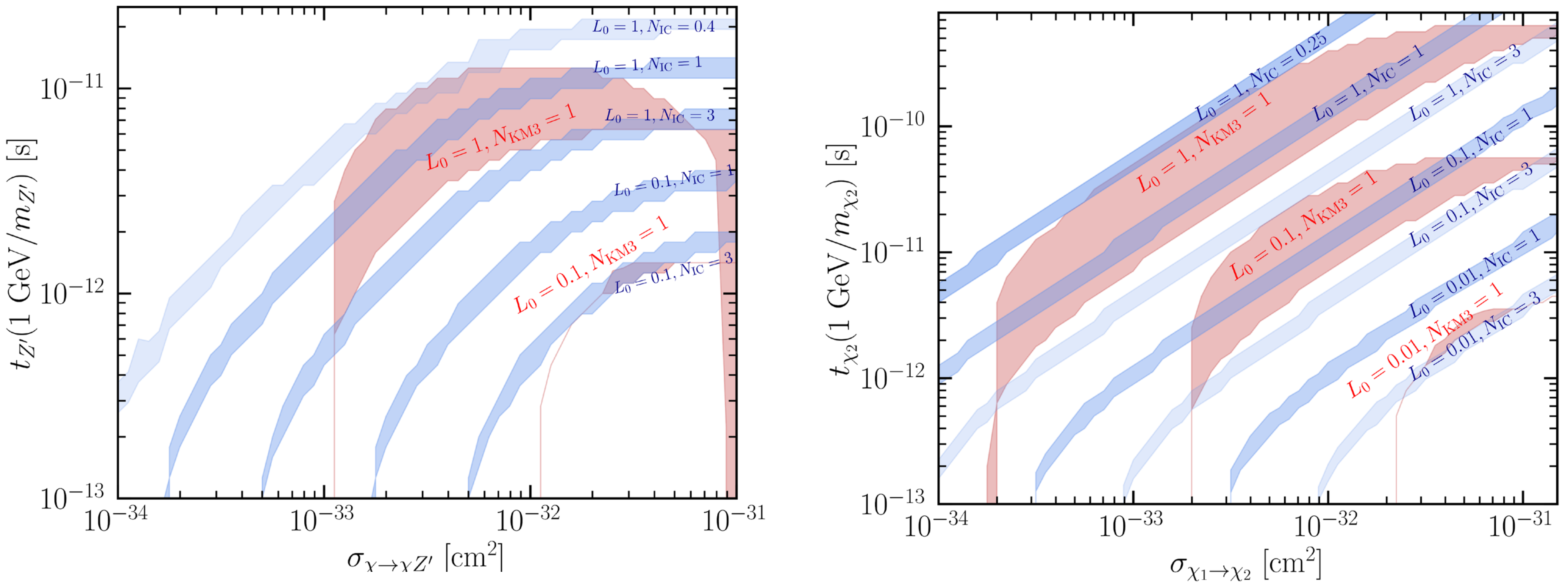


$$\mathcal{L}_{\mathrm{DS1}} = \mathcal{L}_{\mathrm{kin}}^{\chi_1,\chi_2,Z'} + m_{\chi_1}\bar{\chi}_1\chi_1 + m_{\chi_2}\bar{\chi}_2\chi_2 + \frac{m_{Z'}^2}{2} Z'^{\alpha} Z'_{\alpha} + g_\chi \bar{\chi}_2\gamma^\alpha\chi_1 Z'_\alpha + g_{Z'} Z'_\alpha\Big(\bar{\mu}\gamma^\alpha\mu + \sum_{q=u,d}\bar{q}\gamma^\alpha q\Big)$$

$$\mathcal{L}_{\mathrm{DS2}} \supset \mathcal{L}_{\mathrm{kin}}^{\chi,\phi,Z'} + m_\chi\bar{\chi}\chi + \frac{1}{2}m_{Z'}^2 Z'^{\mu} Z'_{\mu} + \frac{1}{2}m_\phi^2\phi^2 + g_\chi\bar{\chi}\chi\phi + \frac{1}{2}g_{\phi Z'\gamma}\phi F^{\alpha\beta}F'_{\alpha\beta} + g_{Z'}Z'_\alpha\bar{\mu}\gamma^\alpha\mu$$

KM3NeT and IceCube: Using Blazars

- The direction of KM3Net event: the distance traveled by DM arising from blazars is 59 km and 418 km.
- The corresponding range of distance to reach IceCube is between 12 km and 17 km.

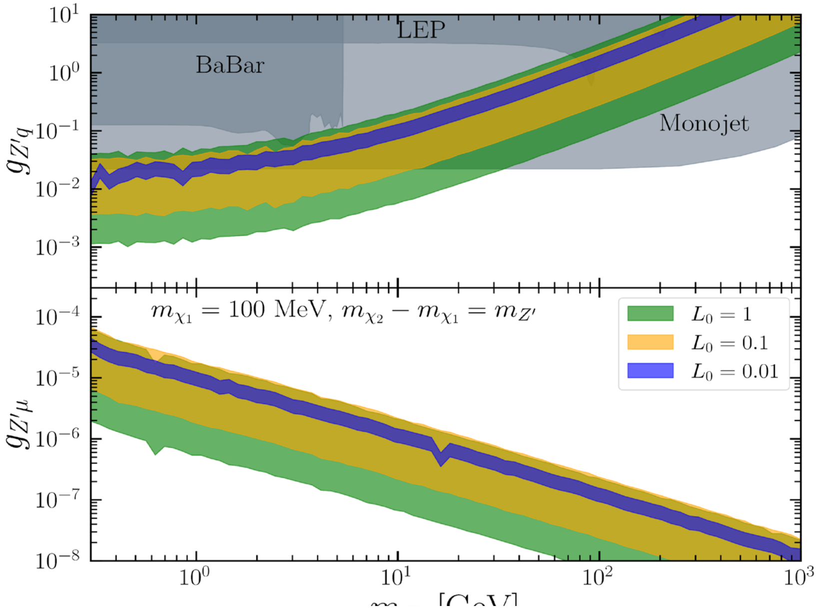


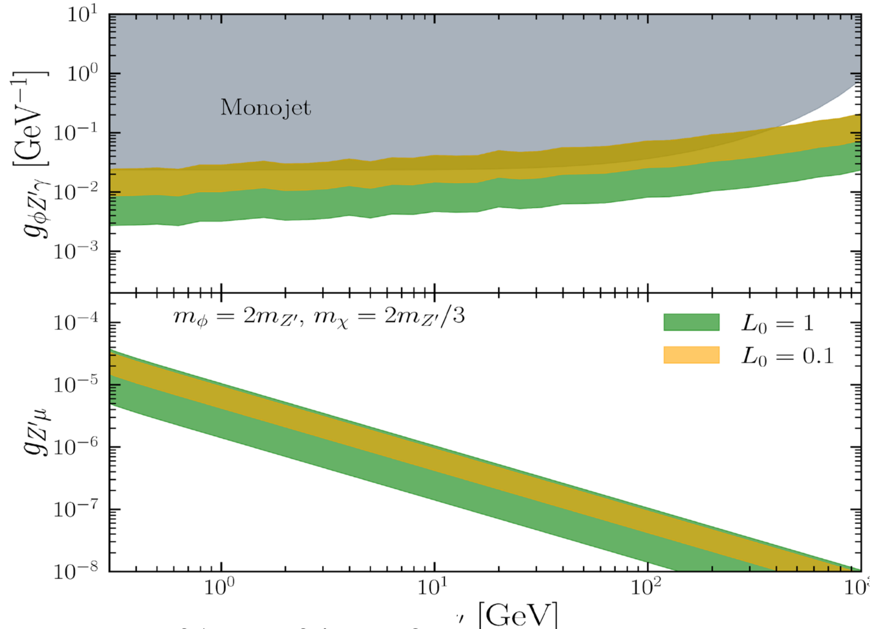
DM flux: $\dfrac{d\phi}{dE_\chi} = \dfrac{L_\chi f_{\rm beam}}{4\pi d_L^2 E_\chi^2}$ $\qquad N_{\rm evt} = T_{\rm exp}\displaystyle\int_{E_\chi^{\rm min}}^{E_\chi^{\rm max}} dE_{\chi_i}\frac{d\phi}{dE_{\chi_i}} A_{\rm eff}(N_{\rm PMT}, E_{\chi_i}, E_{\rm th}, d_b, \delta)$

$L_\chi = L_0\ 10^{48}$ erg/s Blazar dark matter luminosity with $f_{\rm beam} = 10^3$

Dev, Dutta, Karthikeyan, Maitra, Strigari, Verma, 2505.22754

KM3NeT and IceCube





- The dark matter nucleon cross-section 10^{-31}-10^{-34} cm^2
- The blazar luminosity 10^{49}- 10^{51} erg/s
- Why no visible EM cascade?
  Depends on source redshift and IGMF.

Fang, Halzen, Hooper, 2502.09545
Crnogorčevića, Blanco, Linden, 2503.16606

Dev, Dutta, Karthikeyan, Maitra, Strigari, Verma, 2505.22754
Also see, Brdar and Chattopadhaya, 2502.21299, Hostert and Farzan, 2505.22711

Outlook

- DM scattering diagrams 2➔n can explain various anomalies and investigate new parameter space
- New signals from the scattering benefit from the energetic dark matter
- Explore new regions of parameter space for light dark matter searches at neutrino beam dump facilities
- Explain the MiniBooNE, MicroBooNE low-energy excesses, KM3Net event
- Astrophysical sources can be used to probe dark matter, utilizing the new scattering channels