"Meson-scopy": Looking into New Physics via Mesons

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Outline

I.   Motivation of Dark Sector Probes

II.   Meson-scopic Dark-Sector Particle Searches: Intensity Frontier

- Exotic charged meson decays, dark-sector interpretation of the MiniBooNE excess, light dark matter search at SBND

III.   Meson-scopic Dark-Sector Particle Searches: Energy Frontier
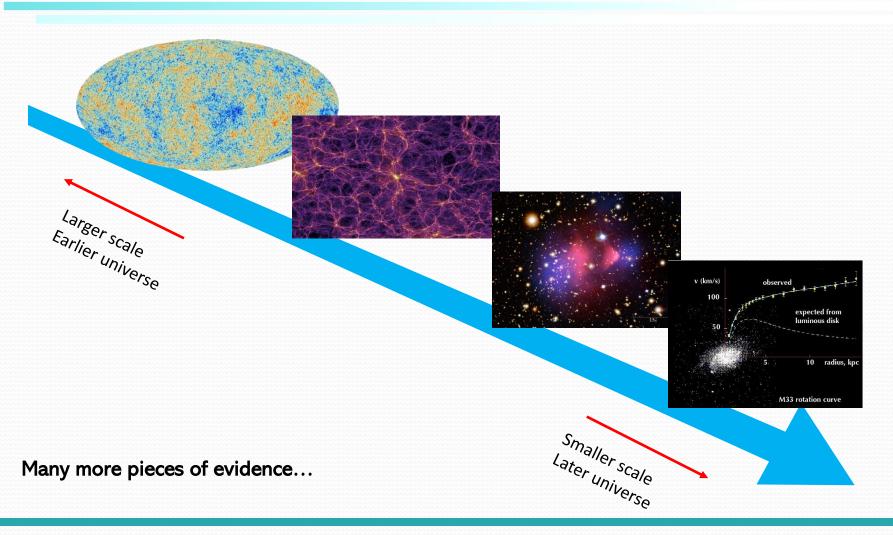
- Search at forward physics facilities (e.g., FASER), search in the LHC detectors (e.g., muon system of CMS)

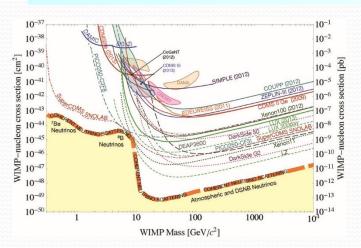**IV.   Meson-scopic Dark-Sector Particle Searches: Cosmic Frontier**

- Charged mesons in the cosmic shower

V.   Conclusions
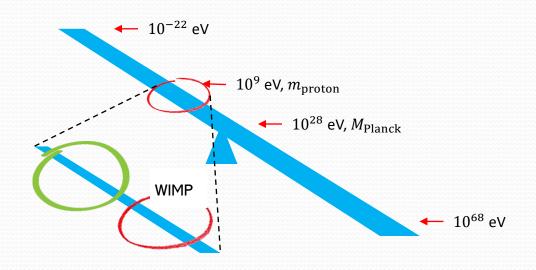
Dark Matter Puzzle

Larger scale
Earlier universe

Smaller scale
Later universe

Many more pieces of evidence…

Light Dark Matter and Light Mediators

Null observation of (WIMP) dark-matter signal

through non-gravitational interactions

Light dark matter and light mediators

- ✓ Can be a thermal dark matter candidate

- ✓ Less constrained by current searches

- ✓ Often **feebly/weakly interacting** with SM particles and involving **similar mass-range mediators**

Mediator as a Portal to Dark Sectors

☐ **Spin 0**

- Higgs portal $\quad \mathcal{L}_{\text{Higgs portal}}^{d=3,4} = -(\mu S + \lambda S^2) H^\dagger H$

- Axion/ALP portal $\quad \mathcal{L}_{\text{axion portal}} = \frac{a}{4f_G} \text{Tr}\, G^{\mu\nu} \widetilde{G}_{\mu\nu} + \frac{a}{4f_\gamma} F^{\mu\nu} \widetilde{F}_{\mu\nu} + \frac{1}{f_{q_\mu}} a \sum_q \bar{q} \gamma^\mu \gamma^5 q + \frac{1}{f_{l_\mu}} a \sum_l \bar{l} \gamma^\mu \gamma^5 l$

☐ **Spin ½**

- Neutrino portal $\quad \mathcal{L}_{\text{neutrino portal}}^{d=4} = -\sum y_\nu^{\alpha I} (\bar{L}_\alpha H) N_I$

☐ **Spin 1**

- Vector portal $\quad \mathcal{L}_{\text{vector portal}}^{d=4} = -\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'_{\mu\nu}$
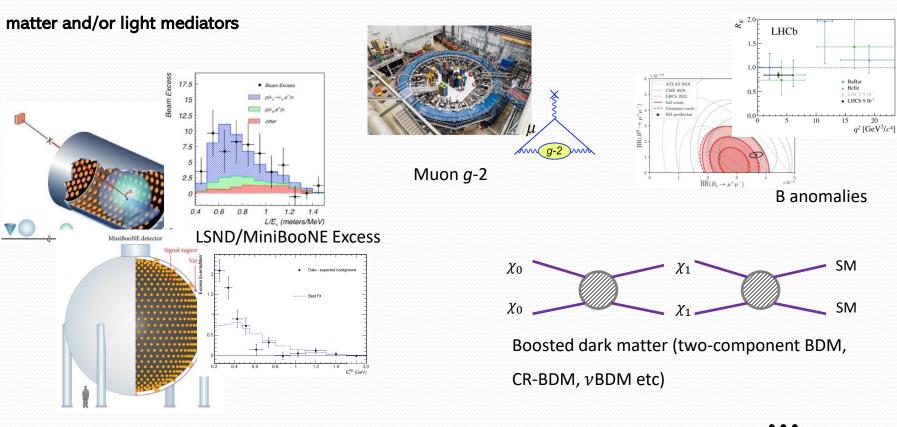

Many models/scenarios have been proposed and related pheno has been investigated for the last decade.

(See also Snowmass2021 Whitepaper "Dark Sector Studies with Neutrino Beams". [arXiv:2207.06898])
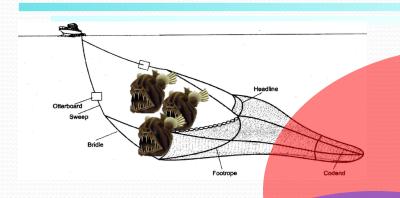
Various Phenomena and Dark-Sector Interpretations

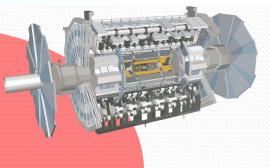Various HEP phenomena including excesses, anomalies, non-minimal dark-sector scenarios motivate light dark matter and/or light mediators

LSND/MiniBooNE Excess

Muon g-2

B anomalies

Boosted dark matter (two-component BDM, CR-BDM, νBDM etc)
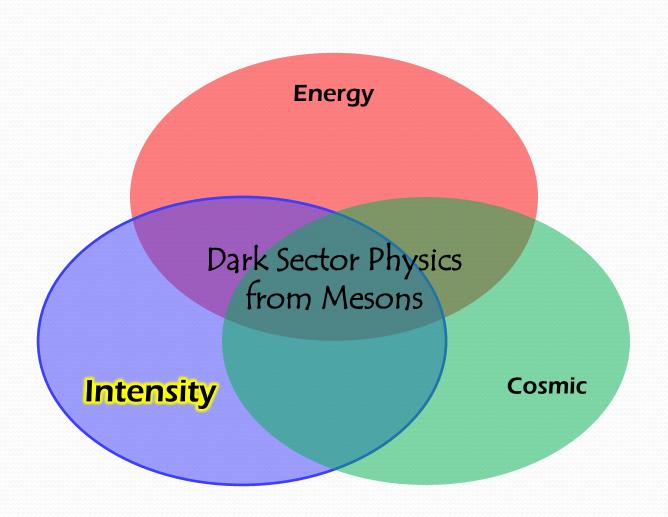
$\cdots$

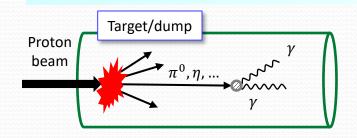Energy

Dark Sector Physics from Mesons

Intensity

Cosmic

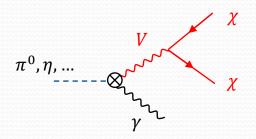**NEU**trino facilities are **NEW** physics machines

as well as neutrino factories.

... much more BSM potentials than expected
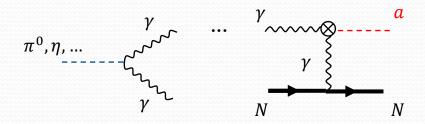
Conventional Meson-Induced New Physics Scenarios

Target/dump

Proton beam

$\pi^0, \eta, \ldots$

γ

γ

Promptly decaying π^0, η

Example 1: vector-portal dark matter (χ)

$\pi^0, \eta, \ldots$

V

χ

χ

γ

+ beam bremsstrahlung, …
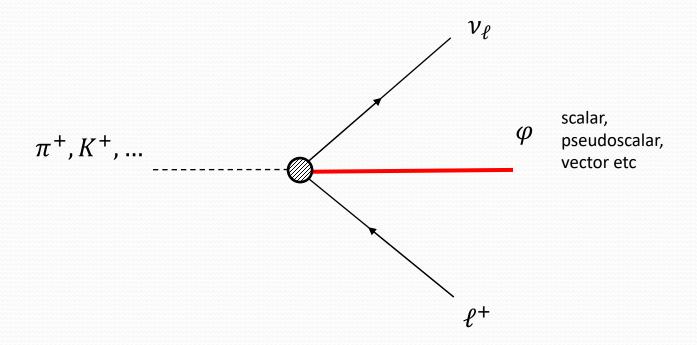
Example 2: axion-like particles (a) interacting with photons

$\pi^0, \eta, \ldots$

γ

γ

…

γ

a

γ

N

N

+ E&M cascade shower photons, …

Neutral mesons have played a crucial role in production of new physics particles.

Contributions from Charged Mesons?

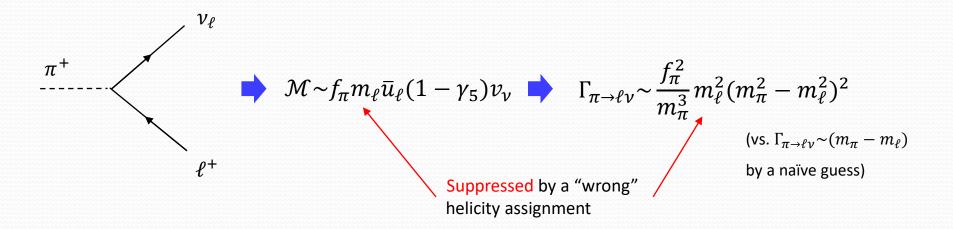$$\nu_\ell$$

$$\pi^+, K^+, \ldots$$

$$\varphi$$ scalar, pseudoscalar, vector etc

$$\ell^+$$

Charged mesons can be focused by a magnetic horn system, 🙂
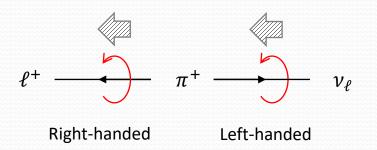
but could this decay be sizable? 🤔

Two-Body Decay of a Charged Meson

π^+ → ν_ℓ, ℓ^+

$$\mathcal{M} \sim f_\pi m_\ell \bar{u}_\ell (1 - \gamma_5) v_\nu$$

$$\Gamma_{\pi \to \ell \nu} \sim \frac{f_\pi^2}{m_\pi^3} m_\ell^2 (m_\pi^2 - m_\ell^2)^2$$

(vs. $\Gamma_{\pi \to \ell \nu} \sim (m_\pi - m_\ell)$

by a naïve guess)

Suppressed by a "wrong" helicity assignment

ℓ^+ ← Right-handed π^+ → ν_ℓ Left-handed
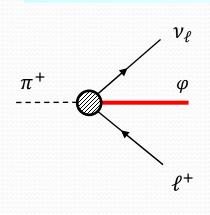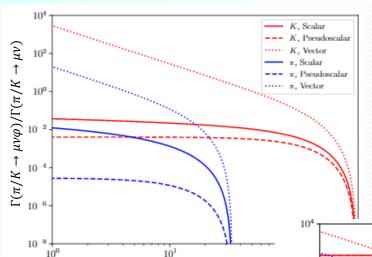
Angular momentum conservation highly **suppresses** the decay of scalar mesons in this way.
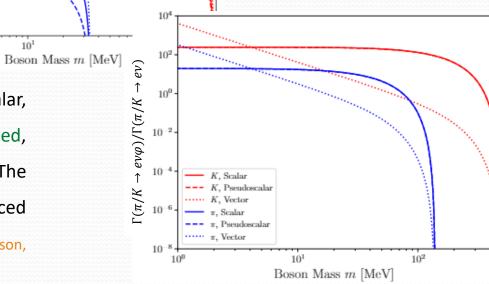
Three-Body Decay of a Charged Meson

- φ is assumed to couple to the charged lepton only and the associated couplings are set to be unity for comparison.
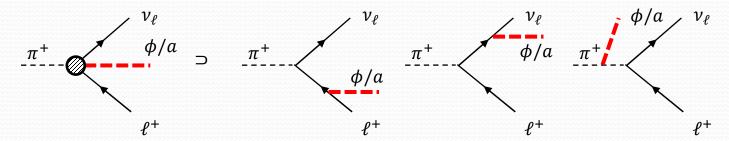
By adding the third particle φ (scalar, pseudoscalar, vector, etc), the helicity suppression can be evaded, i.e., 3-body decays can be **hugely enhanced**. The decay to a massive vector is even more enhanced due to the longitudinal polarization. [e.g., Carlson, Rislow, arXiv:1206.3587]
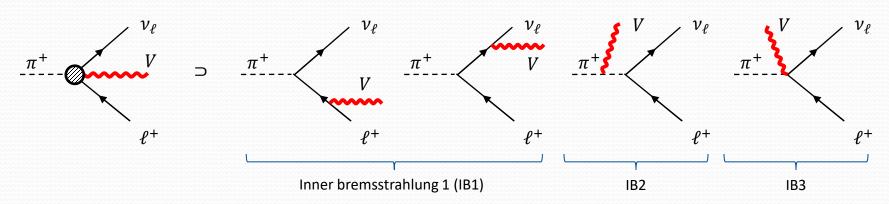
Various Dynamics in the Three-Body Decay

(Pseudo)scalar case

Vector case

Inner bremsstrahlung 1 (IB1)   IB2   IB3

- For models having couplings to the quark contents inside the meson, (QCD-origin) structure-dependent (SD) terms may arise.
- Typically, IB3 contributions ≫ IB2 ≈ IB1
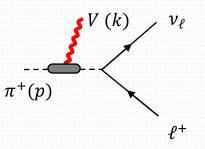
Pion Dark Radiative Decay

$$\mathcal{M} = ig_\pi \varepsilon^\mu \left[\bar{u}_\ell \gamma_\rho (1 - \gamma_5) v_\nu \right] \left[\int d^4 x\, e^{iqx} \langle 0 | T\{ j_\mu(x) \bar{d} \Gamma^\rho u(0) \} | \pi^+ \rangle \right]$$
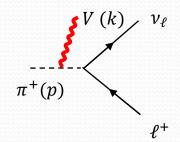
$$j_\mu = \bar{q} \gamma_\mu q$$

The hadronic part of the matrix element can be decomposed into a generic gauge-invariant form:

$$T_{\mu\rho} = \alpha g_{\mu\rho}(p-k)\cdot k + \beta(p-k)_\mu k_\rho + i[g_{\mu\rho}(p-k)\cdot k - (p-k)_\mu k_\rho] F_A + \epsilon_{\rho\mu\lambda\sigma} p^\lambda k^\sigma F_V + \frac{i(2p-k)_\mu (p-k)_\rho}{2p\cdot k - m_X^2} f_\pi$$

Contact interaction   Structure-dependent contributions   IB2

If we wish to satisfy the Ward Identity for our dark current, we require $\alpha + \beta = \dfrac{if_\pi}{(p-k)\cdot k}$.
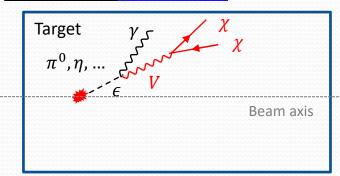
We can choose a family of (unknown) solutions for α and β.

See also more detailed discussions in [Khodjamirian, Weiler, arXiv:hep-ph/0111249].
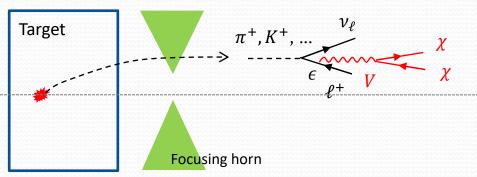
Charged Meson vs. Neutral Meson

In the example of vector-portal dark matter,

<u>Production via neutral meson</u>   <u>Production via charged meson</u>

$$N^{\chi}_{\pi^0-\text{ind}} = \cancel{N}_{\pi^0} \cdot \text{BR}(\pi^0 \to V \to \chi) \cdot f^{\chi}_{\pi^0-\text{ind}} \quad \ll \quad N^{\chi}_{\pi^\pm-\text{ind}} = \cancel{N}_{\pi^\pm} \cdot \text{BR}(\pi^\pm \to V \to \chi) \cdot f^{\chi}_{\pi^\pm-\text{ind}}$$
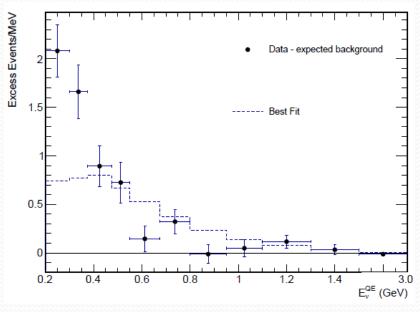
- ■ Comparable production rate: $\pi^0 : \pi^+ : \pi^- : \eta : K^+ : K^- \approx 1 : 1 : 1 : 0.1 : 0.1 : 0.1 \Rightarrow N_{\pi^0} \approx N_{\pi^\pm}$

- ■ No BR enhancement vs. Large BR enhancement $\Rightarrow \text{BR}(\pi^0 \to V \to \chi) \ll \text{BR}(\pi^\pm \to V \to \chi)$

- ■ Unfocused π^0, η vs. Focused $\pi^\pm, K^\pm$

- ■ Wider spreading π^0, η-induced flux vs. Forward-directed $\pi^\pm, K^\pm$-induced flux $\Rightarrow f^{\chi}_{\pi^0-\text{ind}} < f^{\chi}_{\pi^\pm-\text{ind}}$

Production via **charged meson** can be more efficient than production via **neutral meson**!

Example Physics Case 1:

Dark-Sector Solutions to the MiniBooNE Low-Energy Excess

MiniBooNE (MB) Low Energy Excess
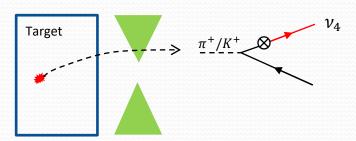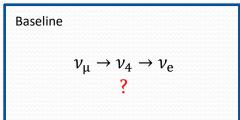
[MiniBooNE Collaboration, arXiv:2006.16883]
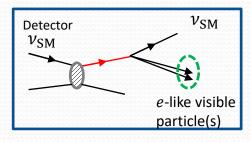
❑ An observational motivation of new physics (4.8σ)

❑ Numerous explanations, all involving neutrino-sector new physics [Karagiorgi, Djurcic, Conrad, Shaevitz, Sorel (2009); Collin, Arguelles, Conrad, Shaevitz (2016); Giunti, Lavender (2011); Gariazzo, Giunti, Lavender, Li (2017); Kopp, Maltoni, Schwetz (2011); Doring, Pas, Sicking, Weiler (2018); Dutta, Ghosh, Li (2020), and many more]

Conventional Explanations

Target π^+/K^+ $\otimes$ ν_4

Baseline

$$\nu_\mu \to \nu_4 \to \nu_e$$

?

Detector ν_{SM} ν_{SM}

e-like visible particle(s)

New particles in the beam

- Sterile neutrino decay
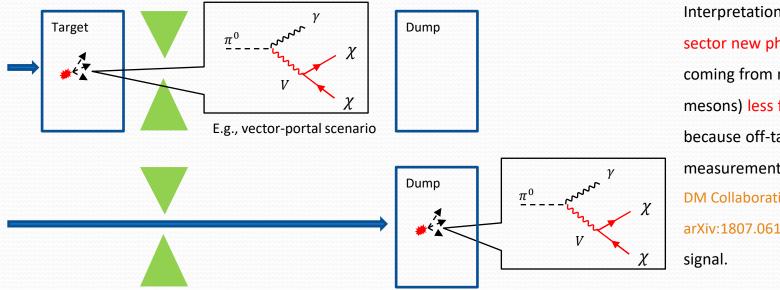
Non-standard flavor transitions

- Oscillations (sterile neutrinos, Lorentz violation, matter effects, large extra dimension etc)
- Lepton number violating decay

New particles produced by neutrino scattering

- Neutrino upscattering involving collimated an e^-e^+ pair
- Neutrino upscattering involving a photon
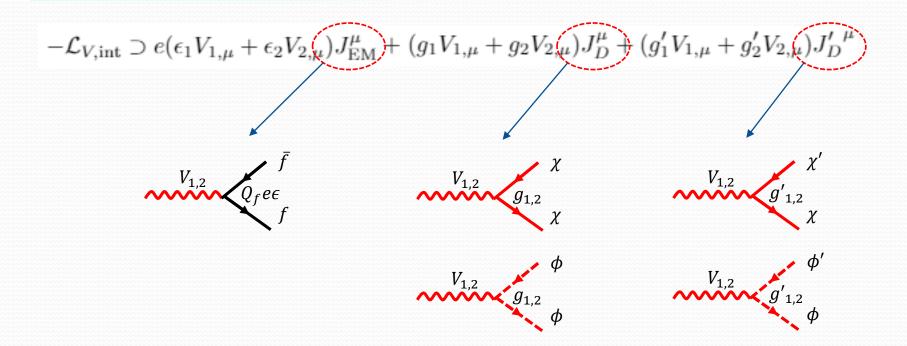
Dark-Sector Solutions? Challenges?

E.g., vector-portal scenario

Interpretations with dark-sector new physics (mostly coming from neutral mesons) less favored because off-target mode measurements [MiniBooNE DM Collaboration, arXiv:1807.06137] show null signal.

We propose an idea of plausible dark-sector scenarios for the MB excess.
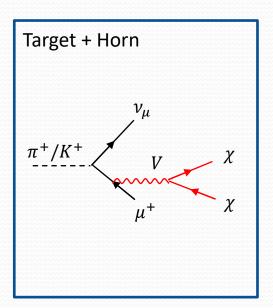
An Example Model: Vector-Portal Dark Matter

$$-\mathcal{L}_{V,\text{int}} \supset e(\epsilon_1 V_{1,\mu} + \epsilon_2 V_{2,\mu}) J_{\text{EM}}^{\mu} + (g_1 V_{1,\mu} + g_2 V_{2,\mu}) J_{D}^{\mu} + (g_1' V_{1,\mu} + g_2' V_{2,\mu}) J_{D}'^{\mu}$$
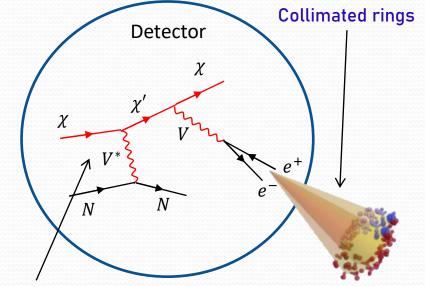
- ❑ Dark photon mediators for purposes of illustration.
- ❑ Two different mediators for purposes of generality.
- ❑ Heavier dark-sector state χ', ϕ' in addition to dark matter state χ, ϕ: up-scattering $\chi \to \chi'$, decay $\chi' \to \chi$ allowed.

A Dark-Matter Interpretation for the MB Excess: Main Idea

$$-\mathcal{L}_{V,\text{int}} \supset e(\epsilon_1 V_{1,\mu} + \epsilon_2 V_{2,\mu})J^\mu_{\text{EM}} + (g_1 V_{1,\mu} + g_2 V_{2,\mu})J^\mu_D + (g'_1 V_{1,\mu} + g'_2 V_{2,\mu})J'^\mu_D$$

Target + Horn

π^+/K^+ → V, ν_μ, μ^+, χ, χ

$\text{BR}(V \to 2\chi):\text{BR}(V \to 2e)$
$= 50\% : 50\%$

Detector

Collimated rings

χ, χ', V, V^*, N, N, e^+, e^-

$\text{BR}(V \to 2\chi):\text{BR}(V \to 2e) = 50\% : 50\%$

for illustration
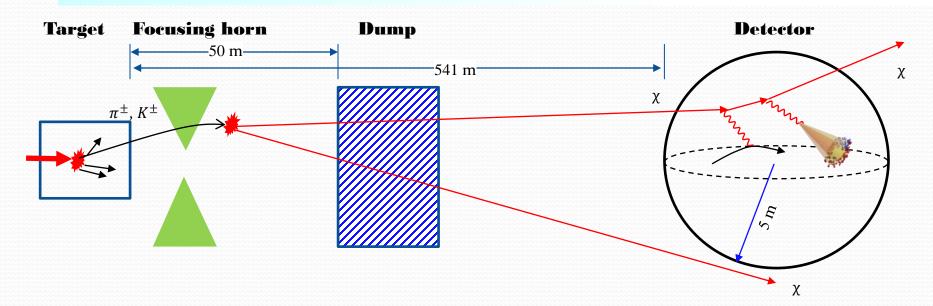
Scattering may happen through an exchange of a
different mediator.
[The different mediator could be massless, e.g.,
dipole operator, $\bar{\chi}' \sigma^{\mu\nu} \chi F_{\mu\nu}$]

Cf. Subdominant π^0-origin contributions are included.

[Dutta, **DK**, Thompson, Thornton, Van de Water, arXiv:2110.11944]

Simulation

Target — **Focusing horn** — 50 m — **Dump** — 541 m — **Detector**

$\pi^{\pm}, K^{\pm}$

χ

χ

χ

5 m
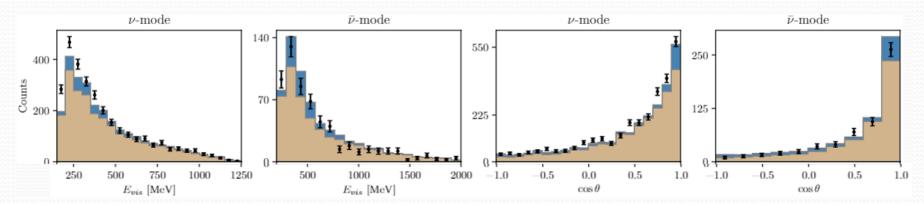
- Sanford-Wang, BMPT-like models for meson production [arXiv:0806.1449]
- Normalization based on the MB result [arXiv:0806.1449]

- Focused and aligned to the beam axis if $\theta \in (30,210)$ mrad
- Meson decay probability (within 50 m) according to the decay law
- Three-body decay of mesons described by MadGraph

- DM upscattering in the detector fiducial volume
- Energy threshold 140 MeV, angular separation $< 10°$, detection efficiency [arXiv:1407.6060]

Example Fit

Example fit in the double-mediator scenario
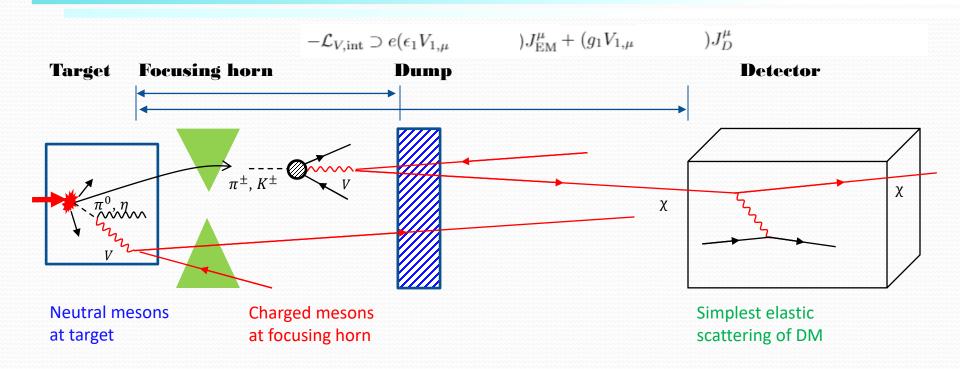
[Dutta, **DK**, Thompson, Thornton, Van de Water, arXiv:2110.11944]

	Vector-portal dark matter		
Scenario	$(m_{V_1}, m_{V_2}, m_\chi, m_{\chi'})$	$\epsilon_1 \epsilon_2 g_2'^2/(4\pi)$	χ^2/dof
Single	$(17, -, 8, 40)$ MeV	3.6×10^{-9}	2.5
Double	$(17, 200, 8, 50)$ MeV	1.3×10^{-7}	2.2

← Reasonable fit in the single-mediator scenario
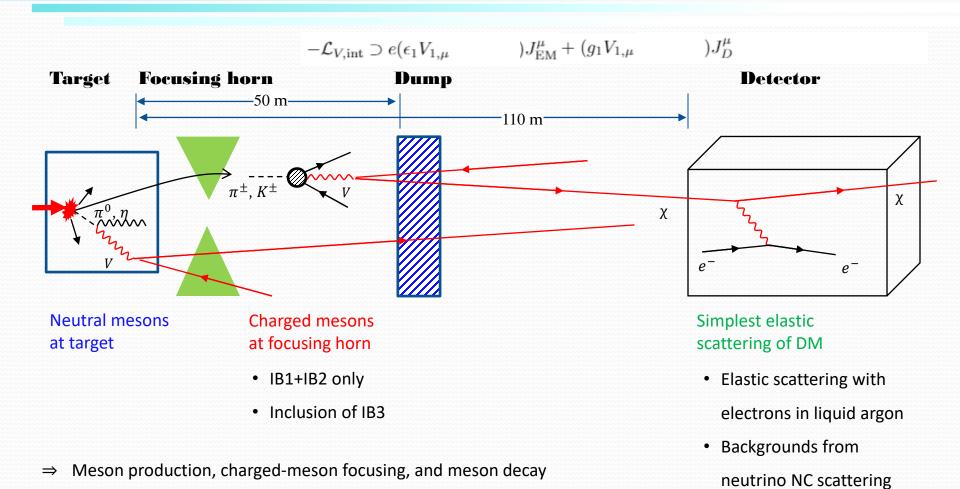
- Best-fit parameter values consistent with the existing constraints including exotic meson decays, dark photon limits, MB off-target mode measurements (see the bonus slides)
- Other dark-sector solutions [e.g., long-lived (pseudo)scalar] available (see the bonus slides)

Example Physics Case 2:
Light Dark Matter Search at SBND

$$-\mathcal{L}_{V,\text{int}} \supset e(\epsilon_1 V_{1,\mu} \qquad)J^\mu_{\text{EM}} + (g_1 V_{1,\mu} \qquad)J^\mu_D$$

Target **Focusing horn** **Dump** **Detector**

$\pi^\pm, K^\pm$

V

π^0, η

V

χ

χ

Neutral mesons at target

Charged mesons at focusing horn

Simplest elastic scattering of DM
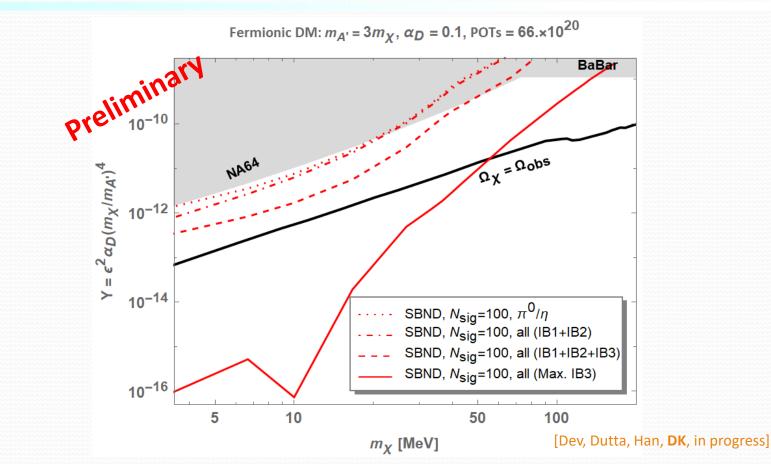
Example Data Analysis at SBND

$$-\mathcal{L}_{V,\text{int}} \supset e(\epsilon_1 V_{1,\mu} \qquad) J^\mu_{\text{EM}} + (g_1 V_{1,\mu} \qquad) J^\mu_D$$

Target   **Focusing horn**   **Dump**   **Detector**

Neutral mesons at target

Charged mesons at focusing horn

- IB1+IB2 only
- Inclusion of IB3

Simplest elastic scattering of DM

- Elastic scattering with electrons in liquid argon
- Backgrounds from neutrino NC scattering
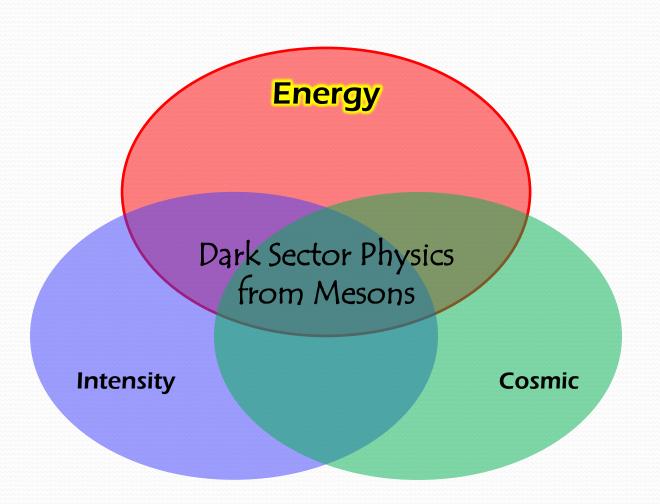
⇒ Meson production, charged-meson focusing, and meson decay dynamics simulation schemes similar to those of the MB case

Expected Sensitivity

Fermionic DM: $m_{A'} = 3m_\chi$, $\alpha_D = 0.1$, POTs $= 66.\times 10^{20}$

Preliminary

BaBar

NA64

$\Omega_\chi = \Omega_{obs}$

$Y = \epsilon^2 \alpha_D (m_\chi / m_{A'})^4$

- ⋯⋯ SBND, $N_{sig}=100$, π^0/η
- —·— SBND, $N_{sig}=100$, all (IB1+IB2)
- — — SBND, $N_{sig}=100$, all (IB1+IB2+IB3)
- —— SBND, $N_{sig}=100$, all (Max. IB3)

m_χ [MeV]

[Dev, Dutta, Han, **DK**, in progress]

Cf. Maximum IB3 contributions are set by the measurements of exotic charged meson decays: $\pi \to \ell \nu_\ell A'$ [PIENU Collaboration, arXiv:2101.07381], $K \to \mu \nu_\mu A'$ [NA62 Collaboration, arXiv:2101.12304].
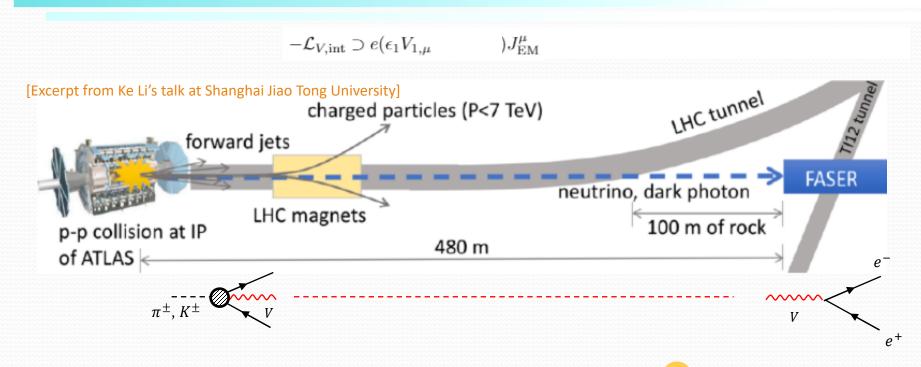
Example Physics Case 3:
Light Mediator Search at LHC

"Forward" Physics and "Central" Physics

Mediator Searches: Main Idea

$$-\mathcal{L}_{V,\text{int}} \supset e(\epsilon_1 V_{1,\mu} \qquad)J^{\mu}_{\text{EM}}$$
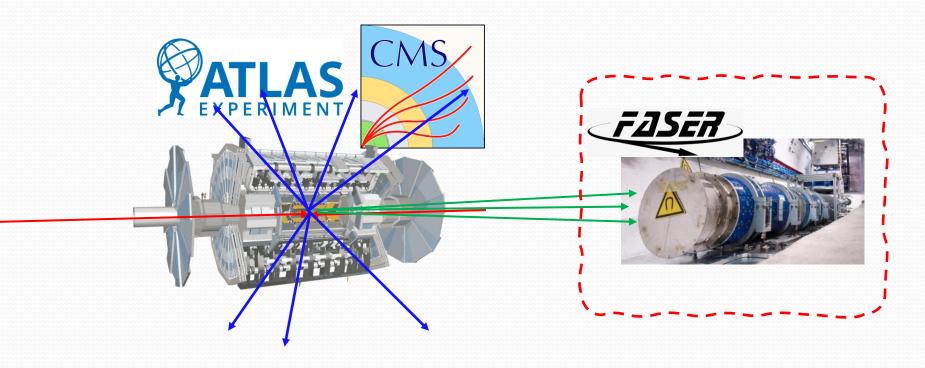
[Excerpt from Ke Li's talk at Shanghai Jiao Tong University]

- Charged mesons are highly boosted, hence **effectively focused**. 🙂

- Distance between the interaction point and the magnet is small, hence **a small fraction of charged meson would decay**. 🤔

- IB3 will enhance the BRs of charged meson exotic decays.
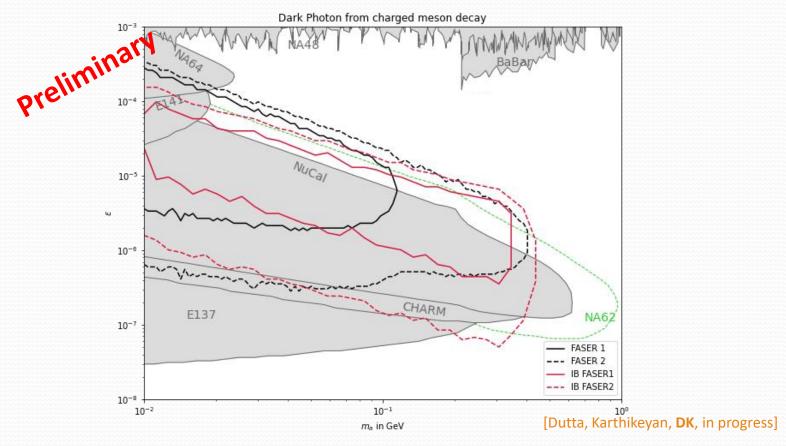
Data Analysis for the Standard Dark Photon Scenario

$$-\mathcal{L}_{V,\text{int}} \supset e(\epsilon_1 V_{1,\mu} \qquad)J_{\text{EM}}^{\mu}$$

[Excerpt from Ke Li's talk at Shanghai Jiao Tong University]

- Production of mesons described by FORESEE (via EPOS-LHC) [Kling, Trojanowski, arXiv:2105.07077]

- Charged mesons allowed to decay (conservatively) within ~20 m
- IB3 included
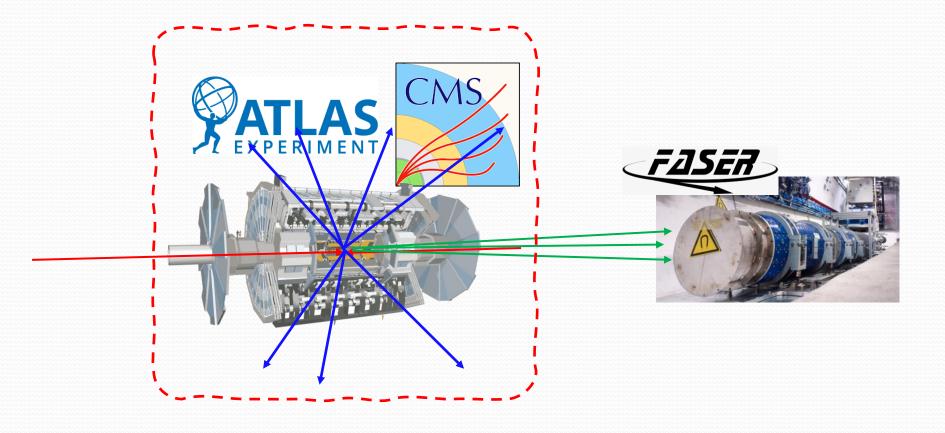
- Produced dark photon should survive before reaching the detector and decay inside the detector.

Expected Sensitivity

Dark Photon from charged meson decay

[Dutta, Karthikeyan, **DK**, in progress]
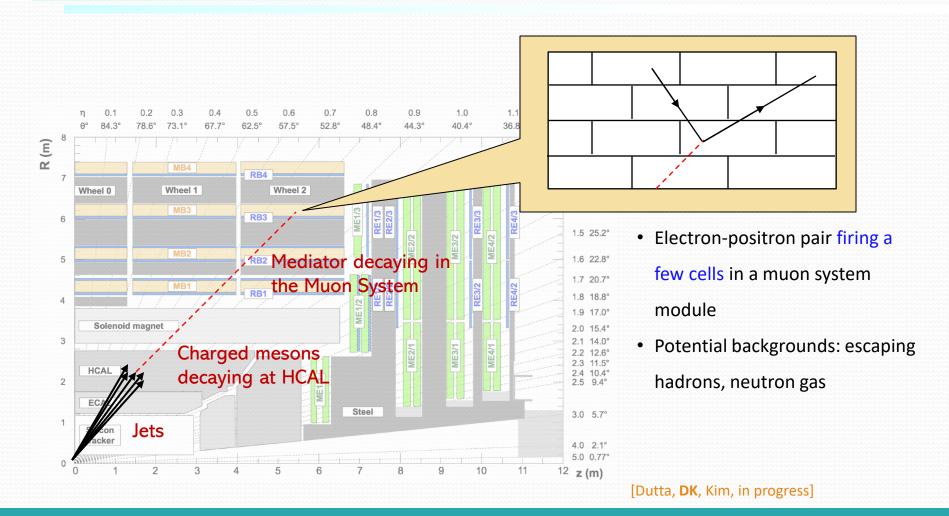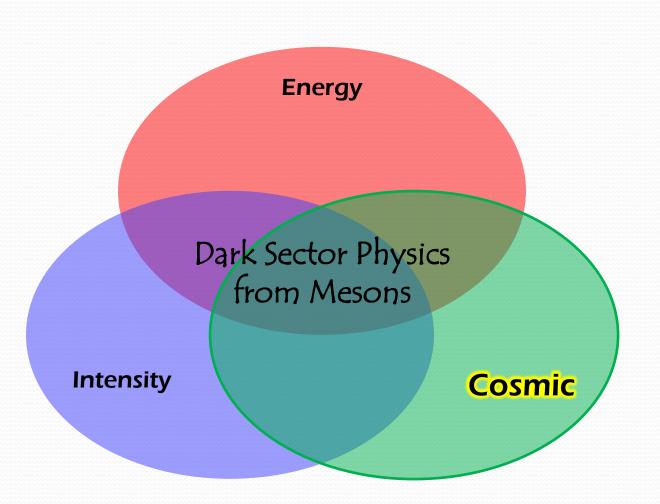
IB3 contributions are maximized with BRs set by the measurements of exotic charged meson decays: $\pi \to \ell \nu_\ell A'$ [PIENU Collaboration, arXiv:2101.07381], $K \to \mu \nu_\mu A'$ [NA62 Collaboration, arXiv:2101.12304].
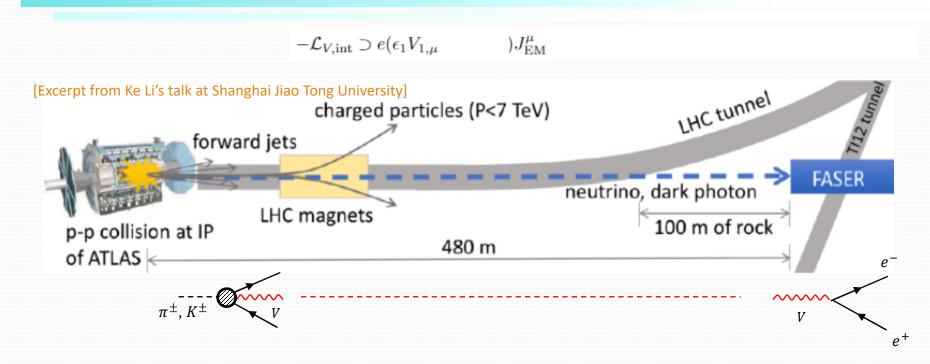
"Forward" Physics and "Central" Physics
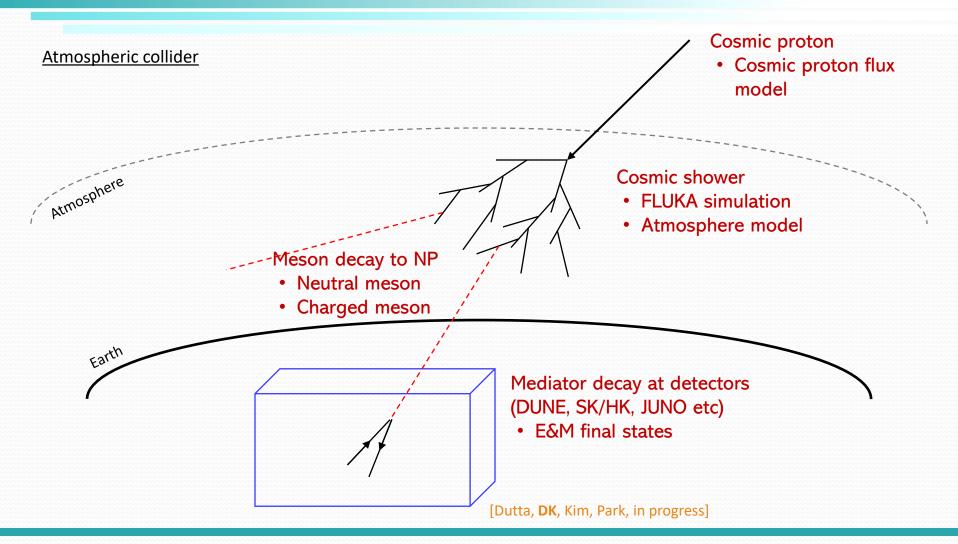
Mediator Searches at Muon System: Main Idea

- Electron-positron pair *firing a few cells* in a muon system module

- Potential backgrounds: escaping hadrons, neutron gas

[Dutta, **DK**, Kim, in progress]
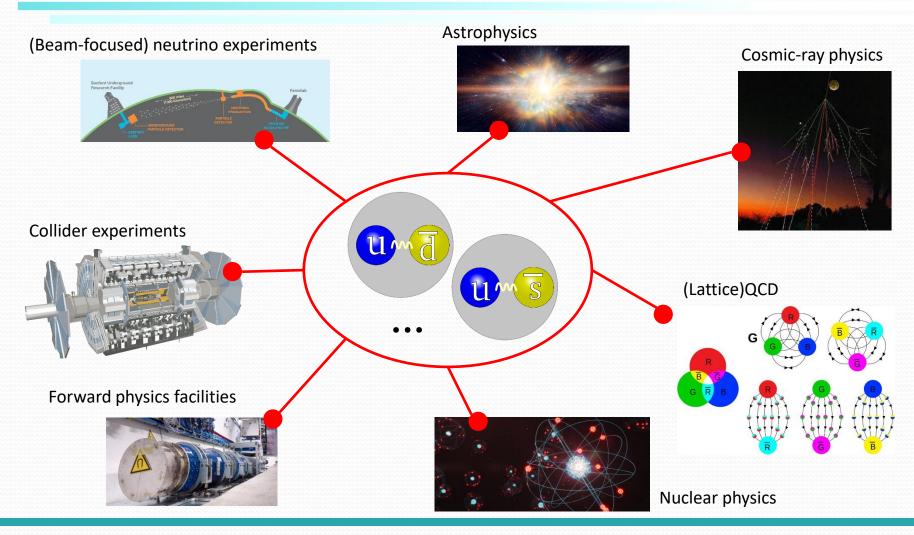
Dark-Sector Probes Using Cosmic Showers: Main Idea

Atmospheric collider

Cosmic proton
- Cosmic proton flux model

Atmosphere

Cosmic shower
- FLUKA simulation
- Atmosphere model

Meson decay to NP
- Neutral meson
- Charged meson

Earth

Mediator decay at detectors
(DUNE, SK/HK, JUNO etc)
- E&M final states

[Dutta, **DK**, Kim, Park, in progress]

Various Physics Opportunities with Charged Mesons

(Beam-focused) neutrino experiments

Astrophysics

Cosmic-ray physics

Collider experiments

Forward physics facilities

Nuclear physics

(Lattice)QCD

Conclusions

❑ Mesons can serve as windows to look into new physics.

❑ Charged mesons are overlooked but **efficient sources** of new physics particles (e.g., mediators, dark matter)

  ✓ **BRs of three-body** meson decays ≫ BRs of two-body meson decays

  ✓ **Focused flux** of new particles (in beam-focused neutrino experiments, forward physics facilities, cosmic-ray experiments)

❑ Dark-sector signals from charged/neutral mesons can be probed in **intensity-, energy-, and cosmic-frontier experiments/facilities** which provide complementary information.

❑ Many opportunities are still unexplored.

Thank you!

Bonus Slides

Example UV Models

❑ The mediators (scalar, pseudoscalar, and vector) can emerge from various UV complete models where the scalar/pseudoscalar can couple to the SM particles via Yukawa and the vector mediators via gauge couplings.

❑ One can use a vector mediator with coupling $g \sim 10^{-5}$ emerging from pion and then scattering off the nucleus via exchanging a π^0 can fit the MiniBooNE excess. The exchanged particle can be a scalar/pseudoscalar as well. Example models include $U(1)_{T3R}$ [Dutta, Ghosh, Kumar, 1905.02692], $U(1)_X$ [Correia, Fajfer, 1905.03867].
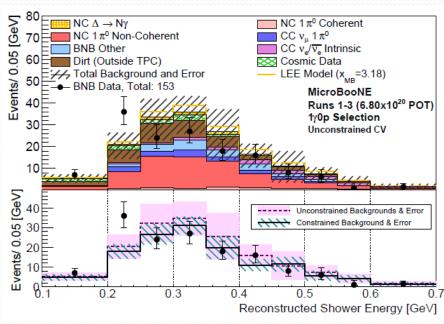
Constraints

- ❏ Limits from exotic decays of charged mesons, e.g., $\text{BR}(\pi/K \to \ell\nu + \nu\nu \text{ or } ee) < \sim 10^{-9} - 10^{-6}$

- ❏ Limits of visibly-decaying dark photons (e.g., E141, BaBar) and invisibly-decaying dark photons (e.g., NA64)

We can find respective coupling values that are consistent with these limits.

- ❏ No significant events in the MB off-target mode

$\longrightarrow$ π^0 contribution $\sim 4(8)\%$, yielding $\sim 2.4 \pm 0.5$ (4.4 ± 0.9) events in the MB off-target mode for the single(double)-mediator scenario $\rightarrow$ Consistent with the measurement within the measurement uncertainty.
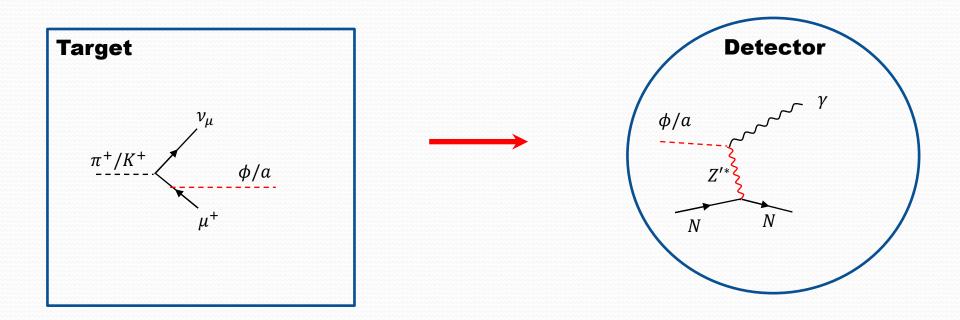
MicroBooNE Results and the MB Excess

[MicroBooNE Collaboration, arXiv:2006.16883]

❑ The (earlier) MicroBooNE result constrains NC $\Delta \to N\gamma$ event rates more stringently, supporting that the MB excess requires a new physics interpretation!

❑ The later result shows no excess in the channels of a single electron + something.

❑ The MicroBooNE data may not be sensitive enough to the MB excess, yet, because of (∼3 times) smaller POTs, (∼6 times) smaller detector volume, (∼3 times) smaller photon efficiency.
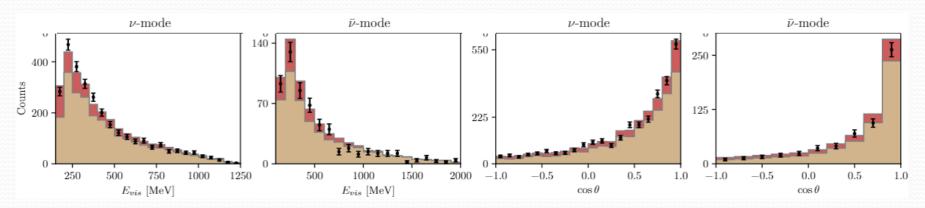
Example Long-Lived (Pseudo)scalar Models

$$\mathcal{L}_{S(P)} \supset g_\mu \phi(ia)\bar{\mu}\mu + g_n Z'_\alpha \bar{u}\gamma^\alpha u + \frac{\lambda}{4}\phi(a)F'_{\mu\nu}F^{\mu\nu} + \text{h.c.}$$

Example fit in the scalar scenario
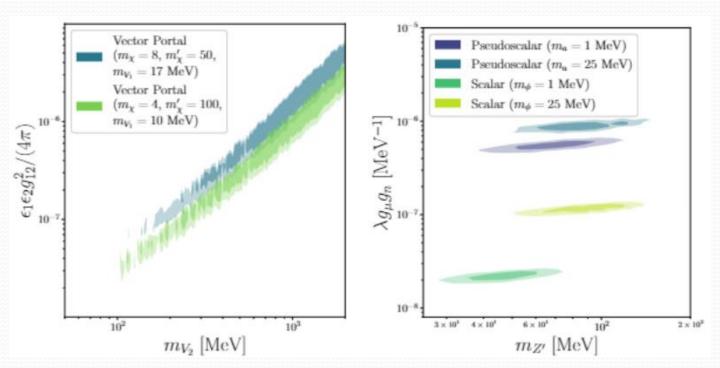

[Dutta, DK, Thompson, Thornton, Van de Water, arXiv:2110.11944]

Long-lived (pseudo)scalar			
Scenario	$(m_{Z'}, m_{\phi/a})$	$(g_\mu g_n \lambda)$ [MeV^{-1}]	$\chi^2/$dof
Scalar	$(49, 1)$ MeV	2.2×10^{-8}	1.6
Pseudoscalar	$(85, 1)$ MeV	5.9×10^{-7}	1.6

Credible Regions

[Dutta, DK, Thompson, Thornton, Van de Water, arXiv:2110.11944]