Exploring Dark Sector Physics at Neutrino Facilities

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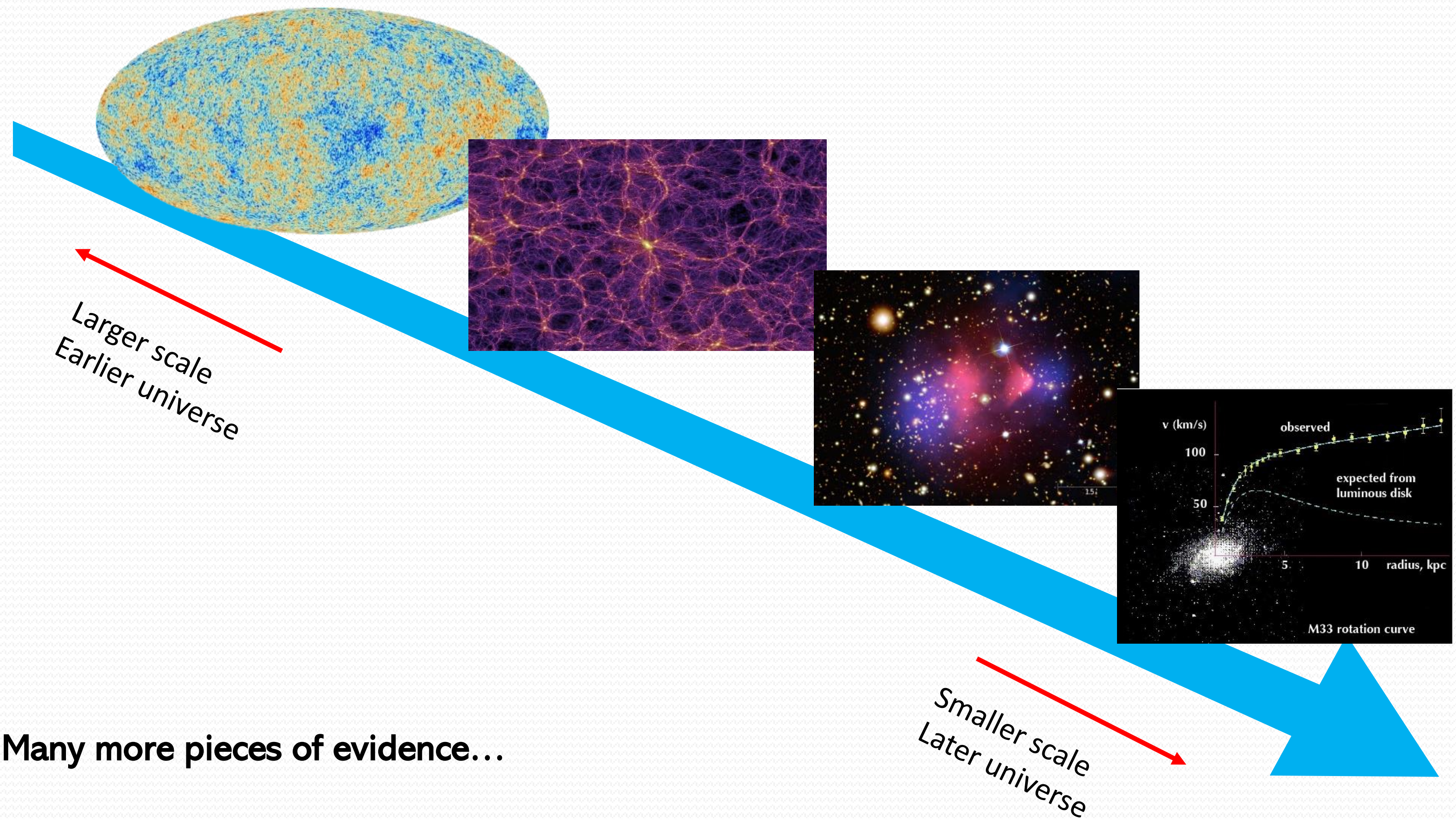
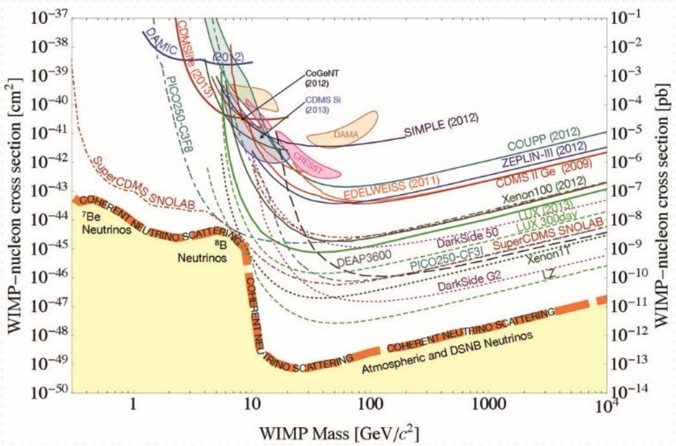
Dark Matter Puzzle



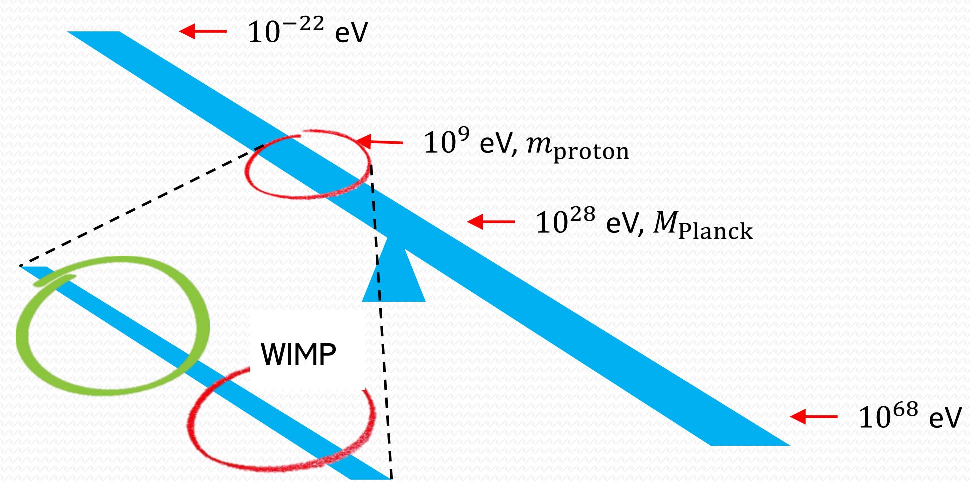
Many more pieces of evidence…

Probing Dark Sectors: Light Dark Matter and Light Mediators



Null observation of (WIMP) dark-matter signal

through non-gravitation interactions

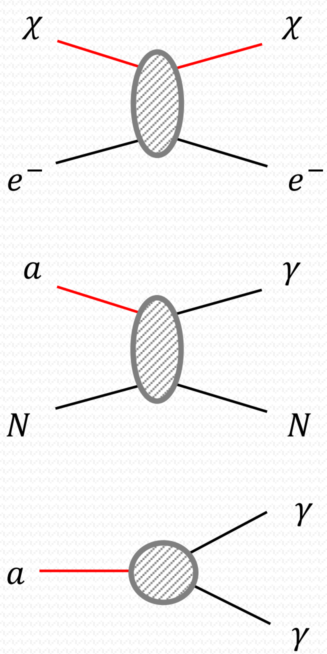


Light dark matter and light mediators

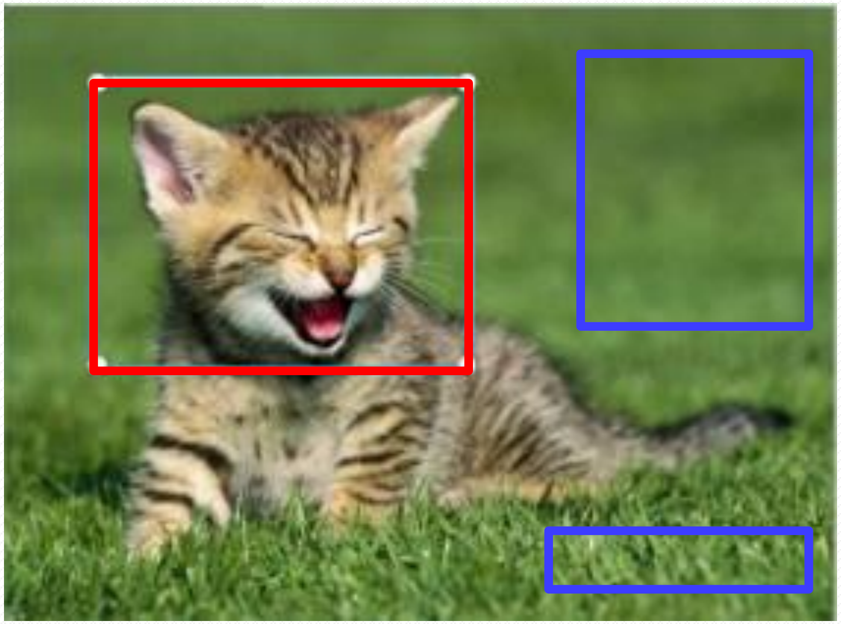
- ✓ Can be a thermal dark matter candidate
- ✓ Less constrained by current searches
- ✓ Often **feebly/weakly interacting** with SM particles
- ✓ Probing dark sectors at high-intensity and (relatively) low-energy experiments (e.g., fixed-target/beam-dump type neutrino experiments): low-mass dark matter (LDM) + (light) new mediators (e.g., dark photon)

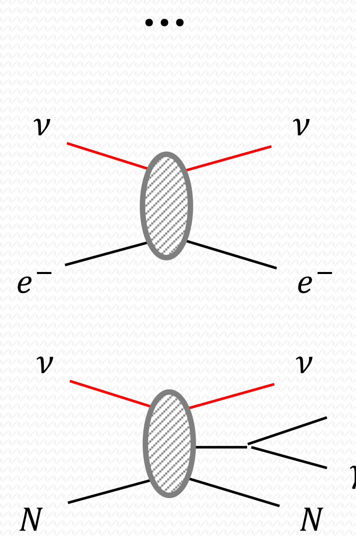
Backgrounds to Dark-Sector Signals

Signal: dark matter scattering, scattering of dark-sector mediators, mediator decays …



…

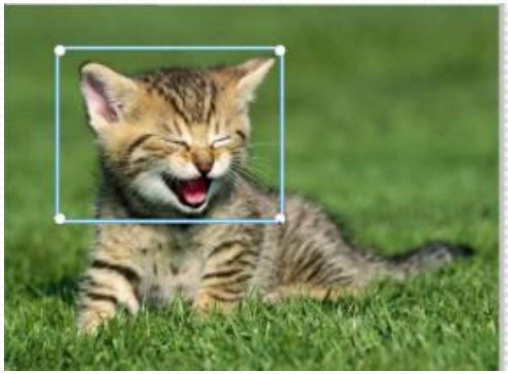




Background: neutrino-induced scattering events, …

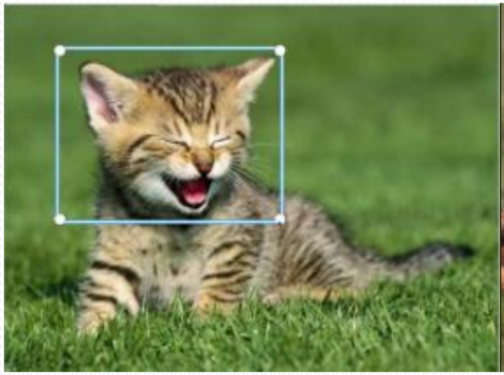
Improving Signal Sensitivity

1) Removing backgrounds

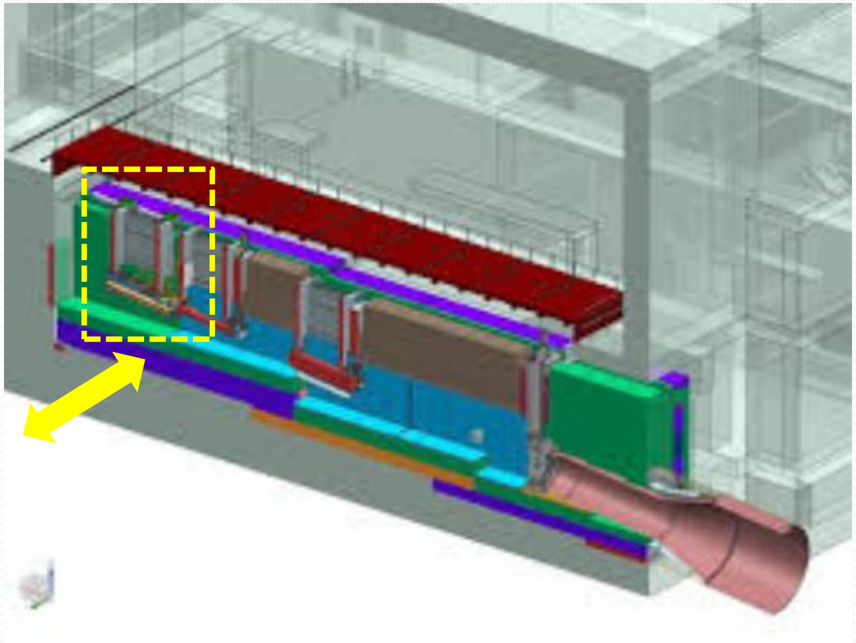


Dump mode measurements

2) Adding new, strong (forgotten/overlooked) signal channels



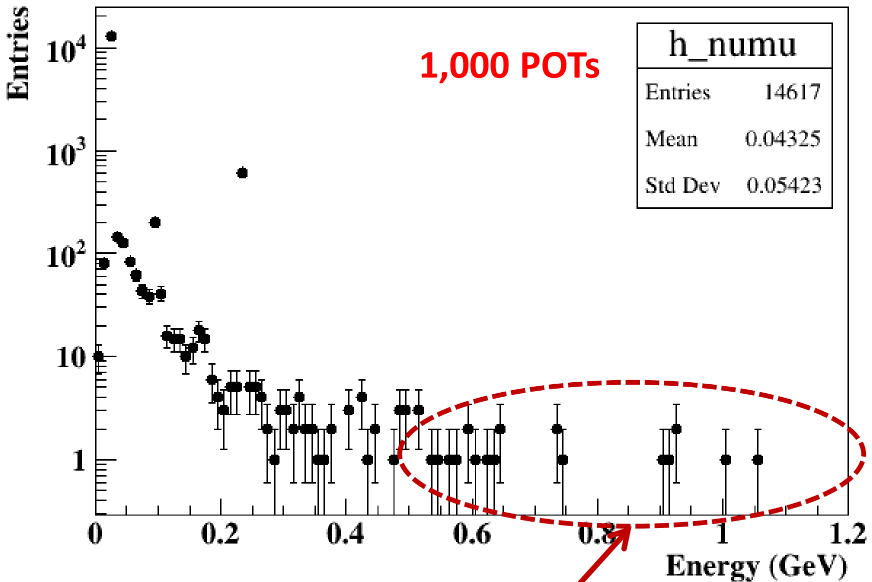
Motivations of the Off-Target Mode Experiment

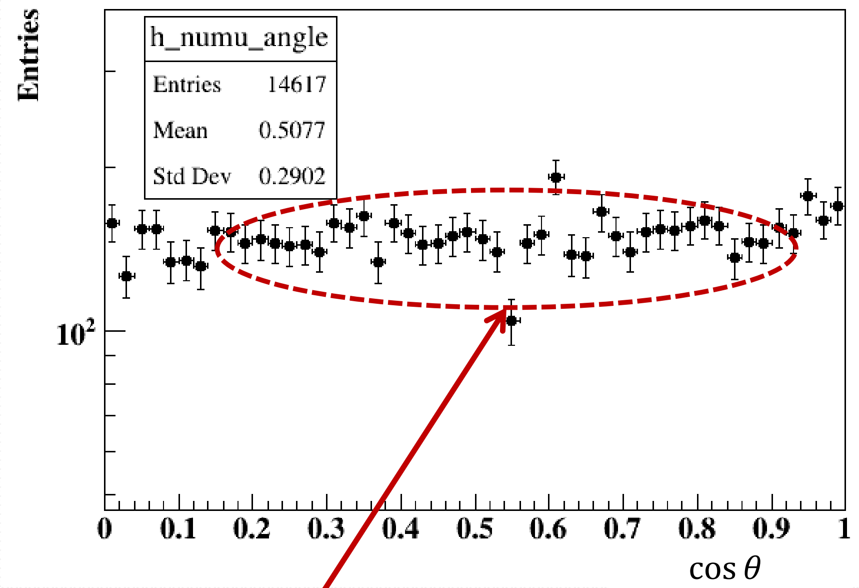


- Proposing a **movable target system** (or similar, e.g., at DUNE) making it possible to dump protons directly to the dump area [Bhattarai, Brdar, Dutta, Jang, **DK**, Shoemaker, Tabrizi, Thompson, Yu, to appear soon], inspired by off-target mode data collection in MiniBooNE.

- Expected gains
  - ✓ Shorter distance between the source point and the detector $\Rightarrow$ more signal (e.g., low-mass dark matter, axion-like partcles) flux entering the detector
  - ✓ Significantly reduced ν-induced backgrounds
  - ✓ Confirming/disproving non-neutrino-sector new physics signals

Estimates of Neutrino-Induced Backgrounds



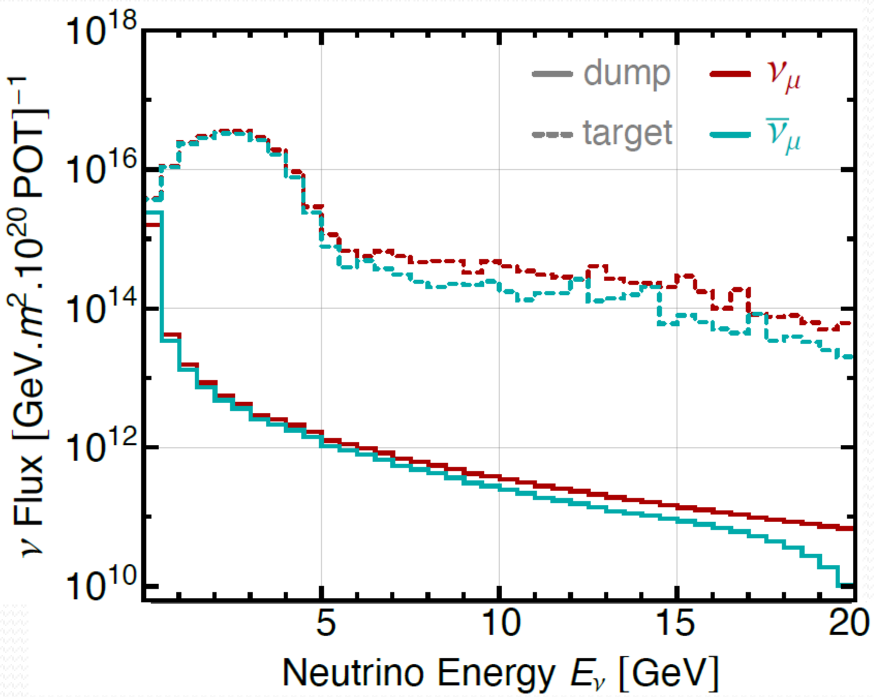


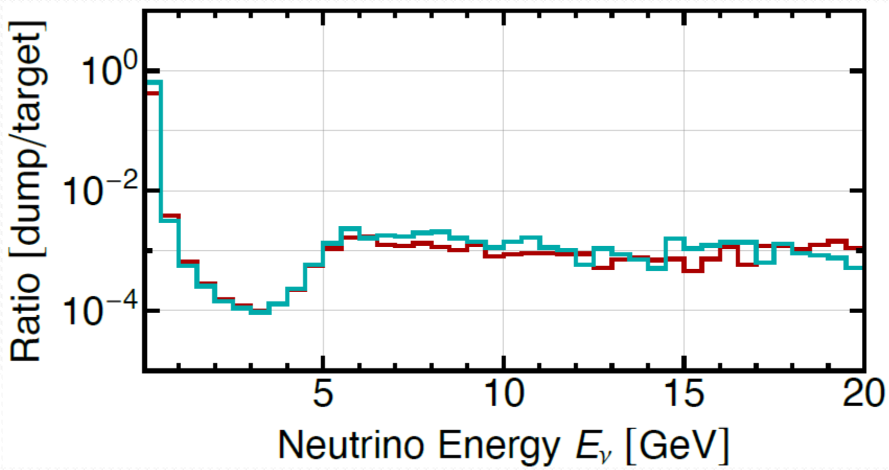
Low production rate of high energy ν's

Isotropic neutrino flux

Cf. See Wooyoung Jang's talk for more simulation details.

Estimated Muon-Neutrino Flux at ND



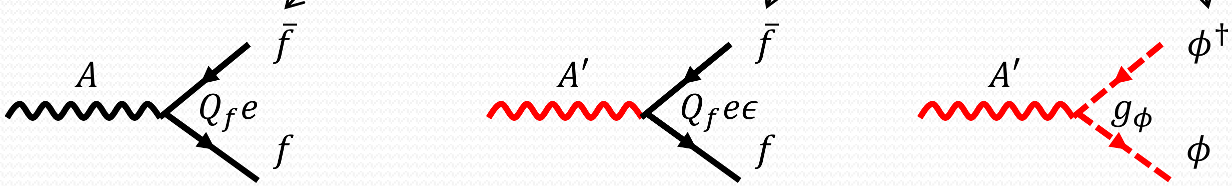


$\sim 10^{-2}$ recoil-electron-only events with a 0.6 MW·3 months exposure.

Cf. DUNE beam's nominal power: 1.2 MW

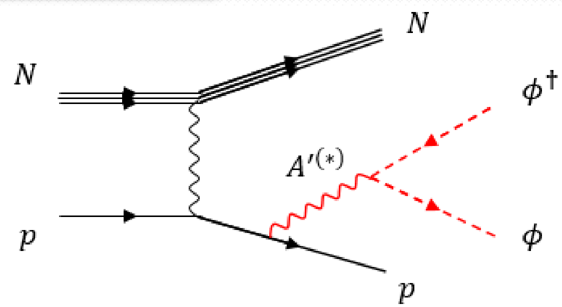
Vector-Portal Dark Matter

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu + eA_\mu J^\mu_{\mathrm{EM}} + \epsilon e A'_\mu J^\mu_{\mathrm{EM}} + g_\chi A'_\mu J^\mu_D + \mathcal{O}(\epsilon^2)$$

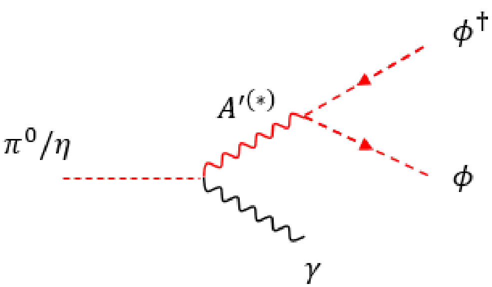


Production and Detection of Dark Matter

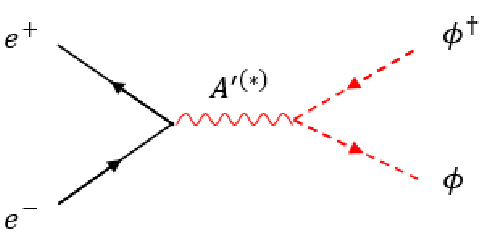
DM production



Beam bremsstrahlung

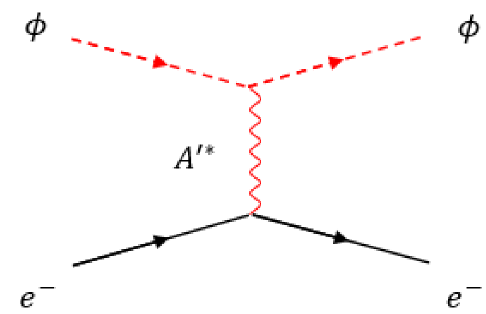


Neutral meson decays



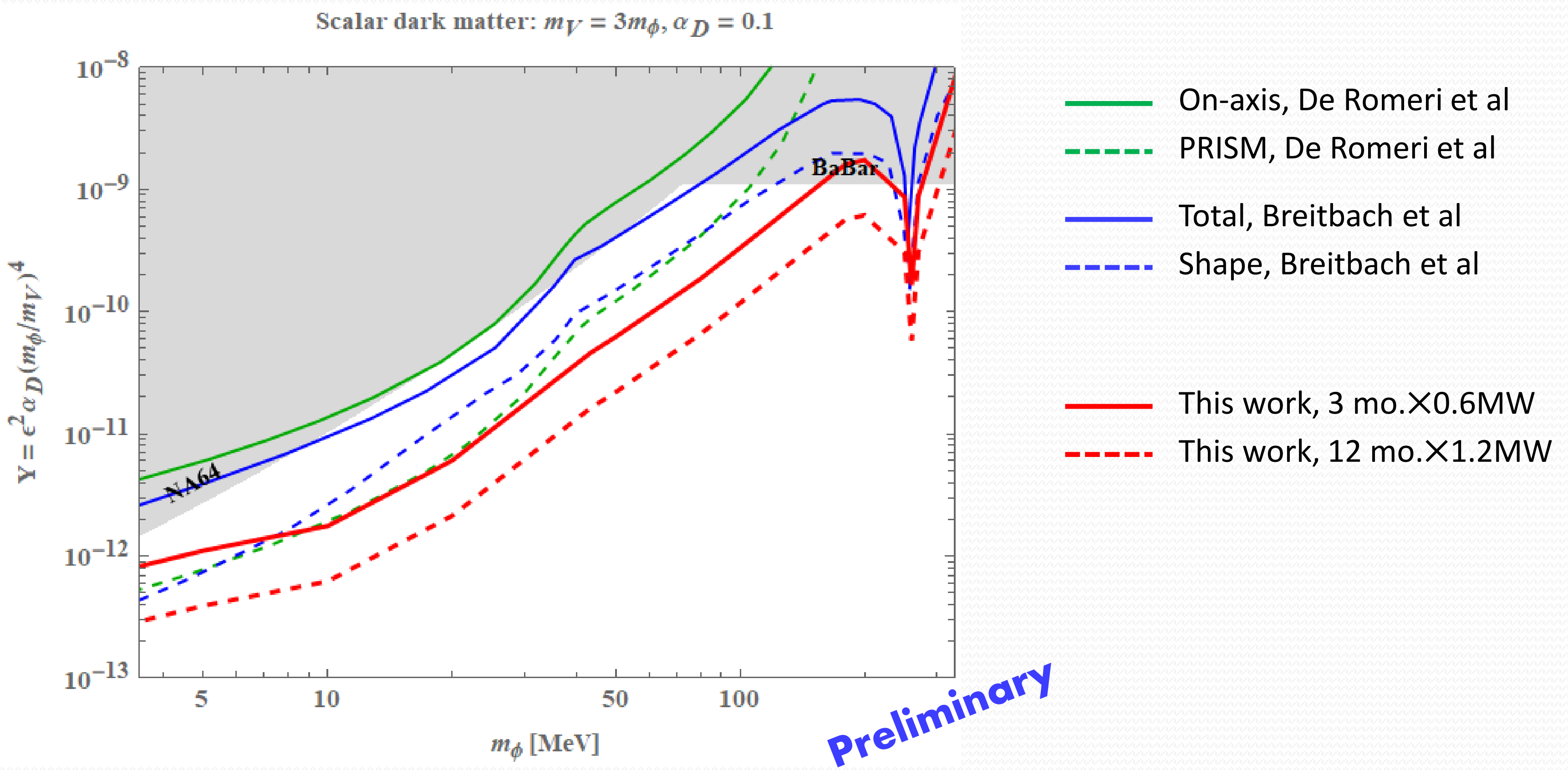
Resonance production

DM detection



Elastic scattering with an electron

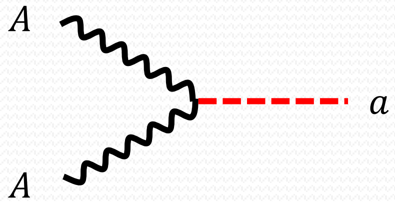
Sensitivity Result: Vector-Portal Dark Matter

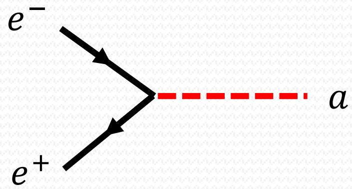


[Bhattarai, Brdar, Dutta, Jang, **DK**, Shoemaker, Tabrizi, Thompson, Yu, to appear soon]

Axion-Like Particles

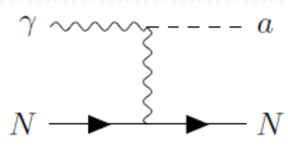
$$\mathcal{L}_{\rm int} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} - g_{aee} a \bar{\psi}_e \gamma_5 \psi_e$$



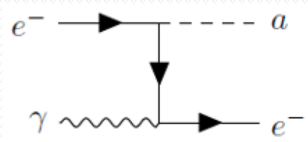


Production and Detection of ALPs

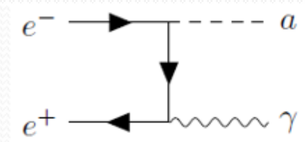
ALP production



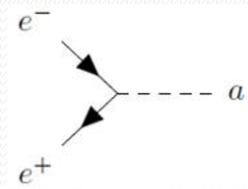
Primakoff



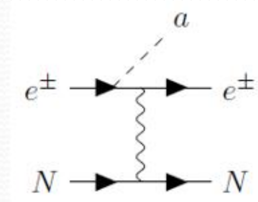
Compton



Associated production

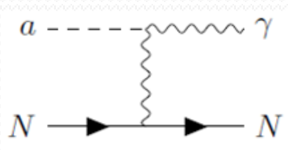


Resonant production

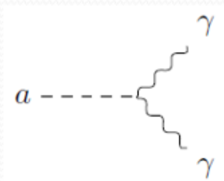


ALP-bremsstrahlung

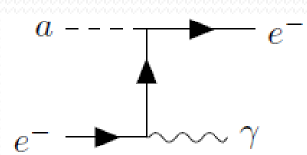
ALP detection



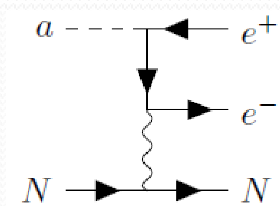
Inverse Primakoff



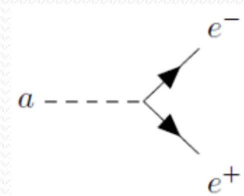
Diphoton decay



Inverse Compton

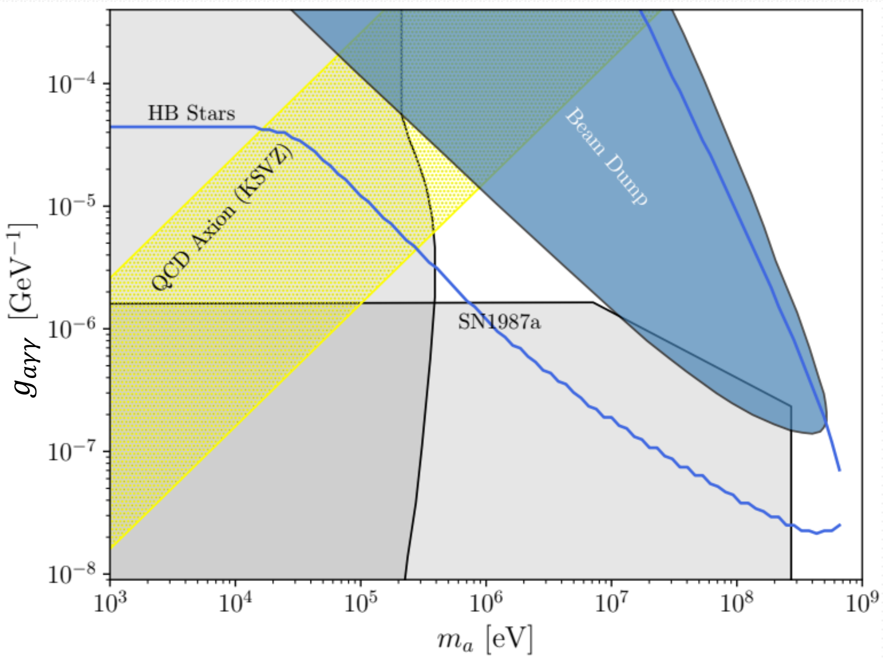


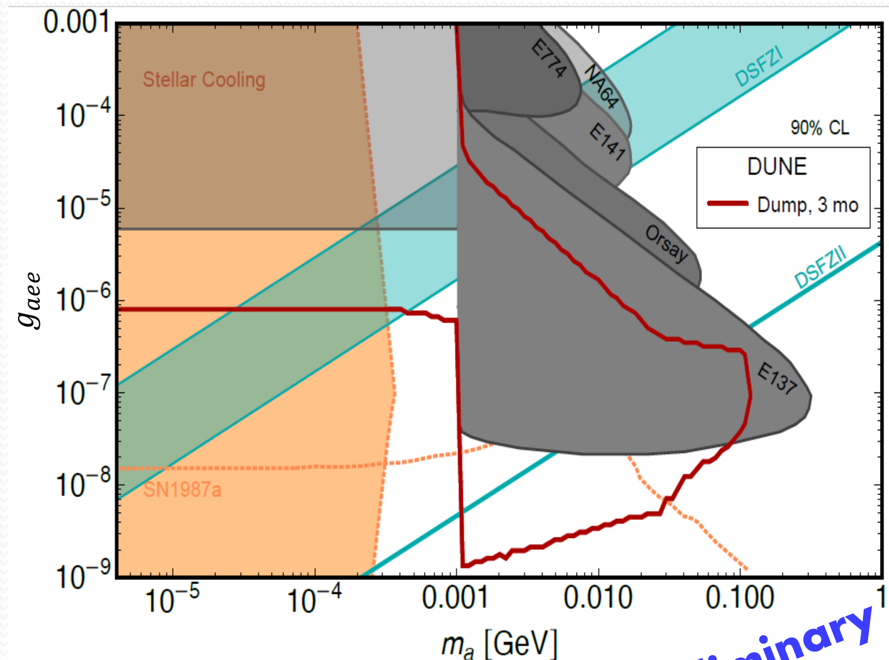
External pair conversion



Di-lepton decay

Sensitivity Result: ALP





Preliminary

[Bhattarai, Brdar, Dutta, Jang, **DK**, Shoemaker, Tabrizi, Thompson, Yu, to appear soon]

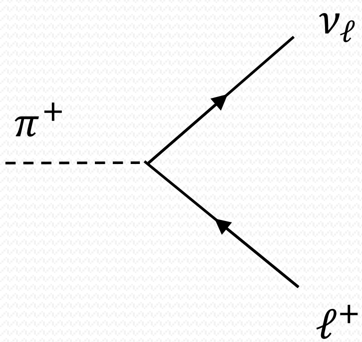
Improving Signal Sensitivity

1) Removing backgrounds

2) Adding new, strong (forgotten/overlooked) signal channels

"Focused" dark-sector signals

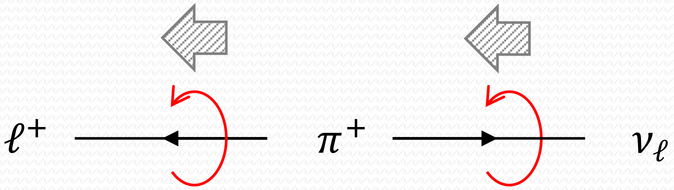
Two-Body Decay of Charged Mesons



$$\mathcal{M} \sim f_\pi m_\ell \bar{u}_\ell (1-\gamma_5) v_\nu \Rightarrow \Gamma_{\pi\to\ell\nu} \sim \frac{f_\pi^2}{m_\pi^3} m_\ell^2 (m_\pi^2 - m_\ell^2)^2$$

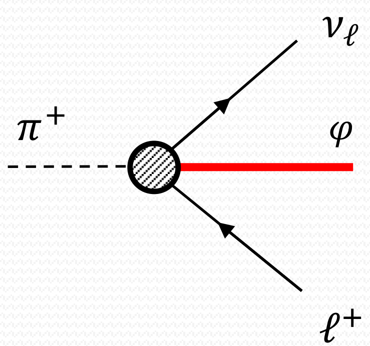
Suppressed by a "wrong" helicity assignment

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

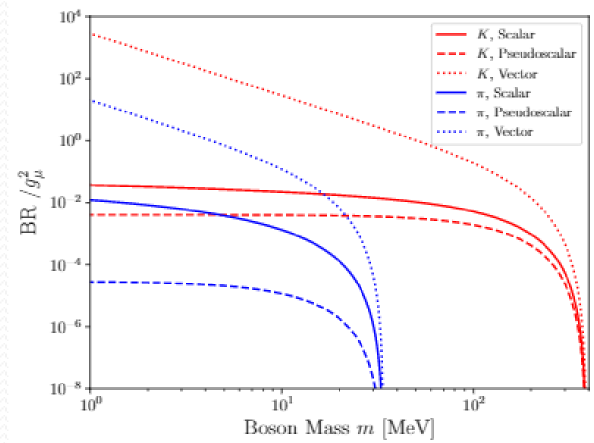


Angular momentum conservation highly suppresses the decay of scalar mesons in this way.

Three-Body Decay of Charged Mesons

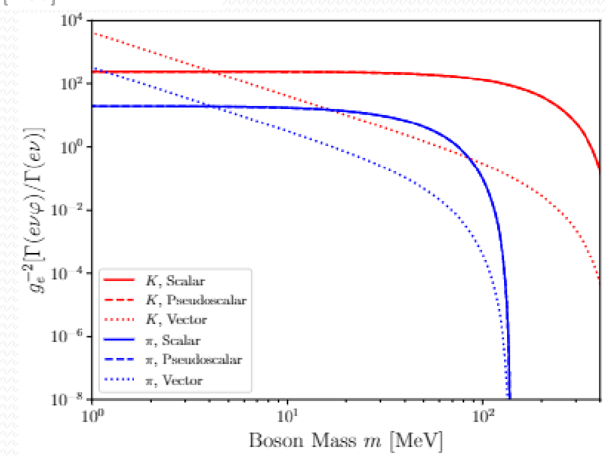


- scalar,
- pseudoscalar,
- vector etc

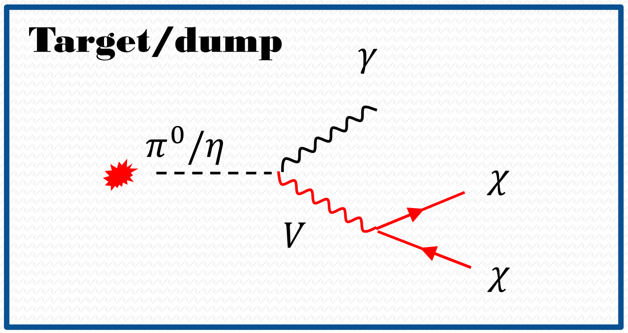


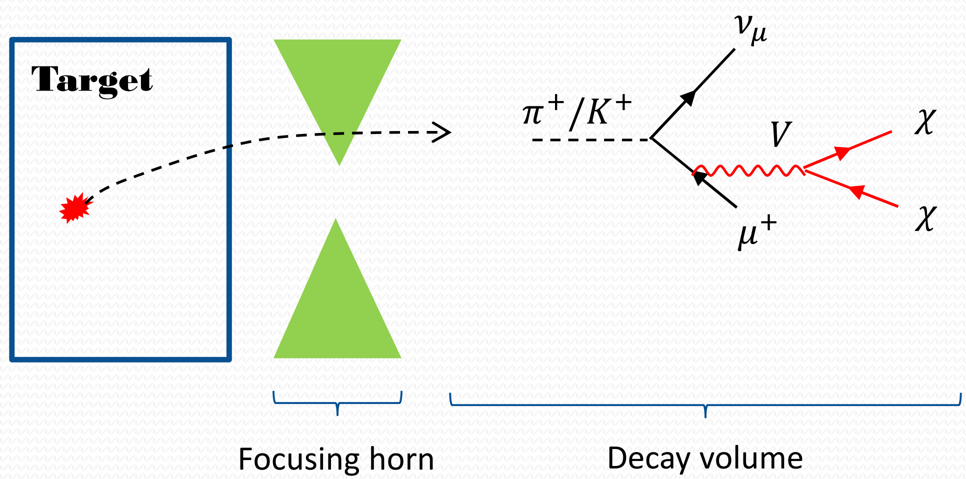
- φ is assumed to couple to the charged lepton only and the associated couplings are set to be unity for comparison.

By adding the third particle φ, 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, 1206.3587; Laha, Dasgupta, Beacom, 1304.3460; Krnjaic, Marques-Tavares, Redigolo, Tobioka, 1902.07715; Altmannshofer, Gori, Robinson, 1909.00005]



Neutral Meson Contributions vs. Charged Meson Contributions

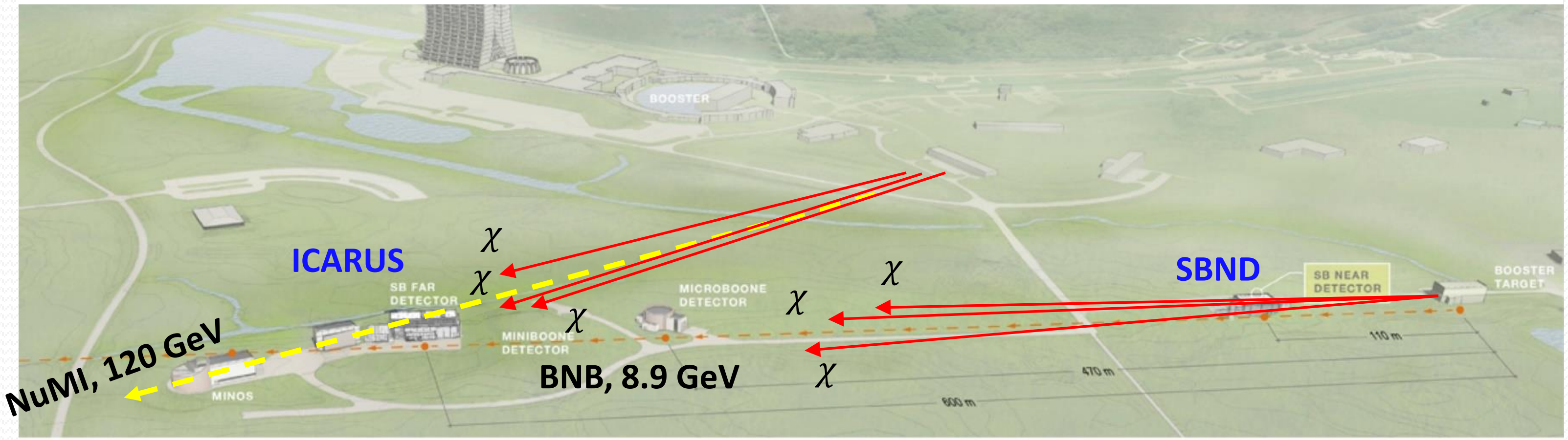




- Comparable production rate: $\pi^0 : \pi^+ : \pi^- : \eta : K^+ : K^- \approx 1:1:1:0.1:0.1:0.1$
- Unfocused π^0, η vs. Focused $\pi^\pm, K^\pm$
- Wider spreading π^0, η-induced DM flux vs. Forward-directed $\pi^\pm, K^\pm$-induced DM flux
- No BR enhancement vs. Large BR enhancement

Vector-Portal Dark Matter at SBN with BNB and NuMI Beams

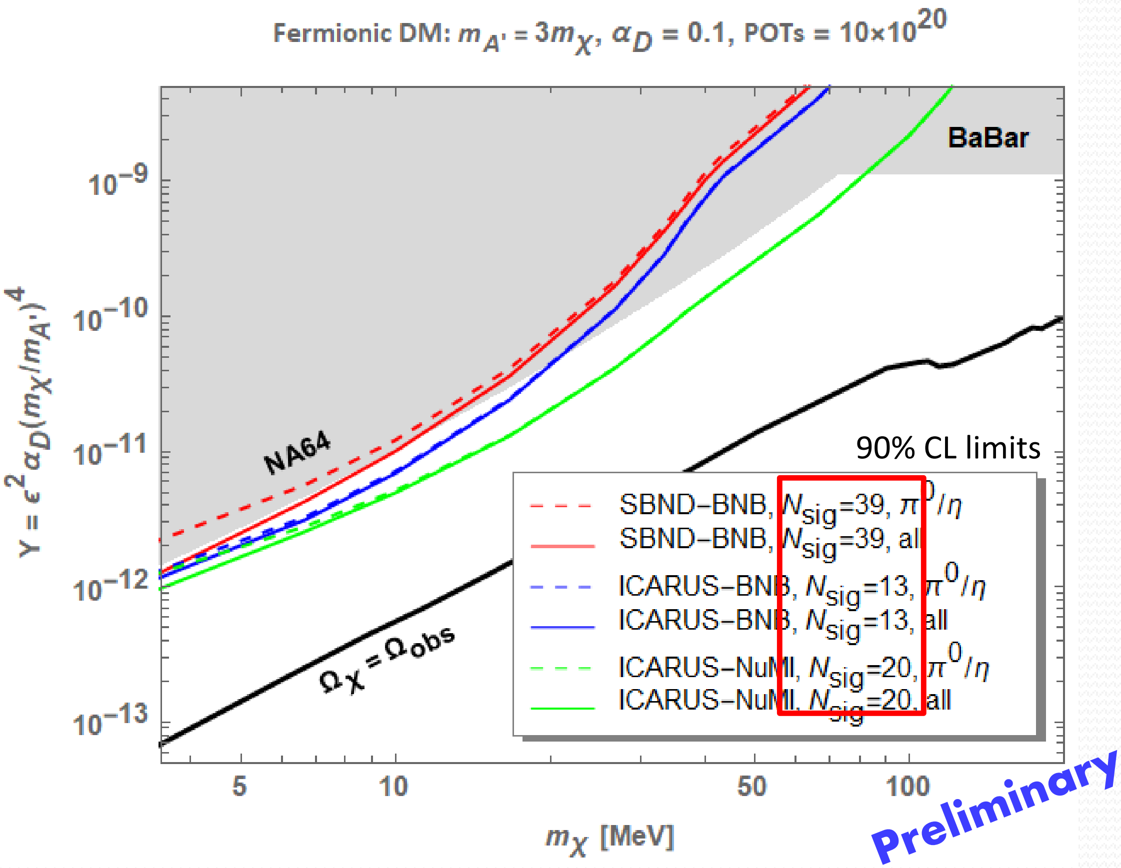
$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_{\mu}A'^{\mu} + eA_{\mu}J^{\mu}_{\rm EM} + \epsilon e A'_{\mu}J^{\mu}_{\rm EM} + g_{\chi}A'_{\mu}J^{\mu}_{D} + \mathcal{O}(\epsilon^2)$$



Focused dark-matter "beam" (+ unfocused neutral-meson contributions)

Cf. See Adrian Thompson's talk for the application to the MiniBooNE low energy excess.

Sensitivity Result: Vector-Portal Dark Matter



[Dev, Dutta, Han, **DK**, Qin, in preparation]

- Charged meson contributions can improve the signal sensitivity. (For leptophilic scenarios, e.g., $L_\mu - L_\tau$, the difference will be even more significant.)
- ICARUS-NuMI (an off-axis detector) can accept dark-matter signals from three-body decays of charged mesons more efficiently.

Conclusions

- Probing dark-sector physics at neutrino facilities is timely and promising, and provides various interesting phenomenology.
- We discussed two possible avenues of improving the sensitivity to dark-sector signals:
  - **Dump mode measurements**: Neutrino-related backgrounds can be significantly reduced. Good for dark-sector signals coming from the neutral meson decays.
  - **New channels of focused dark-sector signals**: The signals coming from the charged meson decays can be effectively focused by the magnetic horn system and the related BRs can be enhanced. This new channel is (almost) exclusively sensitive to leptophilic dark-sector scenarios.