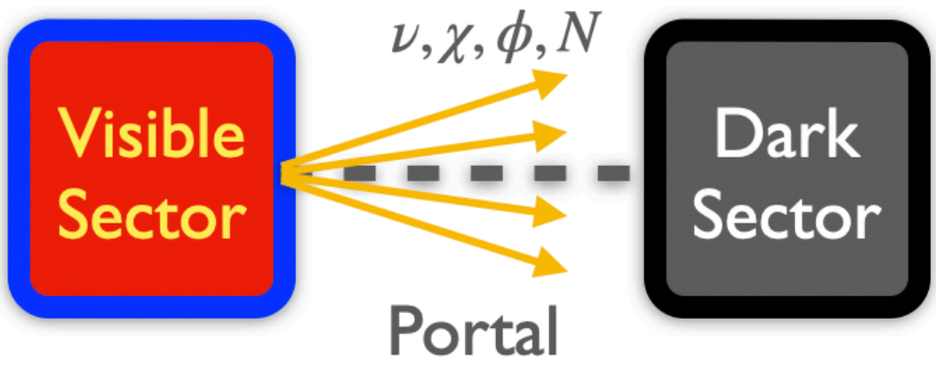
Accelerator-Based Dark Sector Searches: Connections with the Neutrino Frontier



Brian Batell
University of Pittsburgh

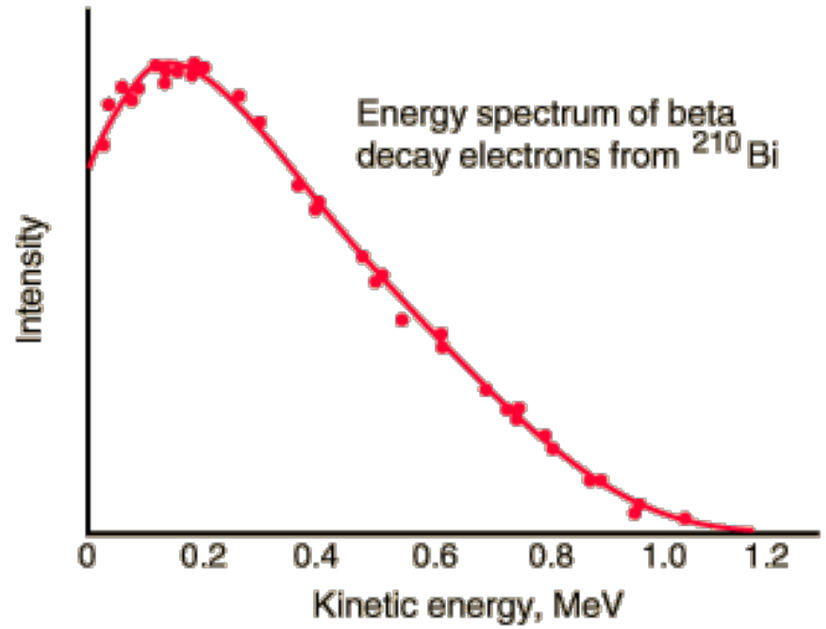
Snowmass Agora
April 22, 2022

Neutrinos as a prototype for a dark sector

- 1930s, Beta decay:

$$n \to p + e^-$$

Continuous spectrum!



- Pauli proposes a radical solution - the neutrino

$$n \to p + e^- + \bar{\nu}$$

- Good prototype for a dark sector!
  - neutrino is electrically neutral
  - weakly interacting, light
  - interacts with e, p, n through "portal" - $(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu \nu)$

How do we study neutrinos?

- (Weak) Decays of heavy particles ($\mu, \tau,$ hadrons, W, Z, t)
- Reactors
- Accelerators
- Astrophysical systems (stars, supernovae, cosmic-rays ...)

We can use similar means to study dark sectors

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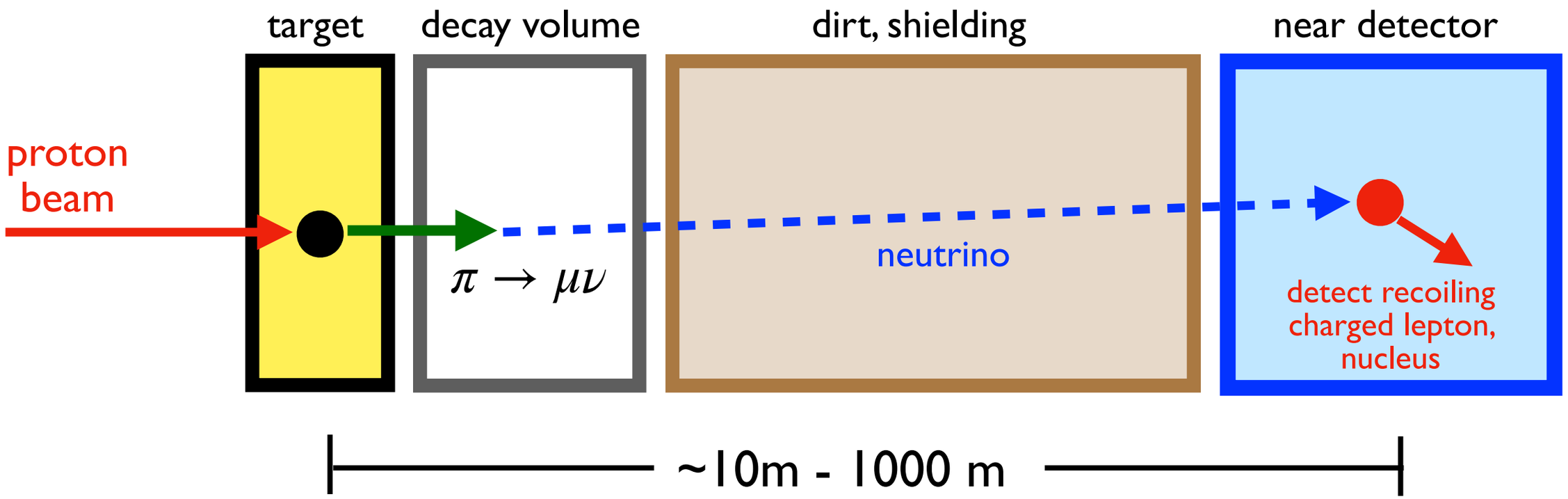
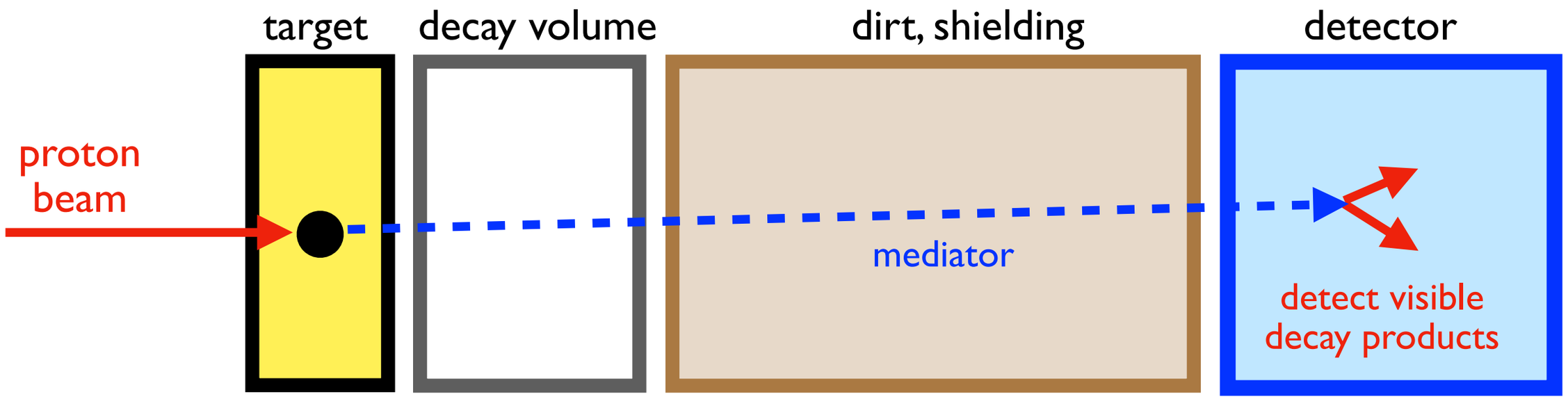
Accelerator neutrino beam experiments



- High intensity proton beam - fixed target experiment — enormous collision luminosities
- Large acceptance due to forward kinematics, short baselines, large volume detectors
- Modern neutrino detectors enjoy excellent particle ID and reconstruction capabilities
- These features also extend to searches for dark sector particles

Dark mediators at accelerator neutrino experiments



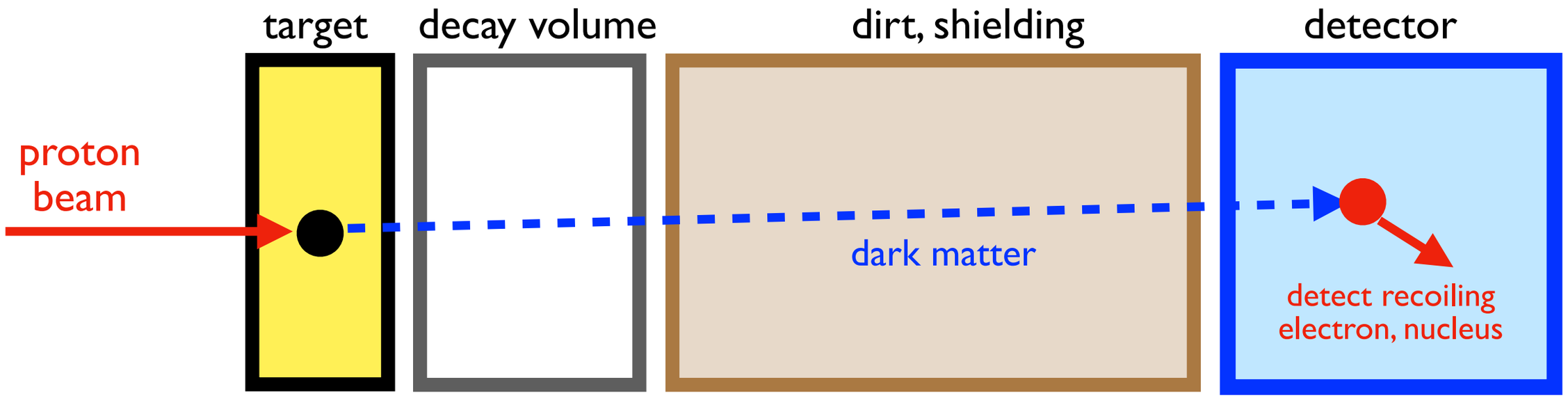
See for example:

[Gorbunov, Shaposhnikov] (HNLs)

[Essig, Kaplan, Harnik, Toro] (ALPs, Dark Photons)

…

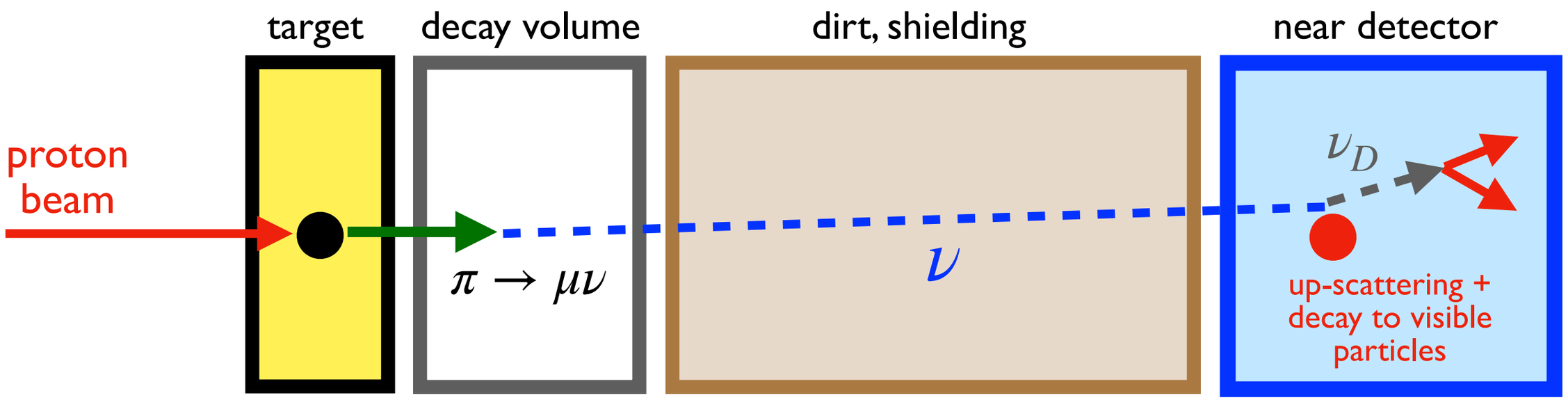
Dark matter at accelerator neutrino experiments



See for example:

[BB, Pospelov Ritz]
[deNiverville, Pospelov Ritz]
[Coloma, Dobrescu, Frugiuele, Harnik]
[Kahn, Krnjaic, Thaler, Toups]
[de Romeri, Kelly, Machado, Krnjaic]
…

Dark neutrinos from neutrino beams



$(\nu \to \nu_D, \nu_D \to \nu\ell^+\ell^-)$

See for example:

[Gninenko]
[Magill, Plestid, Pospelov, Tsai]
[Bertuzzo, Jana, Machado, Funchal]
[Ballett, Pascoli, Ross-Lonergan]
…

Models, production mechanisms, and signatures

Model	Production	Detection
Higgs Portal	K, B decay	Decay ($\ell^+\ell^-$)
Vector Portal	π^0, η Decay Proton Bremmstrahlung Drell-Yan	Scattering (χe^-, χX, Dark Tridents) Decay ($\ell^+\ell^-$, $\pi^+\pi^-$) Inelastic Decay ($\chi \to \chi'\ell^+\ell^-$)
Neutrino Portal	π, K, $D_{(s)}$, B decay	Decay (many final states)
ALP Portal (γ-coupling dominant)	Meson Decay Photon Fusion Primakoff Process	Decay ($\gamma\gamma$) Inverse Primakoff process
Dark Neutrinos	SM Neutrino	Upscattering + Decay ($\nu \to \nu_D$, $\nu_D \to \nu\ell^+\ell^-$)
Dipole Portal	Dalitz Decay	Decay ($\nu_D \to \nu\gamma$)
νphilic Mediators	SM Neutrino	Scattering (Missing $p\!\!\!/_T$, SM Tridents)

Table 1: A selection of models that can be probed by neutrino beam experiments.

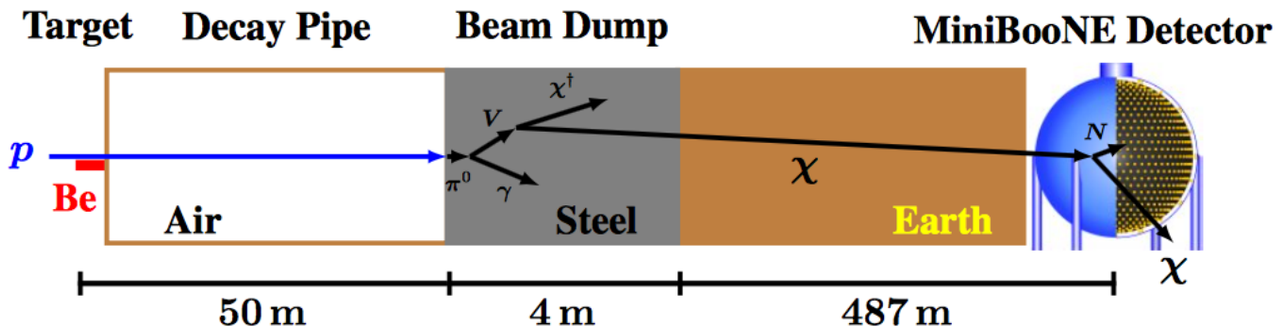
Table from *"Dark Sector Studies at Neutrino Beams NF03 Whitepaper"* (to appear)

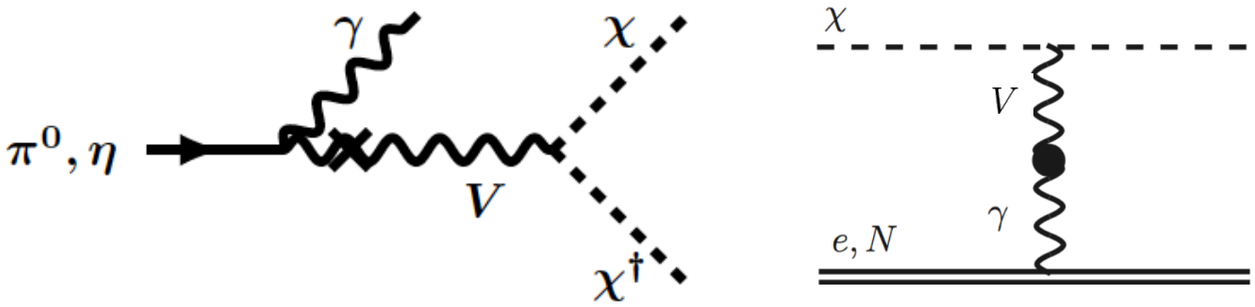
Experimental Landscape

- Past/existing neutrino experiments provide some of the best constraints on dark sectors
  - e.g., CHARM, Nu-Cal, MINOS, MiniBooNE, MINERvA, ArgoNeuT, MicroBooNE, JSNS^2,…
- Coherent Elastic Neutrino Nucleus Scattering (CEvNS) experiments can also provide sensitive probes
  - e.g., COHERENT, CCM, MINER, CONUS, CONNIE, …
- The FNAL SBN Experiments and in the future DUNE (and its near detector complex), as well as new experiments harnessing PIP-2 upgrades, will be able to explore a variety of dark sector models
- Neutrino experiments located in the far forward direction at the LHC offer interesting, complementary sensitivity
  - e.g., FASERν, FORMOSA, FLArE, …

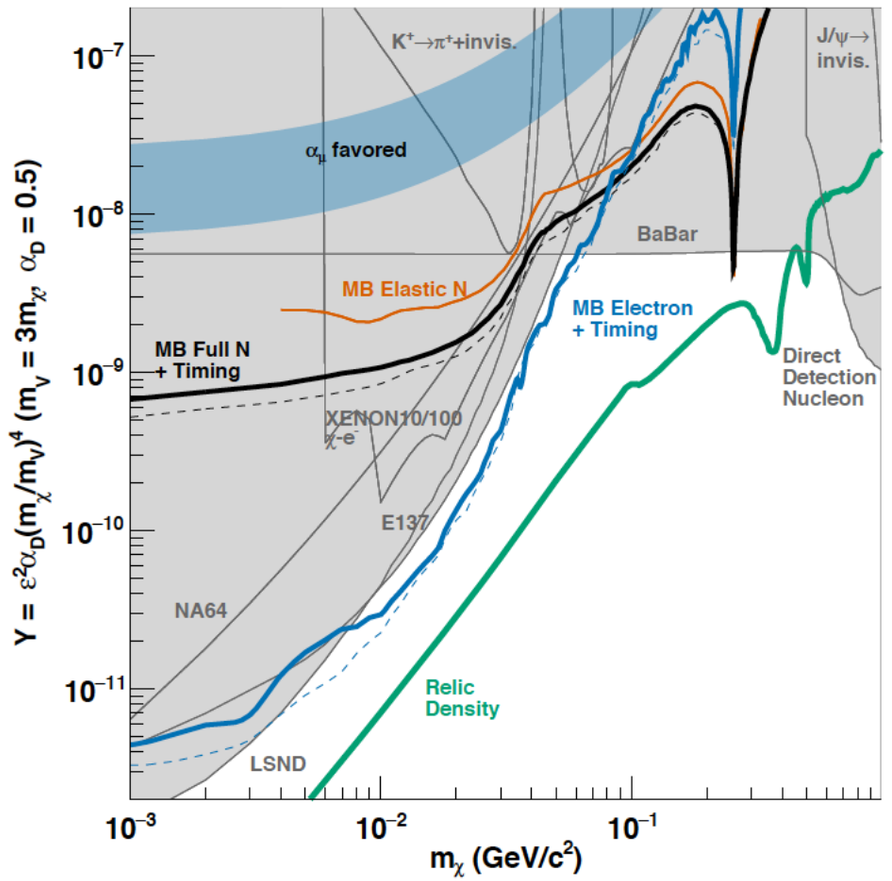
Neutrino beam experiments provide a critical and complementary component of the wider experimental program to search for dark sector searches

MiniBooNE-DM @ FNAL





Vector portal DM

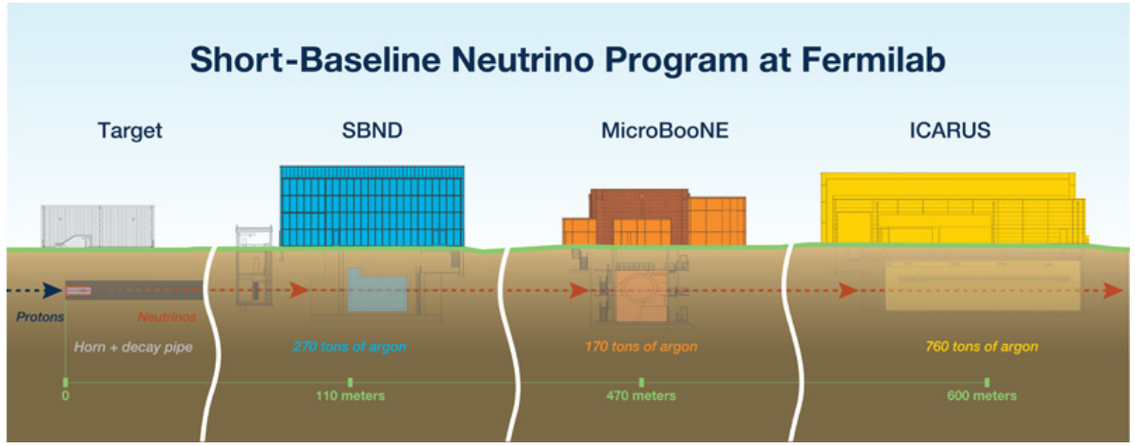


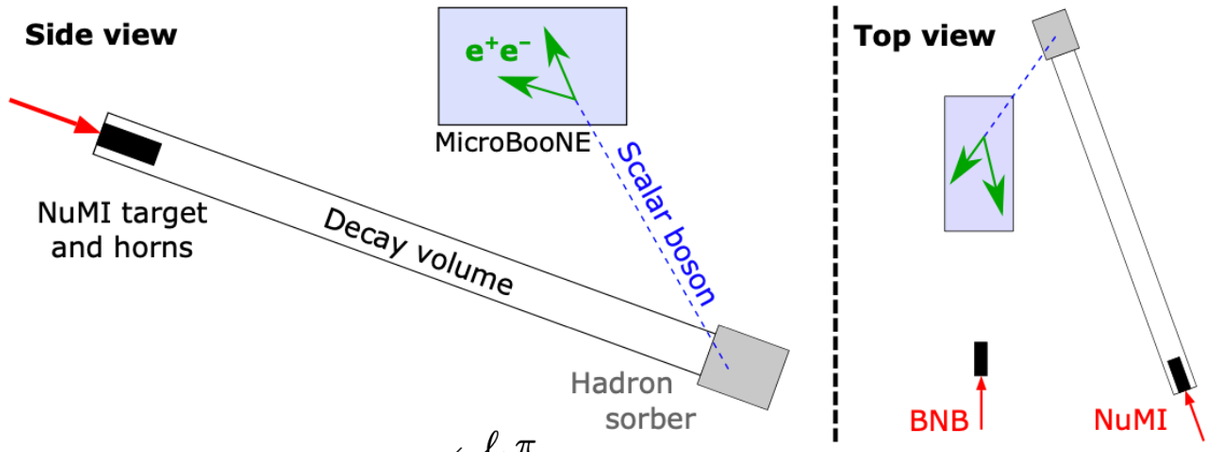
[MiniBooNE-DM, Phys. Rev. D 98 (2018) 11, 112004]

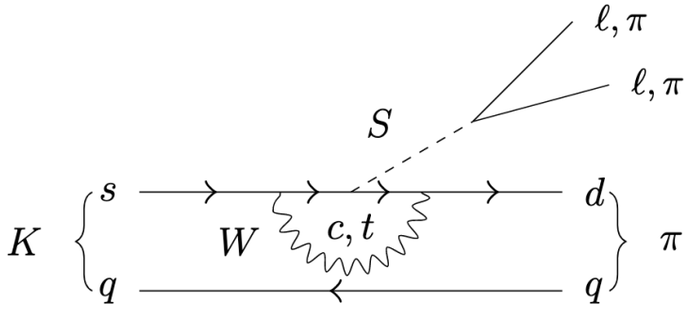
- 8 GeV protons on iron dump; 800 ton mineral oil detector
- Dedicated off target / beam dump run mode, collected 1.9E20 POT
- Leading limits on vector portal dark matter model for ~ 100 MeV mass range
- Demonstrates proton beam dump as an effective search method for light dark matter

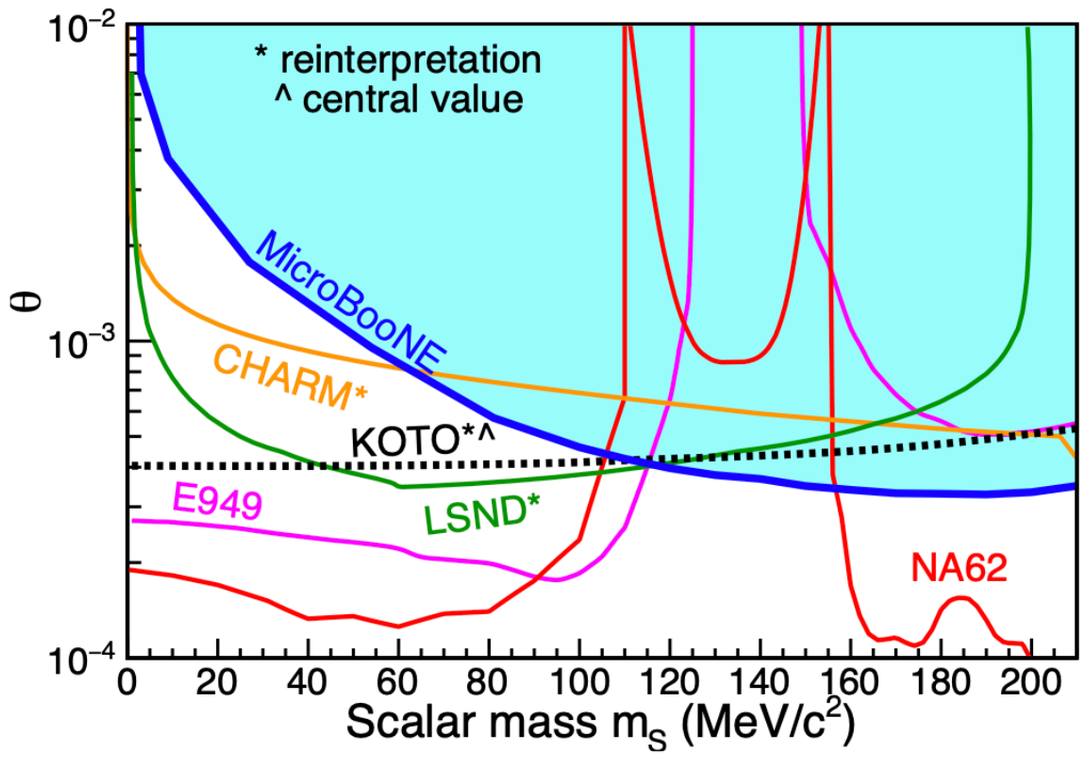
Short Baseline ν-Experiments @ FNAL

- MicroBooNE, SBND, ICARUS LArTPC detectors
- Situated along 8 GeV Booster beam line and slightly off axis from 120 GeV NuMi beam line
- Will collect ~ 10^{21} POT over next several years
- These experiments have sensitivity to a variety of dark sector models
- Example: MicroBooNE search for Higgs portal scalar







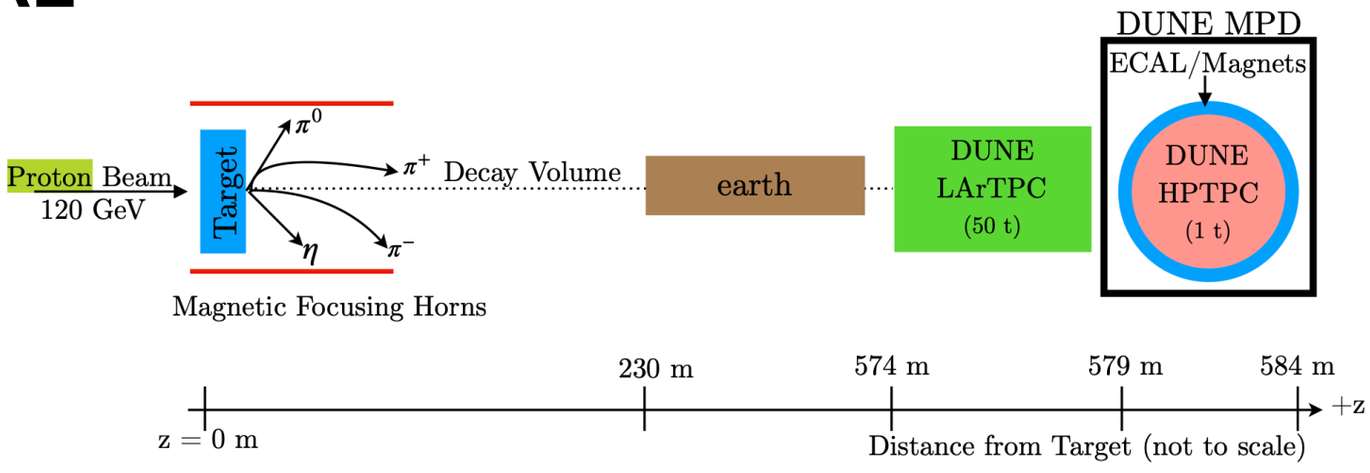


[MicroBooNE, Phys. Rev. Lett 127 (2021) 15, 151803]

[See also BB, Berger, Ismail, 1909.11670, for prospects at ICARUS and SBND]

DUNE Near Detector @ FNAL

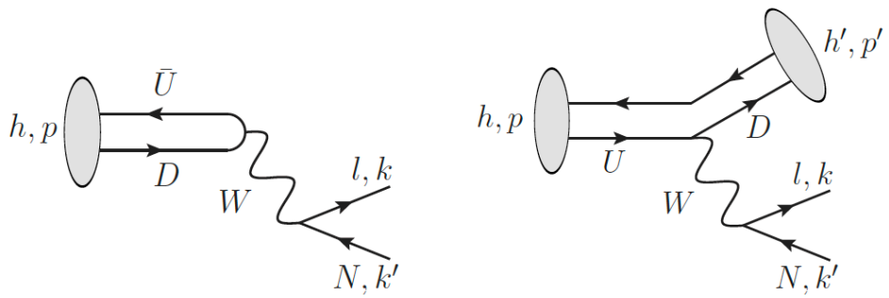
- 120 GeV proton beam, ~10^{22} POT
- Multi-Purpose Near Detector (MPD): 1 ton gaseous Argon TPC, surrounded by ECAL, located 574m downstream of target



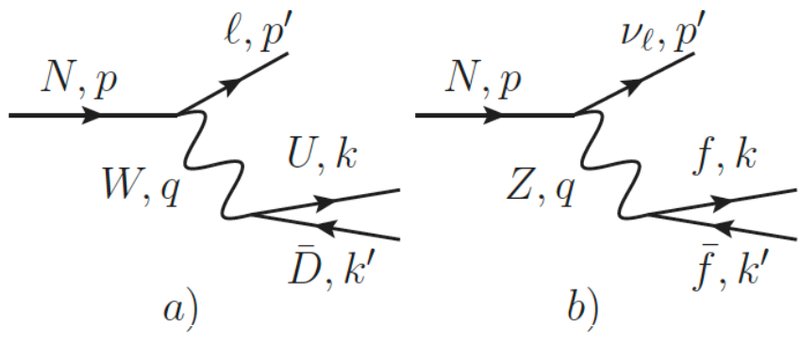
- Sensitivity to a variety of dark sector models
- Example : Heavy Neutral Leptons at DUNE MPD

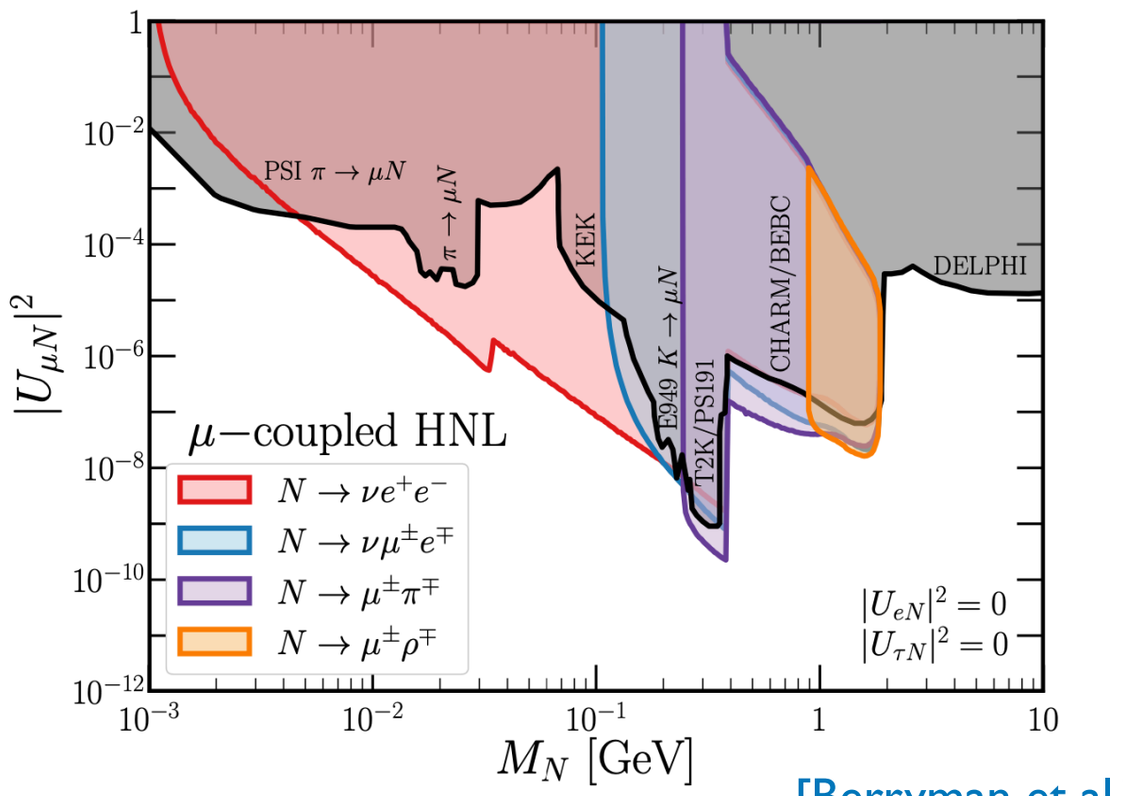
[Berryman, de Gouvea, Fox, Kayser, Kelly, Raaf]
[Ballett, Boschia, Pascoli]
[Coloma, Fernandez-Martınez, Gonzalez-Lopez, Hernandez-Garcia, Pavlovic]

HNL production



HNL decay



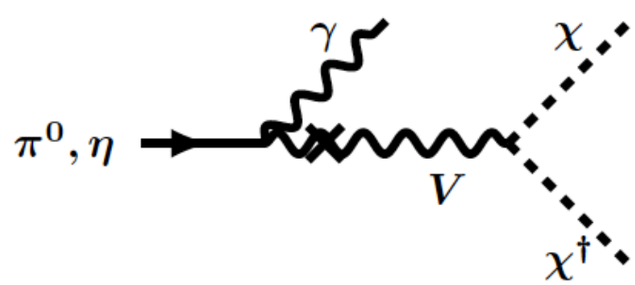


[Berryman et al.]

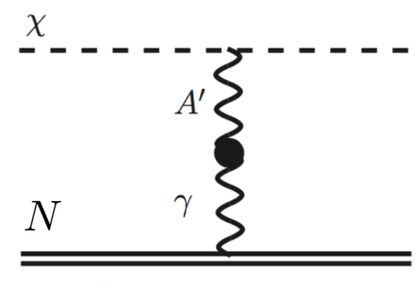
GeV-scale CEνNS Experiments

- First observation of Coherent Elastic Neutrino Nucleus Scattering (CEvNS) by COHERENT!
  [Science 357 (2017) no.6356, 1123-1126]

- CEνNS experiments can probe light dark matter: [deNiverville, Pospelov, Ritz] [Ge, Shoemaker]

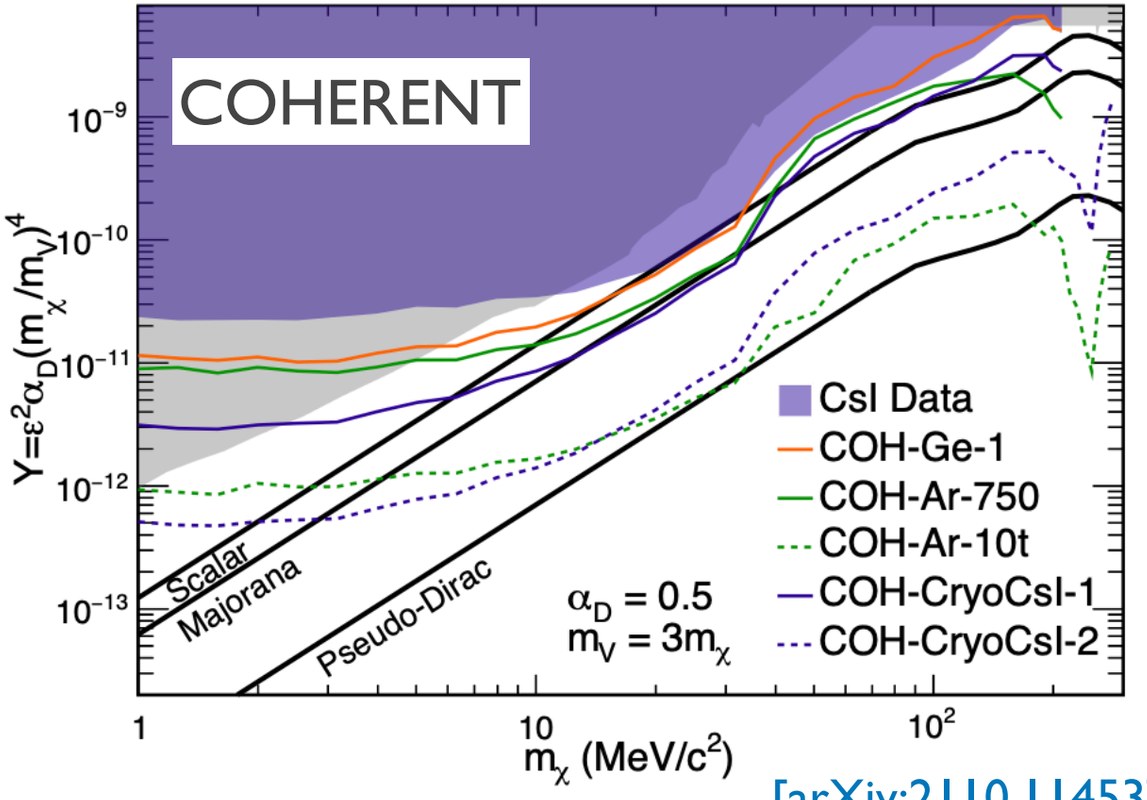


DM production

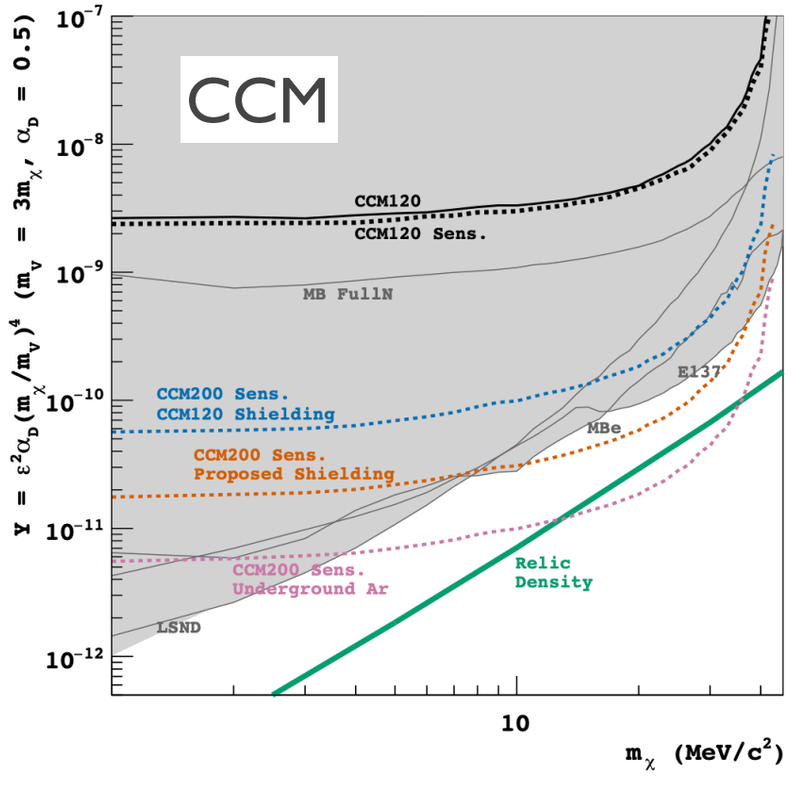


Coherent DM-nucleus scattering

- Example: COHERENT@ORNL and CCM@LANL sensitivity to vector portal DM



[arXiv:2110.11453]



[arXiv: 2105.14020]

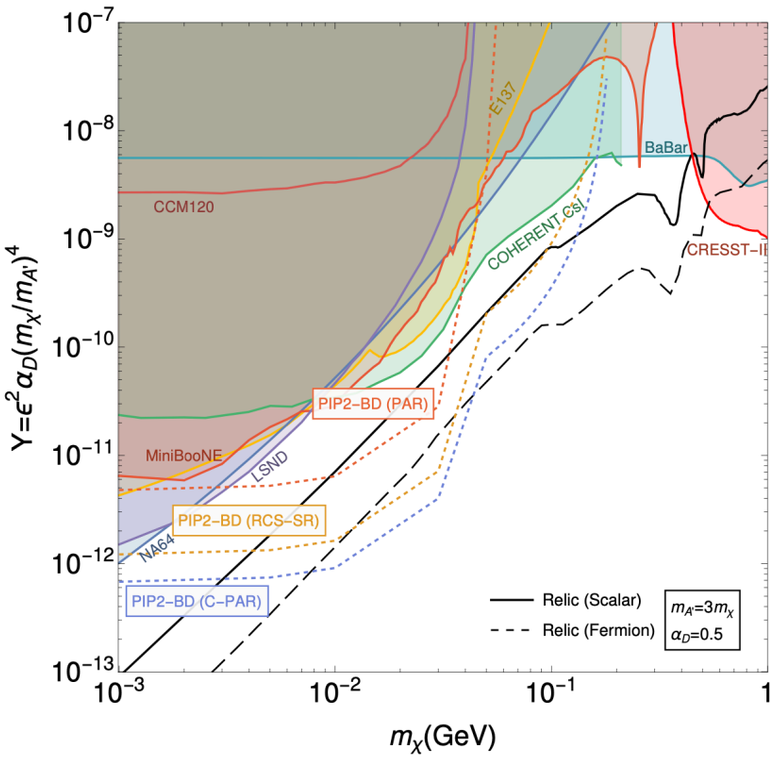
Opportunities with the FNAL Proton Improvement Project 2 (PIP-2)

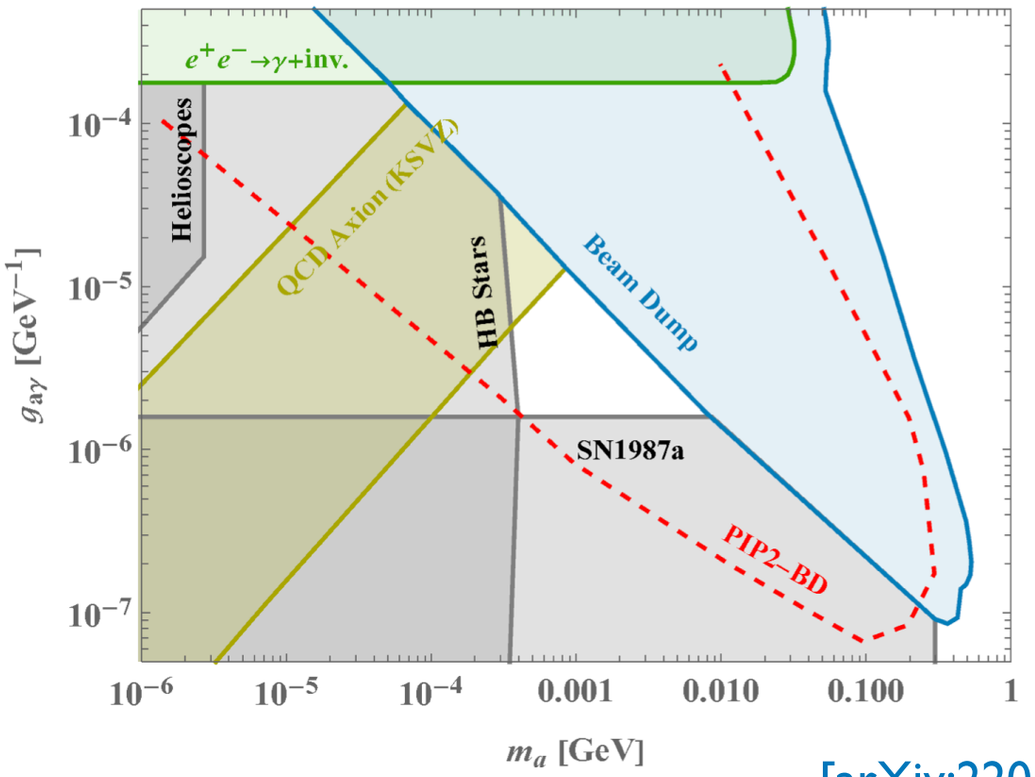
- As part of FNAL PIP-2 upgrade, Booster will be replaced, Main Injector will be upgraded
- Excess protons at ~1 GeV, ~10 GeV, 120 GeV will be potentially available for a variety of physics applications, including dark sector studies.

Proton beam dump experiments: 1 GeV PIP2-BD and 10 GeV SBN-BD

[See Toups et al. 2203.08079, 2203.08102,Snowmass whitepapers]

- Physics opportunities: CEvNS studies, searches for light sterile-ν, sub-GeV DM, ALPs, …
- 1 GeV PIP2-BD capabilities: MW class intensity (10^{22} -10^{23} POT/year), short beam pulse (< 30 ns), low duty factor (10^{-4}-10^{-6})
- Highlights: vector portal DM and axion-like particle coupled to photon at PIP2-BD



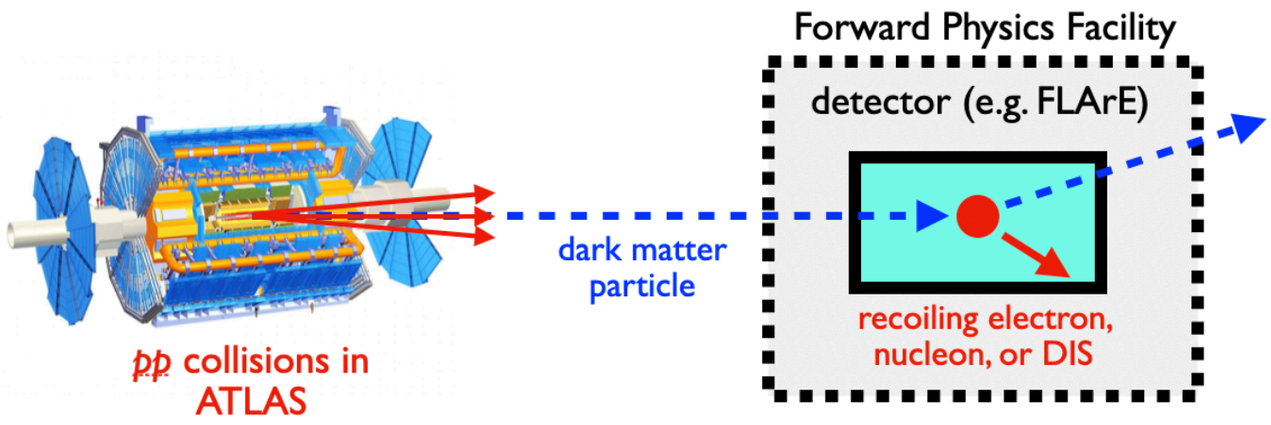


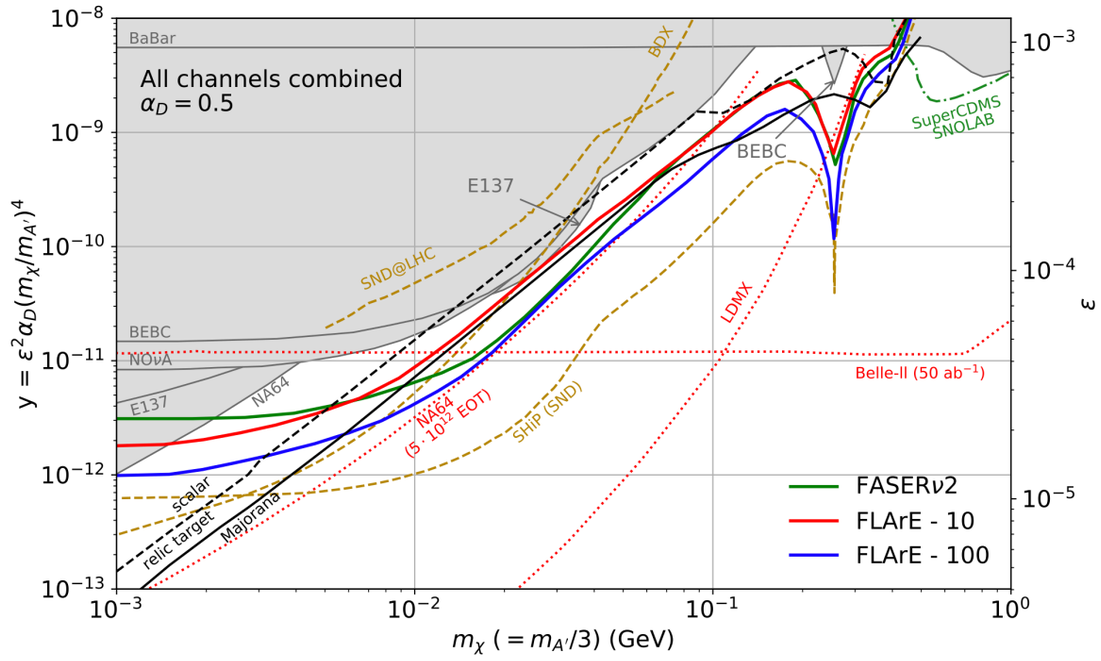
[arXiv:2203.08079]

Forward LHC ν−experiments (FASERν, FLArE, …)

- Total LHC pp cross section is ~100 mb, and is directed in the forward region
  - Copious source of TeV energy neutrinos
  - First collider-produced neutrinos detected by FASERν [arXiv:2105.06197]
  - Exciting prospects at FASERν, SND@LHC (Run 3) and FASERν2, FLArE, FORMOSA (HL-LHC)
- Dark sectors can also be explored with forward LHC experiments See next talk by J. Feng
  - For full physics case, see Forward Physics Facility whitepaper [arXiv:2203.05090]

- Example: vector portal dark matter





[BB, Feng, Feig, Ismail, Kling, Abraham, Trojanowski]
[2101.10338, 2107.00666, 2111.10343]

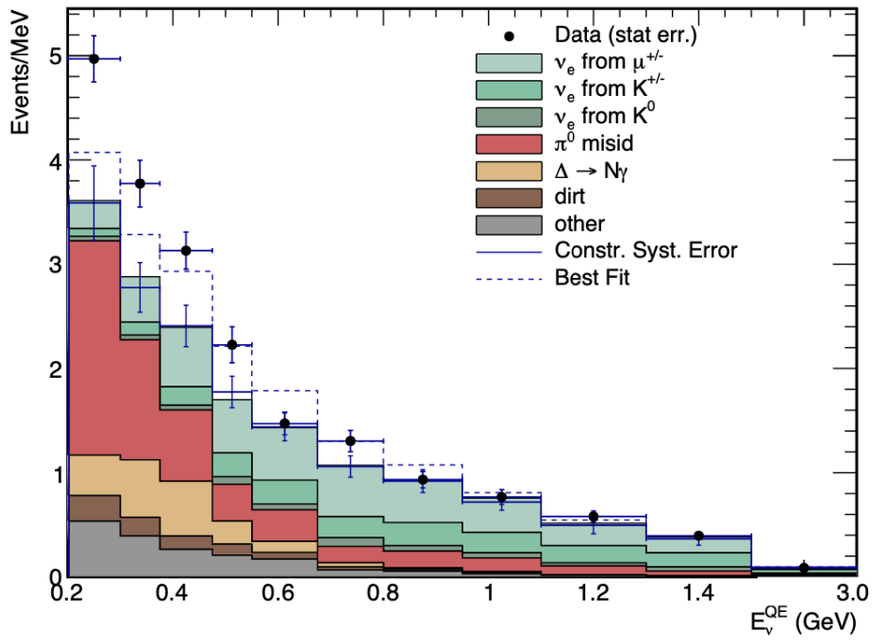
Dark Sectors and the MiniBooNE Low Energy Excess

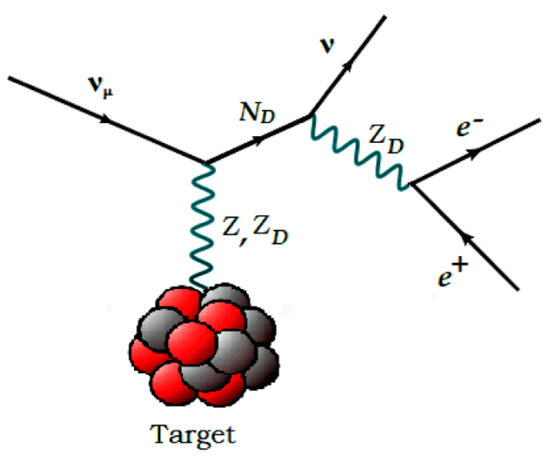
- MiniBooNE observes an excess of low energy electron-like events (LEE)

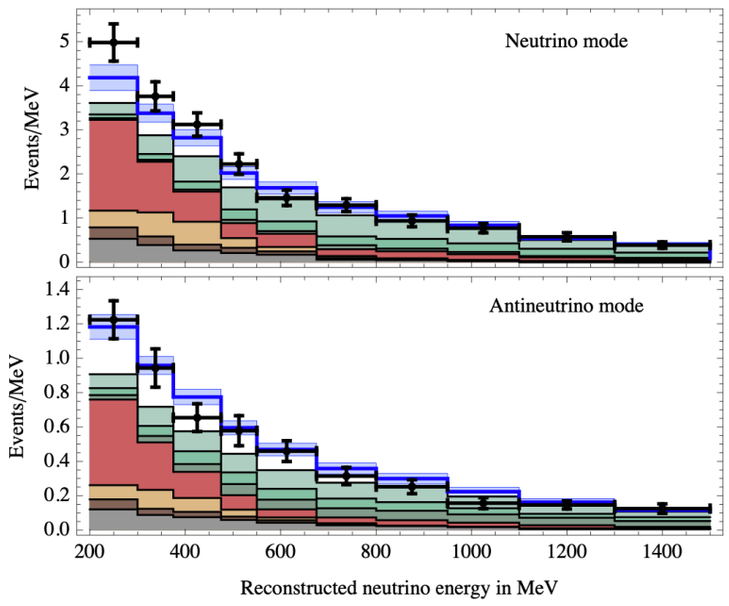
[arXiv:0812.2243, 1805.12028, 2006.16883]

- Several dark sector explanations of the MiniBooNE LEE have been put forth

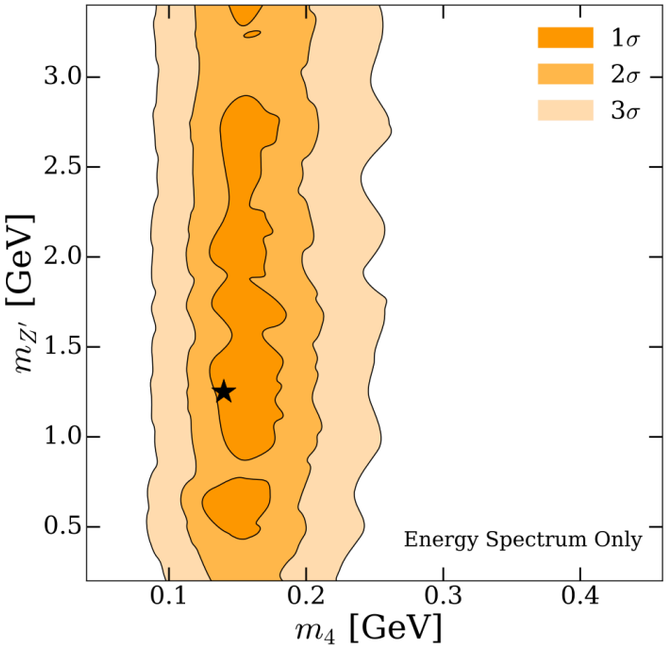
- Example: dark neutrino portal







[Bertuzzo, Jana, Machado, Funchal]



[Ballett, Pascoli, Ross-Lonergan]

For other dark sector explanations, see works of Gninenko; Fischer, Hernandez-Cabezudo, Schwetz; Brdar, Fischer, Smirnov; Datta, Kamali, Marfatia; Dutta, Ghosh, Li; de Gouvea, Peres, Prakash, Stenico; Dutta, Kim, Thompson, Thornton, Van de Water; …

Other exciting topics at the interface of neutrinos, neutrino experiments, and dark sectors

Inelastic DM at neutrino experiments see e.g., [Jordan, Kahn, Krnjaic, Moschella, Spitz]

Neutrino portal dark matter see e.g., [Bertoni, Ipek, McKeen, Nelson], …

Neutrinos (or Sterile Neutrinos) coupled to dark forces

- Non-standard neutrino tridents: see e.g., [Altmannshofer, Gori, Pospelov, Yavin],…
- Probes with CEvNS see e.g., [Liao, Marfatia], [Denton, Farzan, Shoemaker], …
- Neutrino mass models see e.g., [Bertuzzo, Jana, Machado, Funchal], [Ballet, Hostert, Pascoli]

Radioactive sources of dark states: see e.g., [Izaguirre, Krnjaic, Pospelov], [Pospelov, Tsai], …

Atmospheric sources of dark states: see e.g., [Coloma, Hernandez, Munoz, Shoemaker], …

Solar, astrophysical sources of dark states many studies…

See also:

"White Paper on New Opportunities at the Next-Generation Neutrino Experiments (Part 1: BSM Neutrino Physics and Dark Matter)" https://arxiv.org/abs/1907.08311

"Dark Sector Studies at Neutrino Beams NF03 Whitepaper" (to appear)

Summary and Outlook

- Expansive worldwide program of neutrino experiments will provide a fertile ground for dark sector searches in the coming years

- Complementary to other experimental approaches (probing hadronic couplings, neutrino-philic couplings, …)

- Accelerator neutrino experiments already provide some of the best limits on dark sector models. Future experiments will improve on existing limits by 1-2 orders of magnitude

- Still significant room for exploration in theory/model/signature space, particularly regarding scenarios connecting dark sectors to neutrinos

- Many exciting experiments and results on the horizon!