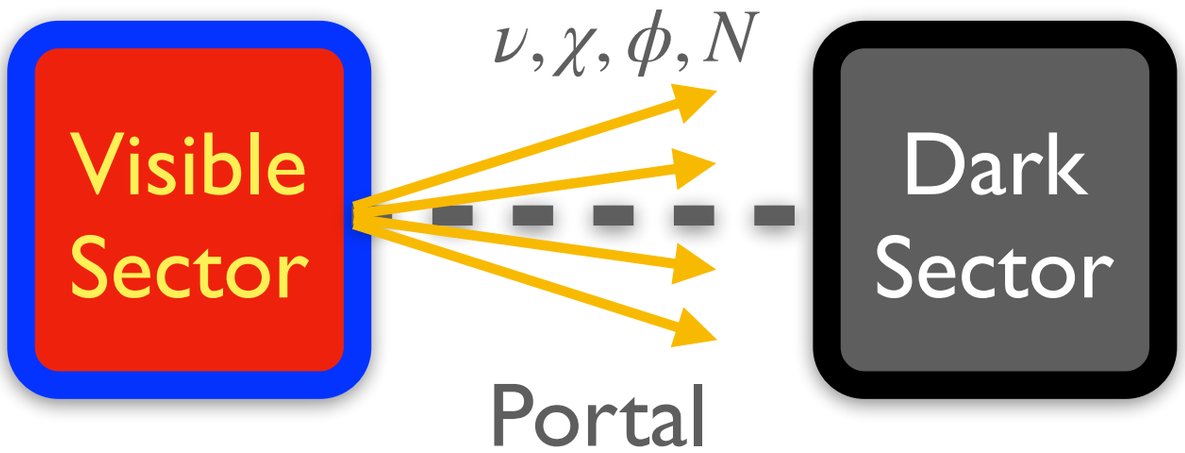
NF03 Report on
Dark Sector Studies with Neutrino Beams

Brian Batell (Pitt) and Jae Yu (UT-Arlington)
on behalf of the working group



Snowmass BSM@ν Workshop
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What is a Dark Sector?

- Set of new particles which do not experience the known forces
- Weakly coupled to visible sector through a mediator or "portal"

Why Dark Sectors?

- General effective field theory logic in exploring the unknown (portal framework)
- Dark sectors may play a role in addressing a variety of puzzles, including dark matter neutrino masses, matter-antimatter asymmetry, naturalness, …
- Experimental anomalies often interpreted in context of dark sectors

Why neutrino beam experiments?

- High intensities allow probes of weak portal couplings
- Neutrino beams allow tests of hadro-philic and neutrino-philic mediators
- Past/existing neutrino beam experiments already provide leading constraints
- Great potential to discover dark sectors and discern their structure with existing/new searches and experiments in the coming years

Dark Sector Studies with Neutrino Beams

NF03 Contributed White Paper to Snowmass 2021

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Many thanks to all of the contributors for their efforts!

Contents

Dark Sectors and Portals

- There are three minimal renormalizable portals that connect the visible and dark sectors

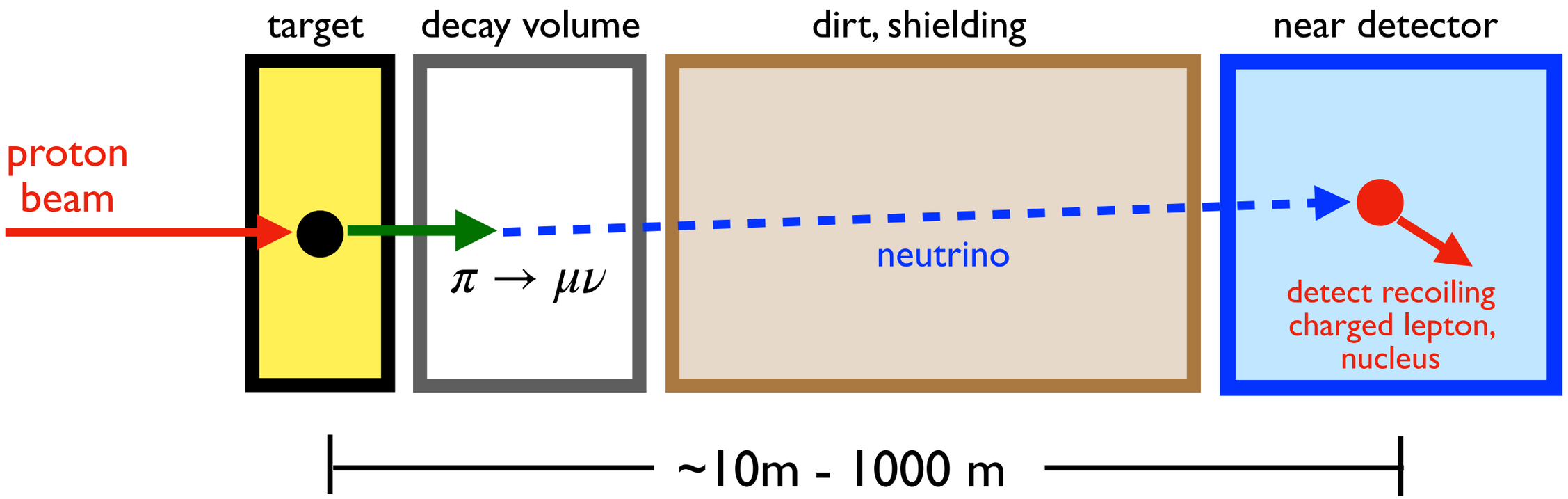
$$\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu} \qquad \text{Vector Portal}$$

$$(A\,S + \lambda\,S^2)\,H^\dagger H \qquad \text{Higgs Portal}$$

$$y N L H \qquad \text{Neutrino portal}$$

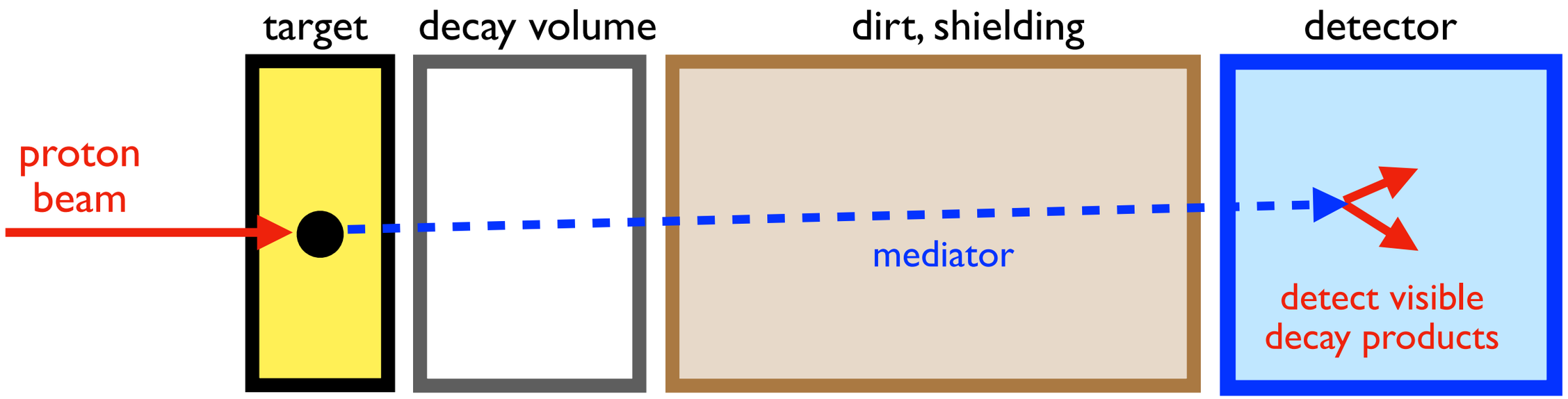
- There are other interesting options for the mediator:
  - Higher dimension portals, e.g. axion-like particle, dipole portal, …
  - Anomaly free (e.g., $B-L, L_\mu - L_\tau$ …) gauge bosons. These lead to neutrino-philic mediators
  - In some cases, these mediators come with additional motivations (e.g., neutrino masses, heavy QCD axion, explanations to experimental anomalies, …)
- The dark sector itself can be minimal or have a rich structure (e.g., dark neutrinos, inelastic dark matter, …)

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



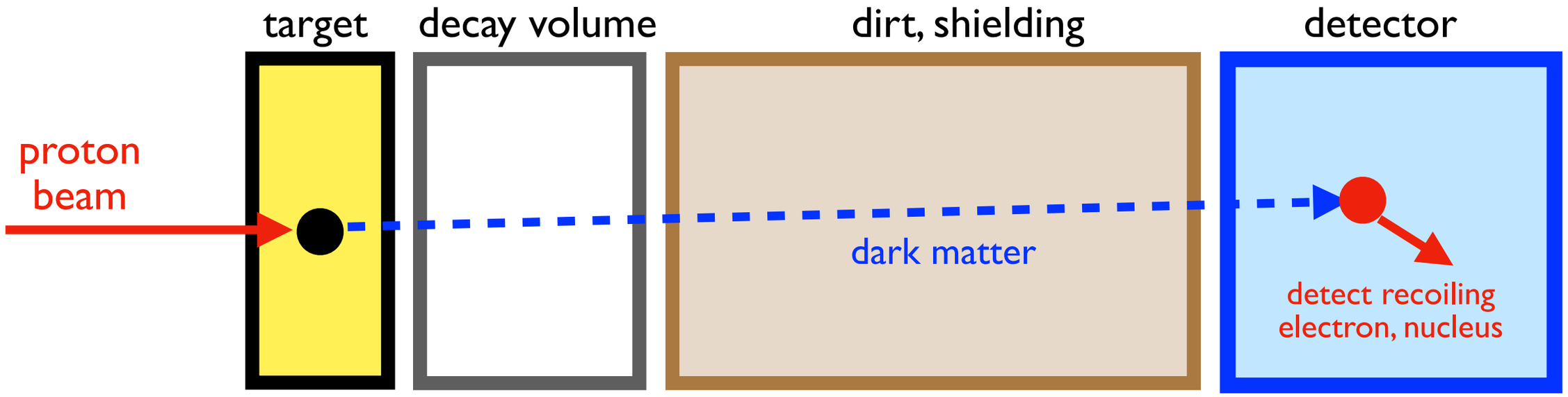
See for example:

[Gorbunov, Shaposhnikov] (HNLs)

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

…

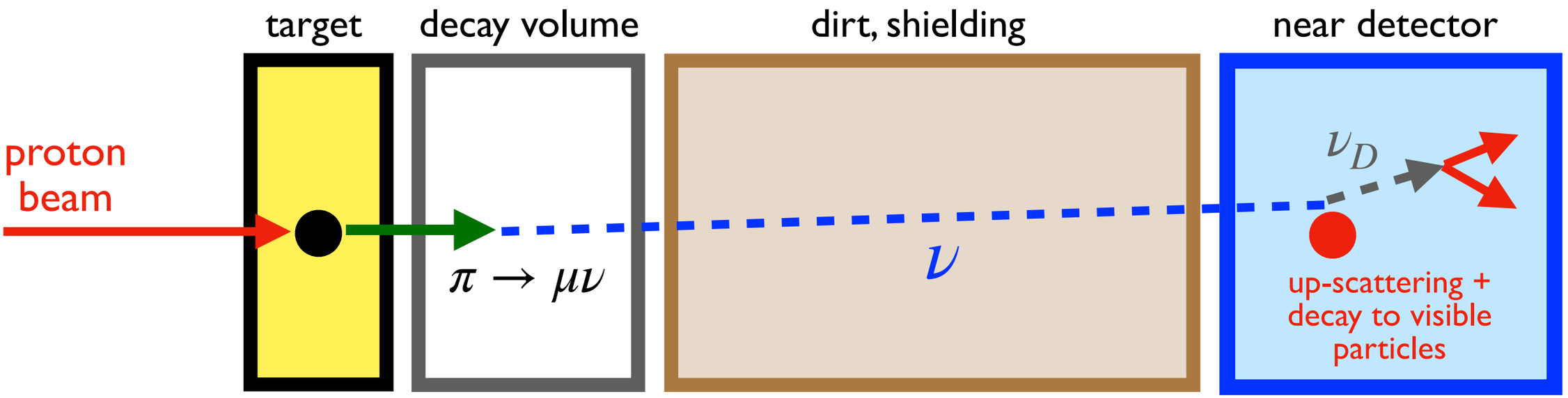
Dark matter at accelerator neutrino experiments



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



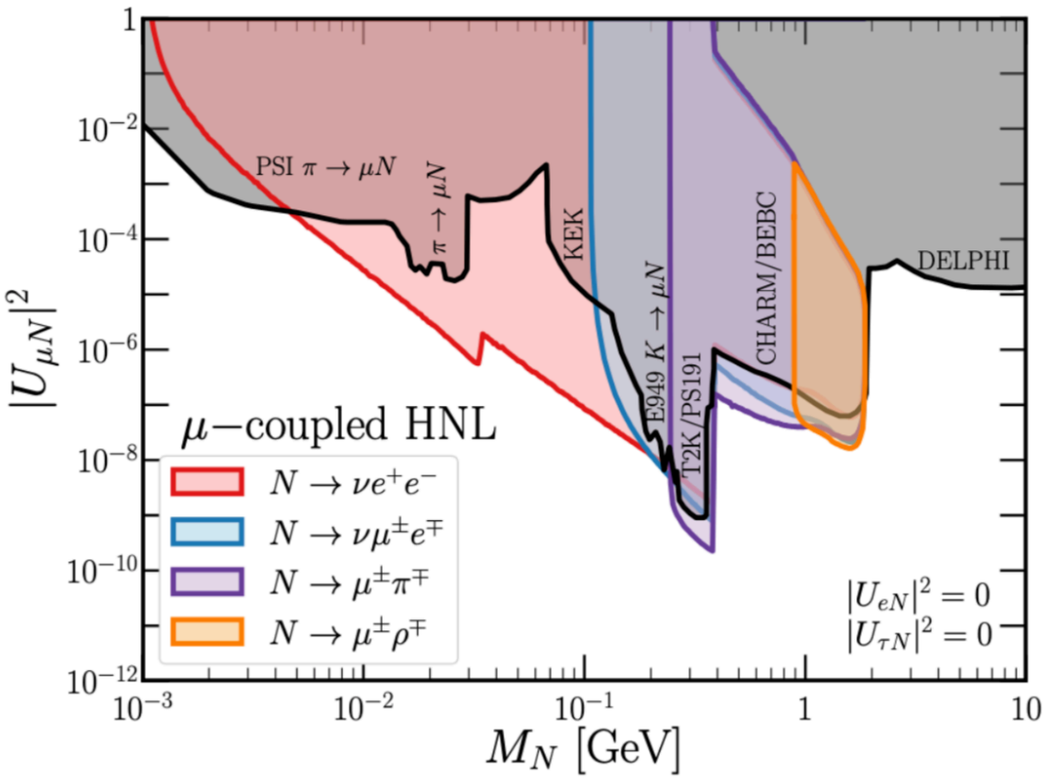
$(\nu \to \nu_D, \nu_D \to \nu\ell^+\ell^-)$

See for example:

[Gninenko]
[Magill, Plestid, Pospelov, Tsai]
[Bertuzzo, Jana, Machado, Funchal]
…

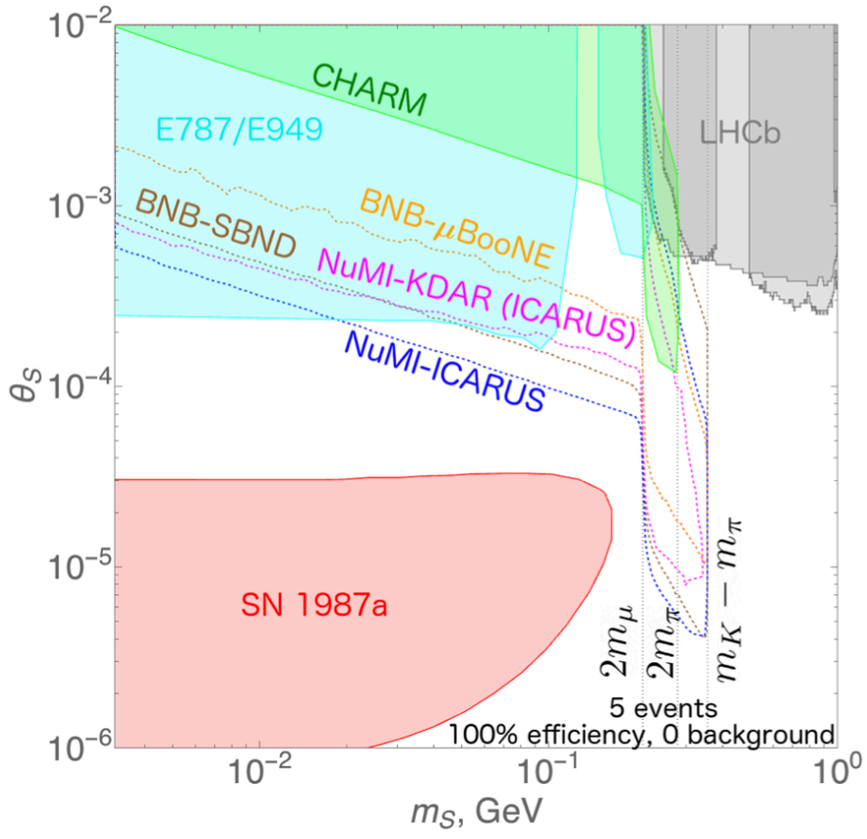
Some Highlights

Heavy Neutral Leptons at DUNE



[Berryman, et al. '19]

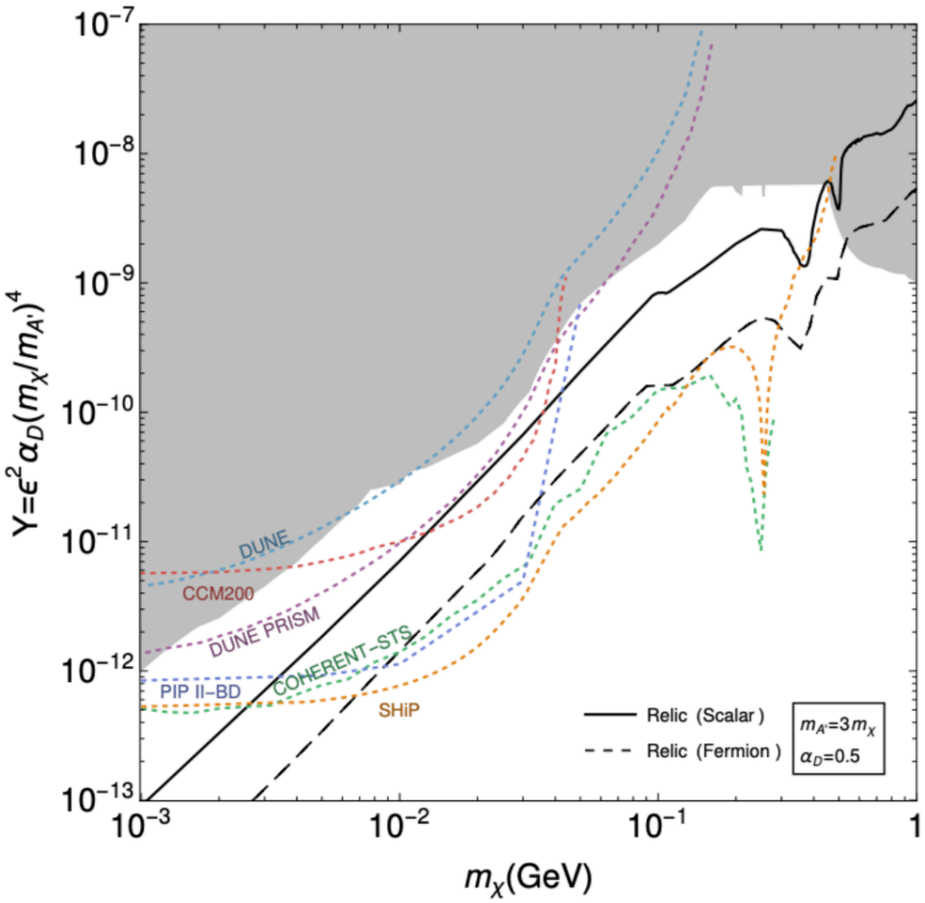
Higgs portal scalar at Fermilab SBN experiments



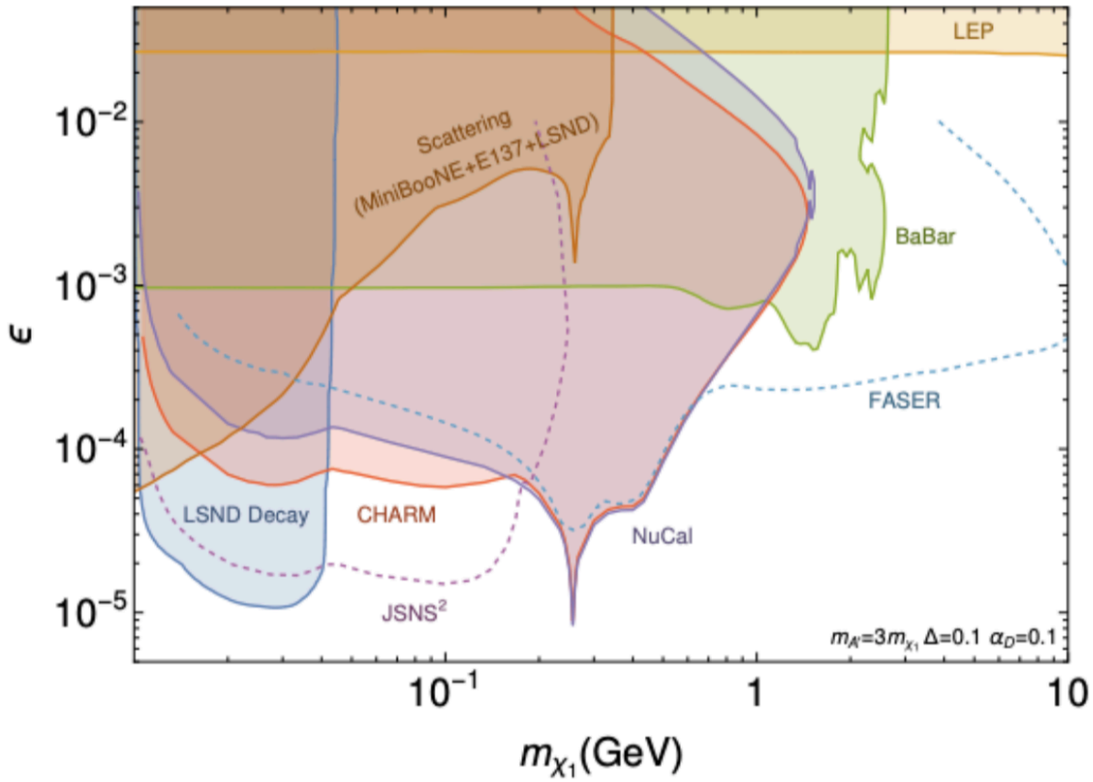
[BB, Berger, Ismail, 19]

Some Highlights

Light Vector Portal Dark Matter



Light inelastic dark matter



Plots from Patrick deNiverville

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.

Experimental Landscape

- Many previous or currently-operating neutrino experiments provide some of the leading constraints on dark sector and light dark matter models
  - e.g., CHARM, Nu-Cal, MINOS, MiniBooNE, MINERvA, ArgoNeuT, MicroBooNE, JSNS^2,…
- Experiments studying Coherent Elastic Neutrino Nucleus Scattering (CEvNS), including reactor based experiments can also provide sensitive probes.
  - e.g., COHERENT, CCM, MINER, CONUS, CONNIE, …
- The Fermilab Short Baseline Experiments (MicroBooNE, ICARUS, SBND) and in the future DUNE and its near detector complex, will be able to explore a variety of motivated dark sector models and parameter space
- 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

Tools

- Dark sector simulation tools are needed as input to experimental searches
- Several factors make such simulations challenging (target geometry and horn, nuclear effects, novel signal topologies, fast detector simulation,…)
- Already, dedicated tools exist for certain models and channels of dark sector particle production, scattering, decay, etc.
  - e.g., BdNMC [deNiverville et al.], MadDump [Buonocore et al.], GENIE [Berger], …
- Further work on developing signal event generators for variety of BSM models is needed
- Likewise, the development of tools for novel approaches to reconstruction and analysis, e.g., involving machine learning methods, is warranted

Significant further work is required to develop the simulation and analysis infrastructure that will allow a broad suite of dark sector searches

Status, remaining questions, work needed

- The bulk of the content and main text of the white paper is in place — many thanks to all contributors for their efforts!!!

- There is still a fair amount of work to be done in terms of editing, crafting a coherent presentation, connecting with big picture motivations, and plot making [Jae and I need to get to work :-)]

- One remaining question, which we hope to discuss during the working session, is about which plots to show and how best to combine sensitivities from various studies.

- Another question that can be discussed is how to handle areas of overlap with other NF03 sub-topical groups (e.g., CEvNS, HNLs) and other frontiers (e.g., RF6)

LOIs

Accelerator Probes:

* Dark Sector Studies With Neutrino Beams
- NF3_NF0-RF6_RF0-CF1_CF3-TF9_TF11-148.pdf

* Physics Beyond the Standard Model in DUNE
- NF3_NF2-TF11_TF0_DUNE-051.pdf

* Search for Axion-Like Particles at the Next Generation Neutrino Experiments
- NF3_NF0-RF6_RF0_Doojin_Kim-028.pdf

* Search for low mass dark matter at ICARUS detector using NuMI beam
- NF3_NF0-RF6_RF0-CF1_CF0_Animesh_Chatterjee-119.pdf

* Forward Physics Facility
- EF9_EF6_EF10_EF5-NF6_NF3_NF10-RF6_RF0-CF7_CF0-AF5_AF0-UF1_UF2_ForwardPhysicsFacility-193.pdf

* Accelerator Probes of Millicharged Particles and Dark Matter
- EF9_EF10_NF3_NF5_CF1_CF3_CF7_TF7_TF8_TF9_AF5_UF3_Yu-Dai_Tsai-114.pdf

* Precision Neutrino-Nucleus Interaction Physics and BSM Searches at the Short-Baseline Near Detector (SBND) at Fermilab
- NF3_NF6_SBND-166.pdf

LOIs

Accelerator Probes, cont'd:

* Physics Opportunities for detection and study of Heavy Neutral Leptons at Accelerator Neutrino Experiments
- NF2_NF3-RF6_RF0_Athanasios_Hatzikoutelis-160.pdf

* Opportunities and signatures of non-minimal Heavy Neutral Leptons
- NF2_NF3-EF9_EF0-RF4_RF6-CF1_CF0-TF8_TF11_Matheus_Hostert-041.pdf

* T2K Experiment: future plans and capabilities
- NF1_NF3__NF06_T2KCollab-130.pdf

* Concept for a Neutral-Rich Three-Dimensional Sign-Selecting Focusing System
- AF1_AF5-NF3_NF0_Jaehoon_Yu-209.pdf

* PASSAT: Particle Accelerator helioScopes for Slim Axion-like-particle deTection – A New ALP Detection Strategy
- NF3_NF0-RF6_RF0-CF1_CF0_Doojin_Kim-016.pdf

* Follow up of anomalies measured in short baseline neutrino experiments
- NF3_NF2-TF11_TF0_Petrillo-189.pdf

LOIs

Probes with CEvNS (accelerator- or reactor-based) experiments:

* ORNL Neutrino Sources for Future Experiments
- NF9_NF5-CF1_CF0-IF8_IF0_JNewby-108.pdf

* Dark Matter Searches at the Next-Generation CEvNS and Neutrino Facilities: from Photon to Dark Photon
- NF3_NF0-RF6_RF0-TF8_TF9_Doojin_Kim-070.pdf

* COHERENT LOI 3: COHERENT Sensitivity to Dark Matter
- NF3_NF9-111.pdf

* Directional detectors for CEvNS and physics beyond the Standard Model
- NF6_NF3_Snowden-Ifft-142.pdf

* Dark Matter Searches at the Next-Generation CEvNS and Neutrino Facilities: from Photon to Dark Photon
-NF3_NF0-RF6_RF0-TF8_TF9_Doojin_Kim-070.pdf

* Search for Axion-Like Particles at the Reactor Neutrino Facilities
NF3_NF0-RF6_RF0_Doojin_Kim-056.pdf

LOIs

Theory/models:

* Testable neutrino mass models
- NF8_NF3-TF11_TF8_Julia_Gehrlein-114.pdf

* Neutrino Minimal Standard Model — a unified theory of microscopic and cosmic scales
- NF3_NF1-EF9_EF0-RF4_RF6-CF1_CF3-TF11_TF9-AF5_AF0-195.pdf

* Neutrino Frontier: White Paper on Neutrino Self-Interactions
- NF3-003.pdf

Tools :

* Event Generators for Accelerator-Based Neutrino Experiments
- NF6_NF5-TF11_TF5-CompF2_CompF0_William_Jay-144.pdf

* Computing Challenges for Event Generators
- CompF2_CompF0_Ilten-063.pdf

Please let us know if we missed your LOI, or if you have a forthcoming whitepaper that is relevant

Feedback, input, and help on whitepaper from the community is welcomed and encouraged

- Jae and I will organize working / writing sessions during this workshop on Thu & Fri afternoon (2-5pm EST) to discuss the status and remaining issues and work on the editing/writing — please join if you are interested!

- If you have general feedback or questions, are interested in helping with the whitepaper, or would like to sign/endorse it, please email us:

batell@pitt.edu
jaehoonyu@uta.edu

- First drafts were due Jan. 28
- We hope to have a final draft of the whitepaper by Feb. 25
- Executive summary will be used as input to NF03 report

Thank you!