Phenomenology of Dark Sectors at the Short Baseline Neutrino Experiments

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PRD 104, 075026: B. Batell, JB, L. Darmé, C. Frugiuele
Fortcoming: B. Batell, JB, J. Dyer, A. Ismail
Snowmass Report 2207.06898

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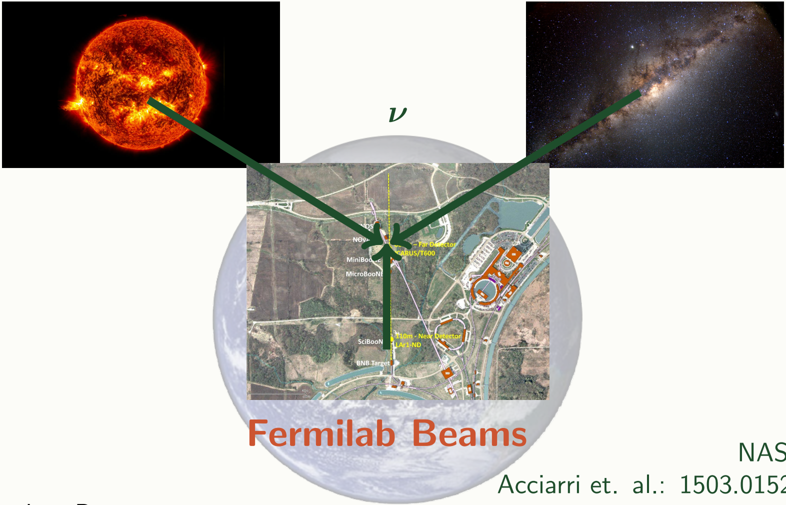
NuFact 2022 - WG5

Why Dark Sectors at ν Facilities?

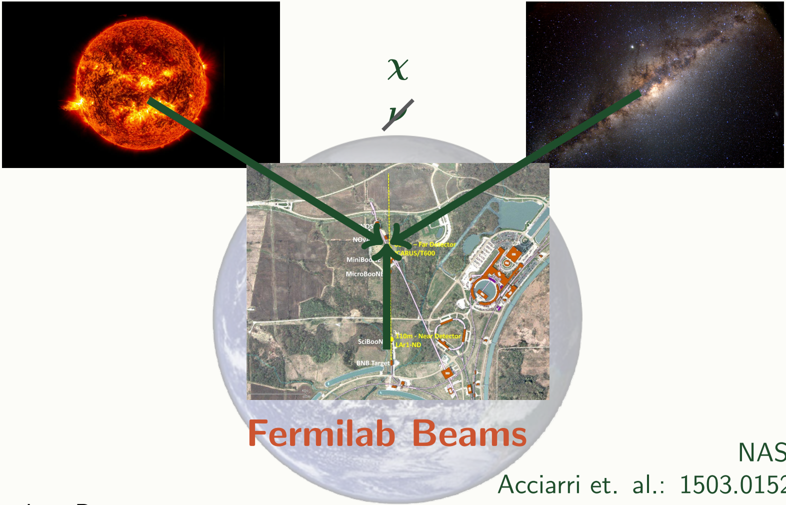
Astrophysical Sources



NASA
Acciarri et. al.: 1503.01520

Why Dark Sectors at ν Facilities?

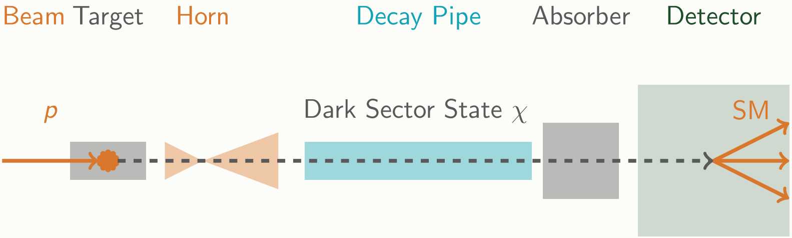
Astrophysical Sources



Fermilab Beams

NASA
Acciarri et. al.: 1503.01520

Beam Production



- SBN experiments sensitive to neutral, long-lived particles produced in the beam
- Several targets of opportunity to complement the neutrino program

The State of Simulation

Process	Production					Dark → Standard					
	Brem.	Direct	Prompt	LL	Flux	Decay	e	N El.	N Inel.	Det.	Reco.
`MadDump`		✓	✓		✓		✓		✓		
`BdNMC`	✓	✓	✓		✓	✓	✓	✓	✓		
`GENIE`							✓	✓	✓		
`Geant4`			✓	✓	✓	✓				✓	
`ACHILLES`						✓	✓	✓	✓		
`FORESEE`	✓	✓	✓	✓	✓	✓	✓	✓			

What's Next

- Event Timing
- Fast Detector Simulations
- MeV-scale Signatures
- Reconstruction of Complex Topologies
- Triggering Non-Neutrino Signals

Two Example Models

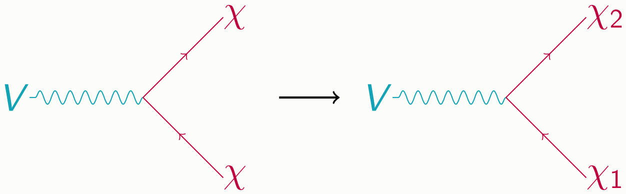
(1) Inelastic Dark Matter

(2) Higgs Portal

Model #1: Inelastic Dark Matter

$\propto \epsilon$

- Broken $U(1) \to$ massive V with gauge portal



$= i\, g_D\, \gamma^\mu$

- Also splits charged fermions into separate Majorana states

Overview of Signals

- Both direct and decay production mechanisms
- Three possible signals in detector:
  - Up-scattering $\chi_1\, e^- \to \chi_2\, e^-$ at short lifetimes
  - Decay $\chi_2 \to e^+\, e^-\, \chi_1$ at long lifetimes
  - Up- and down-scattering at very long lifetimes

$$\gamma\, v\, \tau \approx 10^3 \text{ m} \left(\frac{\Delta_\chi}{0.1}\right)^{-5} \qquad \Delta_\chi = \frac{M_{\chi_2} - M_{\chi_1}}{M_{\chi_1}}$$

Simulation of Signal

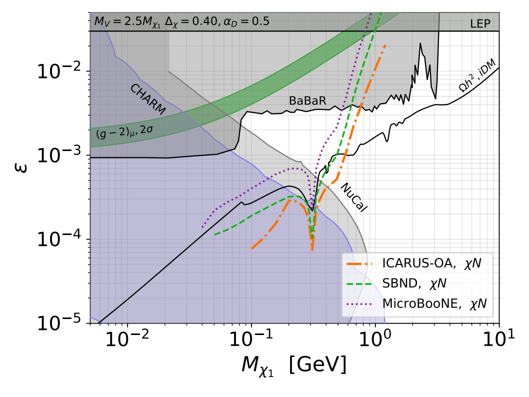
Signal production using modified version of BdNMC

- Meson distributions from empirical Sanford-Wang or Geant4 as available
- Proton bremsstrahlung from BdNMC including interference with vector meson resonances
- DIS using MadDump

de Niverville et. al.: Phys.Rev.D 95 (2017) 3, 035006
Buonocuore et. al.: JHEP 05 (2019) 028

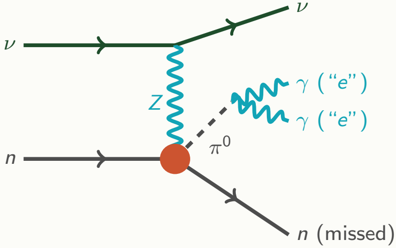
Large Splitting Region

Some space accessible at large splitting via up-scatter



Small Splitting Background

Backgrounds from neutrino beam and cosmic rays



$\chi_2 \to \chi_1 \, e^+ \, e^-$ background

Missed neutron

and

Mismatched timing

and

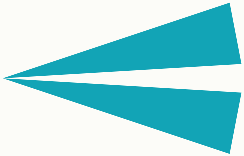
Misreconstructed photons

and

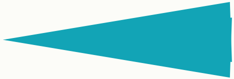
“Correct” angle/mass

More on e^+e^- Background

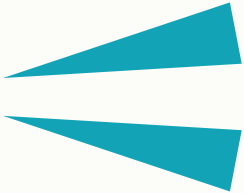
Signal:



Single γ Bkg:

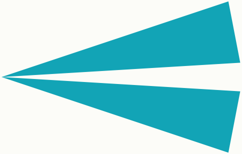


Two γ or $e + \gamma$ Bkg:



More on e^+e^- Background

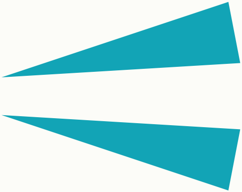
Signal:



Single γ Bkg:

Run photons through `Geant4`

Two γ or $e + \gamma$ Bkg:

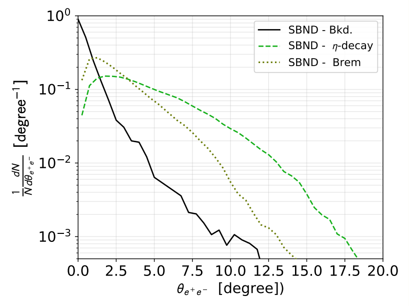


Background Reduction

Background γ give $e^+ + e^-$ with small opening angle

Arbitrarily small angle not reconstructable anyway

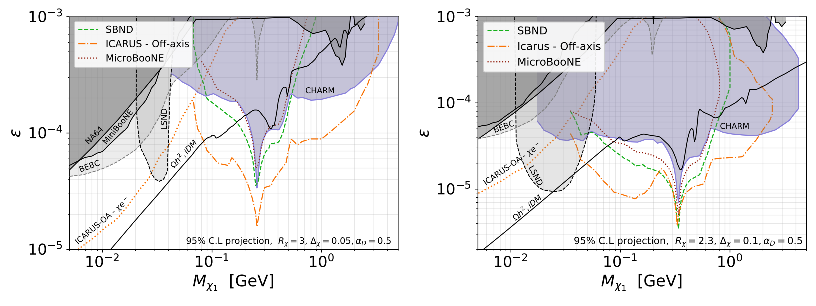
- Place angular cut of 5°



Small Splitting Region

Significant improvements from ICARUS and SBND!

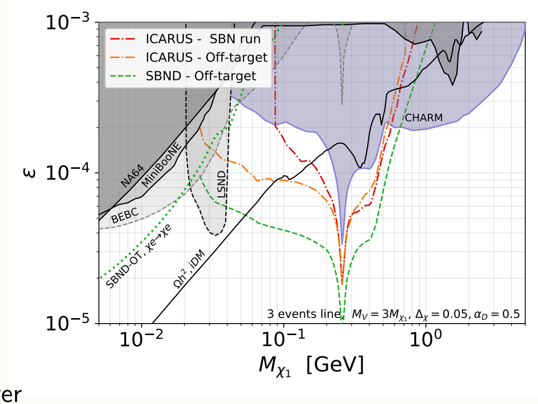
Includes some parts of thermal relic parameter space



Possible "Off-Target" Run

MiniBooNE steered BNB off target and into absorber

Can reduce distance DM needs to travel *and* bkg



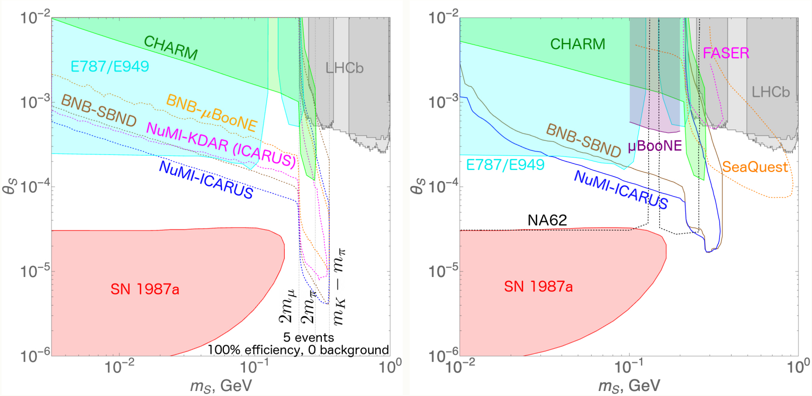
Model #2: Higgs Portal Scalar

- Dark scalar S mixes with the Higgs boson
- Inherits interaction pattern
- Only 2 relevant parameters: m_S and θ_S

High intensity for small mixing

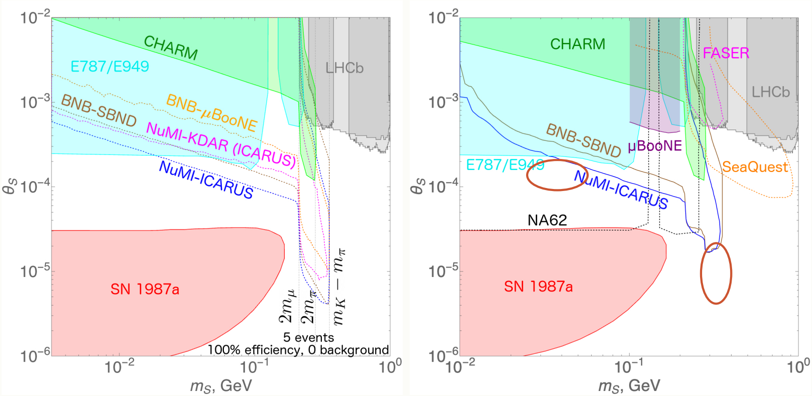
Cosmology & Astrophysics for extremely small mixing

How to Fill in the Gaps



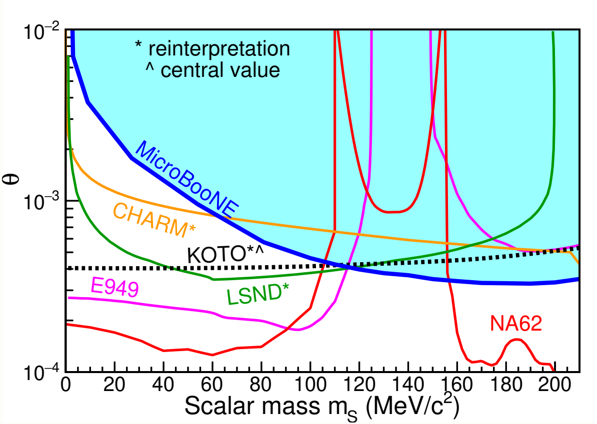
Batell, Berger, Ismail: PRD 100 (2019) 11, 115039

How to Fill in the Gaps



Batell, Berger, Ismail: PRD 100 (2019) 11, 115039

This Search is Happening!

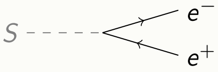


MicroBooNE: PRL 127, 151803 (2021)

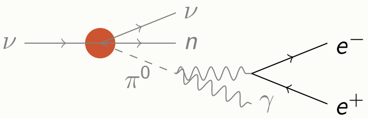
Backgrounds

Focus on $e^+ + e^-$ channel

Signal: e^+e^-



Background: e^+e^-



Small m_S: Small opening e^+e^-

Looks like converted γ

Can we harness machine learning techniques?

Simulation Strategies

- Output of GENIE or dark sector event generation:
  List of four-vectors
  - Fast, not detailed (even w/ smearing, . . .)
- Full detector simulation & reconstruction:
  Highly detailed output in $> 10,000$ wires
  - Slow, but fully detailed

Is there something we can do that is fast, but fairly detailed?

Simplified Simulation

1. Generate 4-vectors from GENIE or signal event generation

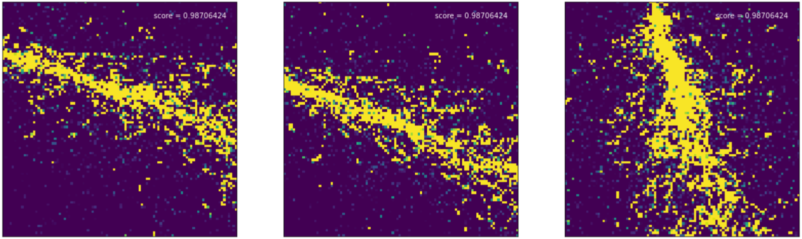
   N.B. GENIE simulates until edge of nuclear remnant
2. Inject each 4-vector in Geant4 box of ^{40}Ar
3. Parameterize detectable charge for each step deposit in Ar

$$Q_{\text{dep}} \approx E_{\text{dep}}/W_{\text{ion}}, \quad Q_{\text{det}} \approx Q_{\text{dep}} \frac{A}{1 + k\,(dE/dx)/|\boldsymbol{E}_{\text{drift}}|}$$

4. Map each x, y, z into wires and sample times

Birks, Proc. Phys. Soc. A 64 874 (1951)
Amerio et. al.: Nucl. Instrum. Meth. A 527 329 (2004)

Sample Event



Cut-Based vs. Machine Learning

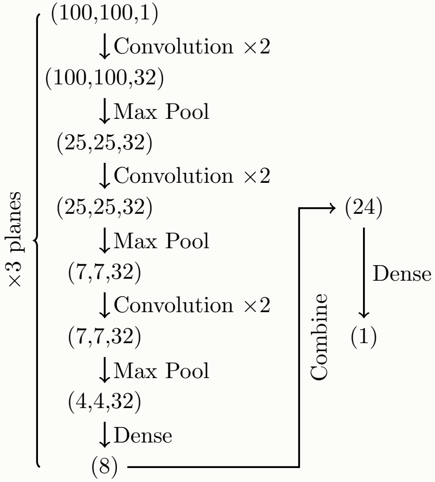
Cut-Based	Convolutional Neural Network
Use generator-level four-vectors	Use fast simulation
Decay mesons using Pythia	Decay mesons in Geant4
Convert photons using Geant4	Propagate all particles in Geant4
Apply parameterized thresholds*	Let network decide thresholds
Reject events w/o correct topology	Let network decide topology
Optimize cut on e^+e^- opening angle	Train network to optimize performance

Assume 20% systematic background normalization uncertainty

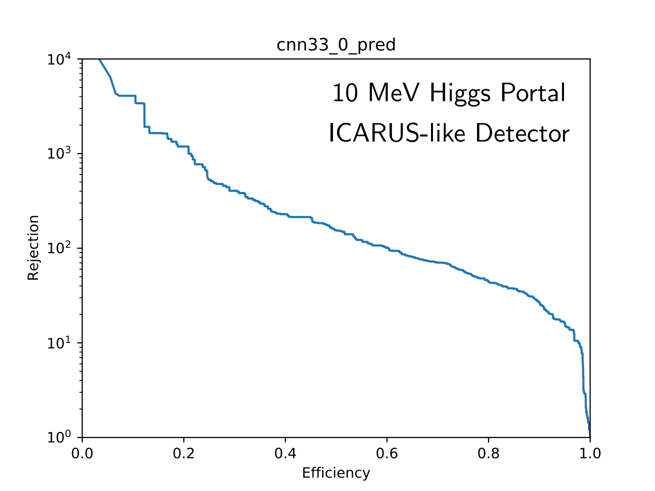
*Based on DUNE CDR 1512.06148

Best CNN

- Focus on 100 × 100 ROI
- Extract non-local info: series of convolutions and pooling for each of 3 images
- Combine & condense into 1 number to tell S from B



Background Rejection vs. Signal Acceptance



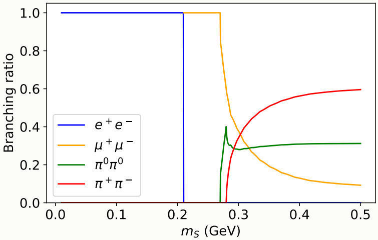
Comparison of Optimal Sensitivity

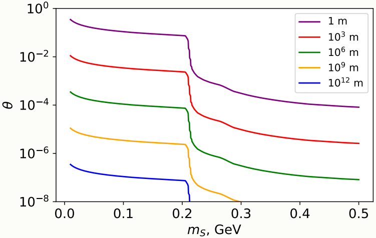
Analysis	Limit on $\sin\theta$
Cut-based	8.1×10^{-4}
CNN	7×10^{-4}

- Modest improvement for $\sin\theta$
- Event rate $\propto \sin^4\theta$
- Significant improvement in rate

Backup

Properties of the Scalar



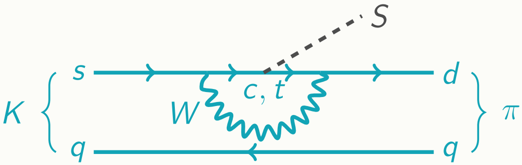


Decays to distinctive pairs of SM particles

Can travel hundreds of meters before decaying

Dark Higgs Production

Mostly K production with penguin decay



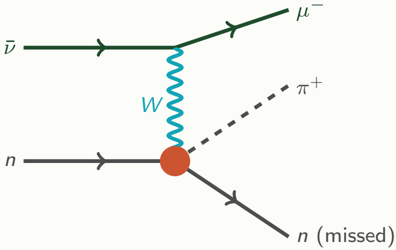
	$\mathrm{Br}(K \to \pi S)$
$K^\pm$	$2.0 \cdot 10^{-3} \, \frac{2\,p_S}{m_K} \, \theta_S^2$
K_L	$7.0 \cdot 10^{-3} \, \frac{2\,p_S}{m_K} \, \theta_S^2$
K_S	$2.2 \cdot 10^{-6} \, \frac{2\,p_S}{m_K} \, \theta_S^2$

At small mixing: very rare

K_S decay is CP violating

New Potential Background: $\mu^+\mu^-$

Backgrounds from neutrino beam and cosmic rays



$S \to \mu^+\mu^-$ background

Missed neutron

and

Mismatched timing

and

Misreconstructed pion

and

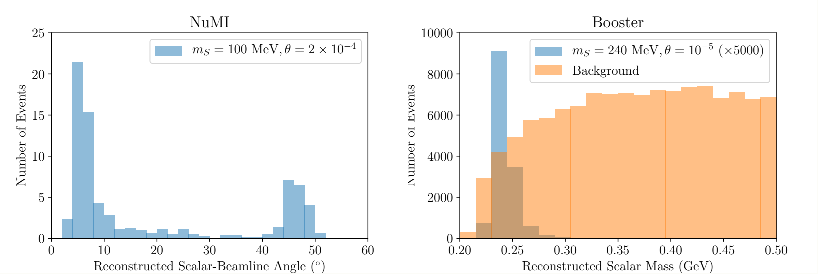
"Correct" angle/mass

Cuts & Background Reduction

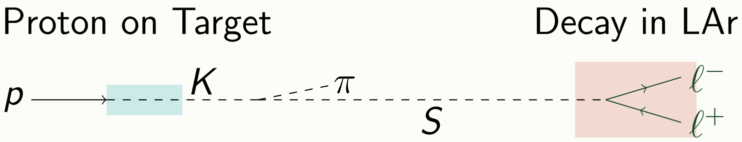
e^+e^-: 10° e isolation required for reconstruction

$\mu^+\mu^-$: Reconstructed invariant mass; $E_S > 2.5$ GeV

Both: Reconstructed S angle wrt beamline



Basic Setup



Scalar S mixing with Higgs with angle θ_S

$\Gamma(K \to \pi\, S) \propto \theta_S^2$: If θ_S too large, S doesn't reach detector

$\Gamma(S \to \ell^+\, \ell^-) \propto \theta_S^2$: If θ_S too small, not enough S produced

More Careful Cut-based