Dark Sector Signals at Neutrino Experiments

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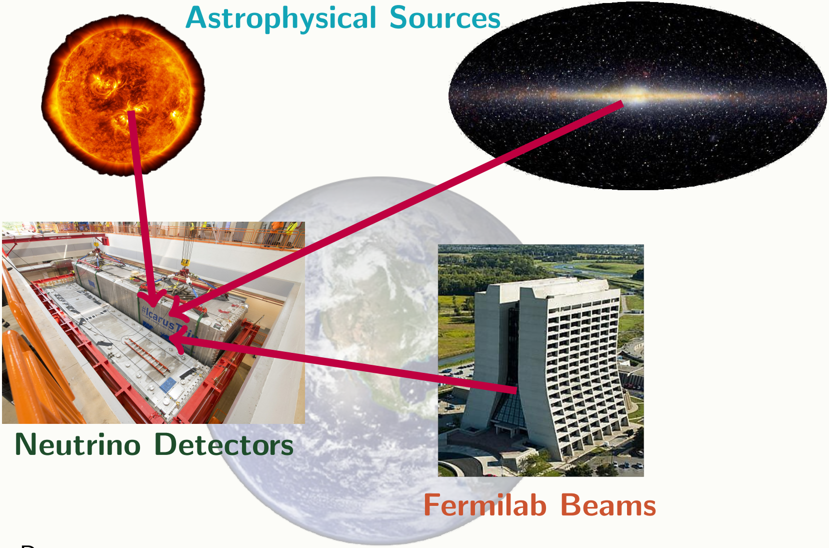
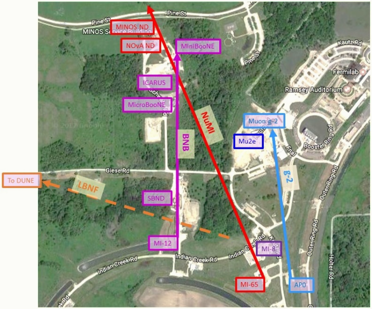
CETUP* 2023

How Do We Get Dark Stuff?



Why Neutrino Experiments?

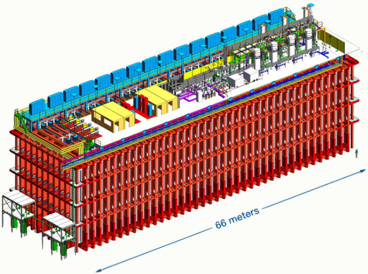
Short Baseline:



✓ Intense Proton Beam!

$\Longrightarrow$ Produce rare events

Long Baseline:



✓ 100s kton-year exposure!

$\Longrightarrow$ Largest DD experiments

Inelastic DM at Short Baseline

Batell, **JB**, Darmé, Frugiuele: PRD104 (2021) 7, 075026

Short Baseline Opportunities

- Long-lived Portal Particles
  - Higgs portal: $S \leftrightarrow h$
    Batell, **JB**, Ismail: PRD100, 115039 (2019)
    MicroBooNE: PRL127, 151803 (2021)
  - Heavy neutral leptons: $N \leftrightarrow \nu$
    Ballett, Pascoli, Ross-Lonergan: JHEP 04 (2017) 102
    MicroBooNE: PRD106, 092006 (2022)
  - Heavy axions: $a \leftrightarrow \pi^0, \eta$
    Aloni, Soreq, Williams: PRL123, 031803 (2019)
    ArgoNeuT: arXiv:2207.08448
  - Dark Photons: $V \leftrightarrow \gamma$
    Berryman et. al.: JHEP 02 (2020) 174
- Light dark matter
  deNiverville, Chen, Pospelov, Ritz: PRD95, 035006 (2017)
- Inelastic dark matter
  Batell, **JB**, Darmé, Frugiuele: PRD104 (2021) 7, 075026
- Millicharged particles
  Magill, Plestid, Pospelov, Tsai: PRL122, 071801 (2019)

The SBN Experiments

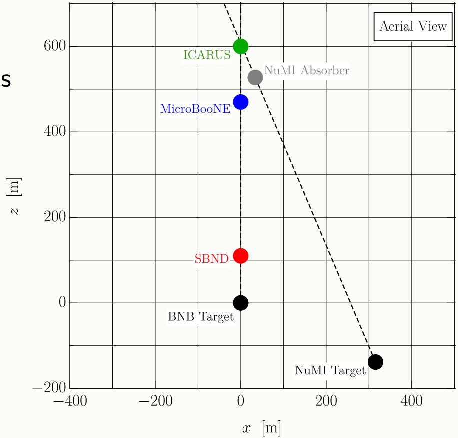
3 Liquid Argon TPC detectors:

- Can reconstruct full 3D events

Two beamlines:

- BNB: 8 GeV, on-axis
- NuMI: 120 GeV, off-axis
- Possible run using BNB absorber (not illustrated)?

Data-taking ongoing now

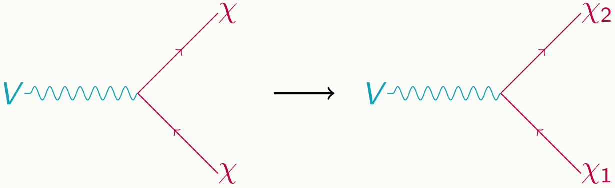


Batell, **JB**, Ismail: PRD 100 (2019) 11, 115039

Example: Inelastic Dark Matter

$\propto \epsilon$

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



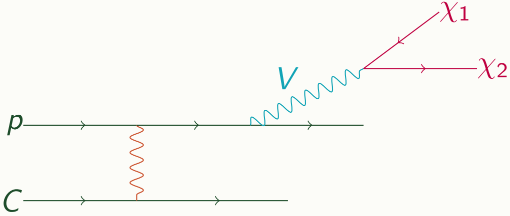
$= i\, g_D\, \gamma^\mu$

- Also splits charged fermions into separate Majorana states

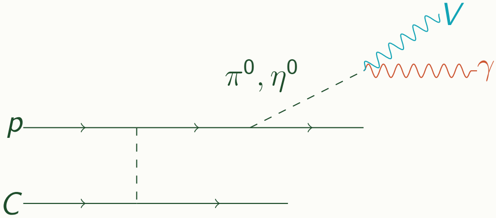
Overview of Signals: Production

- Both direct and decay production mechanisms for V

Dark bremsstrahlung:

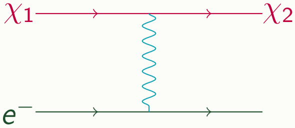


Meson Decay:

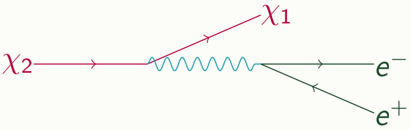


Overview of Signals: Detection

- 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

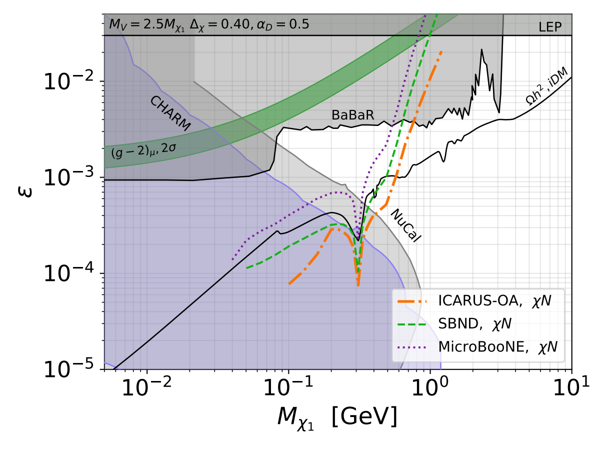
Signal production using modified version of `BdNMC`

- 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

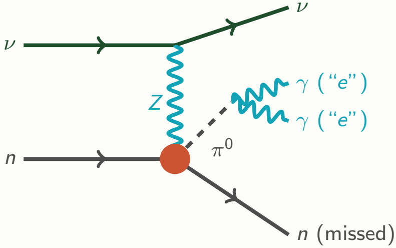
Large Splitting Region

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

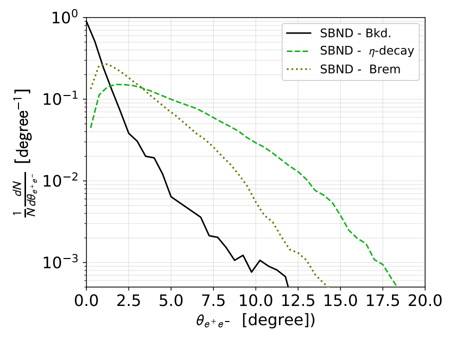
“Correct” angle/mass

Background Reduction

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

Arbitrarily small angle not reconstructable anyway

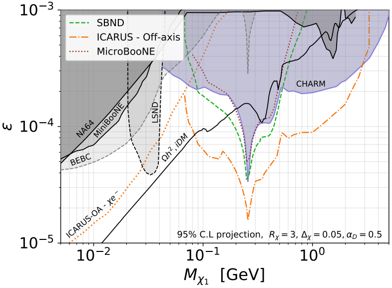
- Place angular cut of 5°

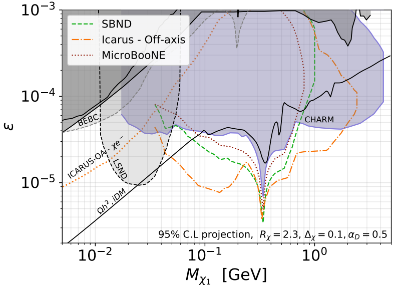


Small Splitting Region

Significant improvements from ICARUS and SBND!

Includes some parts of thermal relic parameter space

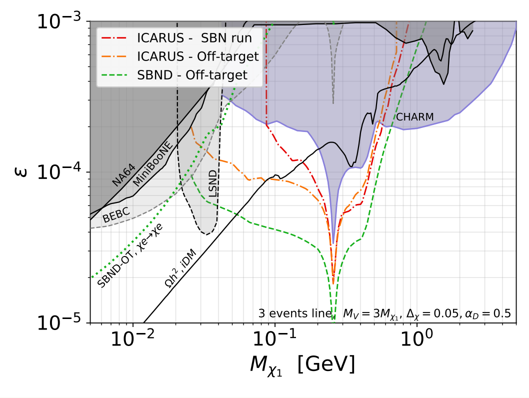




Possible "Off-Target" Run

MiniBooNE steered BNB off target and into absorber

Can reduce distance DM needs to travel *and* bkg



Mesogenesis DM at Long Baseline

JB, Elor: 2301.04165

Matter Anti-Matter Asymmetry

There's more matter than anti-matter:

$$\frac{n_{\mathcal{B}} - n_{\overline{\mathcal{B}}}}{s} \sim 8 \times 10^{-11}$$

How? Sakharov says:

1. *C* and *CP* violation:
   B-meson oscillation
2. Baryon-number violation:
   Store anti-baryon number in dark sector state
3. Out-of-equilibrium:
   Late decay of a heavy scalar

Elor, Escudero, Nelson: PRD 99, 035031 (2019)

Model Structure

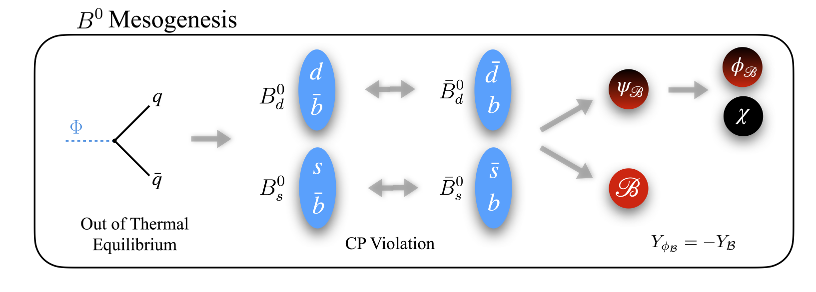
Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{\mathcal{B}}$	Z_2
Y	3	1	$-1/3$	$2/3$	1
ψ_B	1	1	0	-1	1
ϕ_B	1	1	0	-1	-1
ξ	1	1	0	0	-1

Two DM particles (ϕ_B, ξ)

Integrate out TeV-scale Y to get EFT:

$$\mathcal{L} = \frac{y_{u_a d_b}\, y_{\psi d_c}}{M_Y^2} \epsilon_{ijk} \left(u^i_{R,a} d^j_{R,b} \right) \left(\psi_B d^k_{R,c} \right) - y_d \bar{\psi}_{\mathcal{B}} \phi_{\mathcal{B}} \xi + \text{h.c.}$$

B^0 Mesogenesis Mechanism



Elor, Escudero, Nelson: PRD 99, 035031 (2019)

Asymmetry tied to observables:

- Need sufficient B CP violation
- Need sufficient branching to $\psi_{\mathcal{B}}$

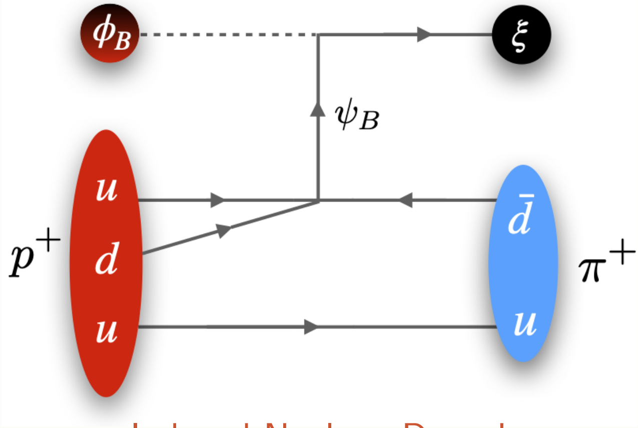
Other Observables

Asymmetry given by:

$$Y_{\mathcal{B}} = \frac{n_{\mathcal{B}} - n_{\overline{\mathcal{B}}}}{s} = 8.7 \times 10^{-11} \, \frac{\mathrm{Br}(B \to \psi_{\mathcal{B}} \, \mathcal{B}_{\mathrm{SM}})}{10^{-2}} \sum_{q=s,d} \alpha_q \, \frac{A_{SL}^q}{10^{-4}}$$

- A_{SL}^q: CP asymmetry in $\overset{(-)}{B}_q \to \ell^{\mp} + X$
  Constrained by LHC, B factories
- Exotic B decays at B factories
- Indirect effects on B^0 oscillation/CP violation
  e.g. $\phi_{1,2}^{d,s}$, $\Delta M_{d,s}$, $\Delta\Gamma_{d,s}$
- Direct production of Y @ LHC

Can We Detect Dark Matter?



Induced Nucleon Decay!

See also: Huang, Zhao: JHEP 02(2014)077

Modeling IND

- Amplitude written in terms of $N \to \pi, K$ form factors

$$\mathcal{A} \propto W_0(q^2) - i\,\frac{\not{q}}{m_N}\,W_1(q^2)$$

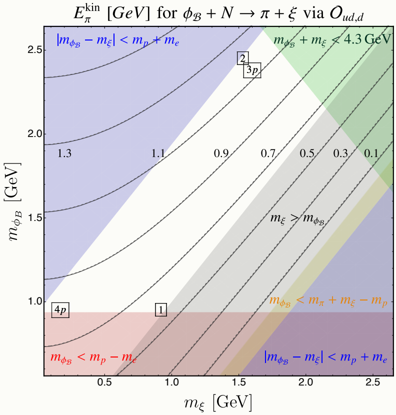
- Calculated on the lattice at $q^2 = 0$, 1 GeV^2

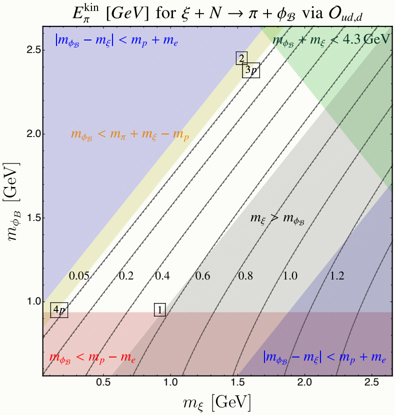
Yoo et. al.: PRD105, 074501 (2022)

- 3 choices of *udd* operator

$$(u_R\, d_R)\, d_R, \quad (u_R\, d_R)\, s_R, \quad (u_R\, s_R)\, d_R$$

Parameter Space: π Channel

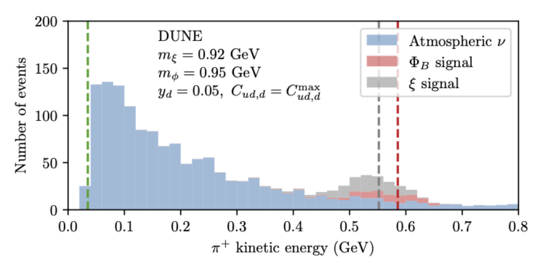


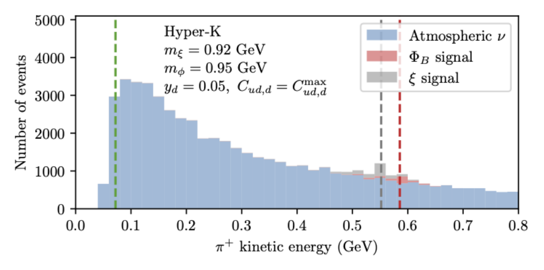


Can We Simulate?

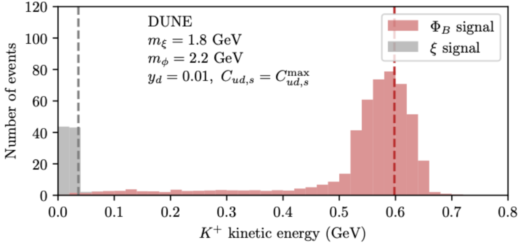
- Hacked together simulation in `GENIE` v3.06
  Based on existing nucleon decay module
- Event generation of model points by request
  `https://github.com/jberger7/Generator-IND`
- Why `GENIE`?
  - Standard tool in ν experiment
  - Includes important nuclear effects
  - Get full kinetic energy distributions!
- Allowed meson FS: π, K, D^0

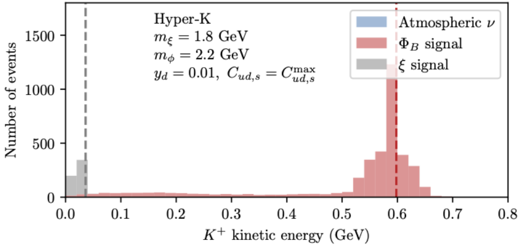
Kinematic Distributions: π Channel





Kinematic Distributions: K Channel





Event Counts

Benchmark and Meson	Bkg. DUNE	$y_d(C_{ud,d}/C_{ud,d}^{\max})$ DUNE sens.	Bkg. Hyper-K	$y_d(C_{ud,d}/C_{ud,d}^{\max})$ Hyper-K sens.
1 π^+	118	0.019	9452	0.020
2 π^+	14	0.007	2323	0.0090
3p π^+	584	0.021	13835	0.015
4p π^+	600	0.040	15653	0.029
1 K^+	0	0.0016	0	0.00061
2 K^+	0	0.00038	0	0.00014
3k K^+	0	0.00063	0	0.00023
4k K^+	0	0.0010	0	0.00038

Min. solar model, 10 years running, $m_{\psi_{\mathcal{B}}} = 4$ GeV

Outlook

Current Status

	Production					Dark $\to$ Standard					
Process	Brem.	Direct	Prompt	LL	Flux	Decay	e	N El.	N Inel.	Det.	Reco.
`MadDump`		✓	✓		✓		✓		✓ (yellow)		
`BdNMC`	✓	✓	✓		✓	✓	✓	✓ (yellow)	✓ (yellow)		
`GENIE`							✓	✓	✓ (yellow)		
`Geant4`			✓ (yellow)	✓ (yellow)	✓ (yellow)	✓ (yellow)				✓ (yellow)	
`ACHILLES`						✓ (yellow)	✓	✓	✓ (yellow)		
`FORESEE`	✓	✓	✓	✓	✓	✓	✓	✓ (yellow)			

Batell, **JB**, et. al. (Snowmass): 2207.06898

Priority Challenges

- Need to simulate: beam production, propagation, detector interaction
- Complex detection topologies possible
- Experimental pipeline is `ROOT`-based
- Nuclear modeling uncertainty propagation
- Large full sim. event size
- No general reconstruction tools or parameterized efficiency/resolution for fast sim.

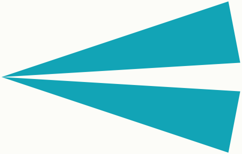
Some Take Aways

- Neutrino experiments (both near and far) are sensitive to a diverse set of dark sector models
- Event generation is challenging and is currently done by hand (or not at all)
- A comprehensive pipeline is needed if we want a broad-based program at some of the flagship particle experiments of the next decade

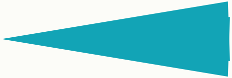
Backup

More on e^+e^- Background

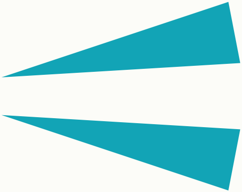
Signal:



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:

Fixed kinetic energy

- In nucleon rest frame: Fixed meson K.E.

$$E^{\mathcal{M},\,\mathrm{kin}}_{\phi_{\mathcal{B}} N \to \xi \mathcal{M}} = \frac{m_{\mathcal{M}}^2 - m_{\xi}^2 + (m_N + m_{\phi_B})^2}{2(m_N + m_{\phi_B})} - m_{\mathcal{M}}$$

- Smeared by nucleon motion:

$$p_{\mathcal{M}} \lesssim p_F \approx 240\ \mathrm{MeV} \quad \text{(Argon)}$$

- Hydrogen in water: no smearing!
- Ideally: simulate this process!

Other Searches

Exp't	E GeV	Beam	Targ.	POT	D (m)	L (m)
E141	9	e^-	W	2×10^{15}	35	32
ν-Cal	70	p	Fe	1.17×10^{17}	64	23
CHARM	400	p	Cu	2.4×10^{18}	480	35
E137	20	e^-	Al	1.9×10^{20}	179	204

- In addition: Supernova 1987A
  Emission of dark photons reduces power in neutrinos

PRL 59 (1987) 755, , PLB 713 (2012) 244-248, PLB 701 (2011) 155-159, PRD 38 (1988) 3375, PRL 113 (2014) 171802, PRD 98 (2018) 015031, PLB 731 (2014) 320-326, JHEP 01 (2017) 107

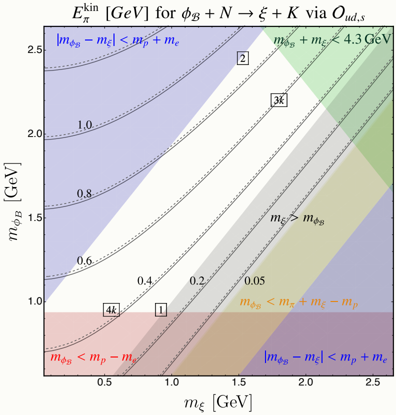
Parameter Space

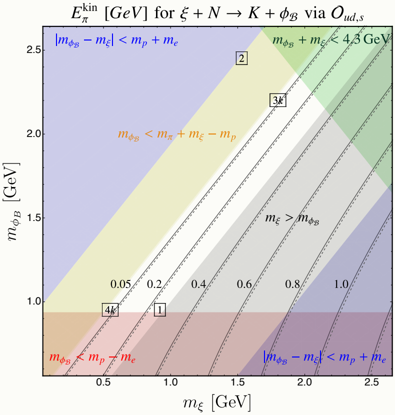
- ✓ $B \to \mathcal{B}_{\mathsf{SM}}\, \psi_{\mathcal{B}}$: $m_{\psi_{\mathcal{B}}} < m_B - m_p \simeq 4.34\,\mathrm{GeV}$
- ✓ $\psi_{\mathcal{B}} \to \xi + \phi_{\mathcal{B}}$: $m_{\psi_{\mathcal{B}}} > m_\xi + m_{\phi_{\mathcal{B}}}$
- × $\phi_{\mathcal{B}} + \xi \to \mathcal{B}_{\mathsf{SM}}$: $|m_{\phi_{\mathcal{B}}} - m_\xi| < m_p + m_e \simeq 938.8\ \mathrm{MeV}$
- × $\mathcal{B}_{\mathsf{SM}} \to \phi_{\mathcal{B}}, \xi$: $m_{\phi_{\mathcal{B}}}, m_\xi < m_p - m_e$
- ✓ $\phi_{\mathcal{B}} + \overline{\phi}_{\mathcal{B}} \to \xi + \xi$: $m_{\phi_{\mathcal{B}}} > m_\xi$

Benchmarks

Benchmark	$m_{\phi_{\mathcal{B}}}$ [GeV]	m_ξ [GeV]
1	0.95	0.92
2	2.45	1.53
3p	2.38	1.6
3k	2.2	1.8
4p	0.95	0.17
4k	0.95	0.55

Parameter Space: K Channel



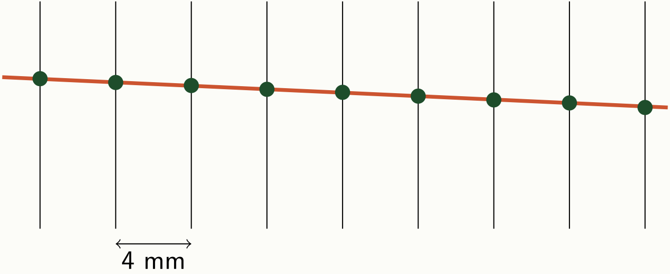


Backgrounds: Atmospheric ν

- Trickiest background: atmo ν NC with $\nu + N \to \nu + n + \pi$
- Also: CC, p FS with missed particles
- Bkg: events with only π above threshold
- K background extremely tiny
- Model ν scattering in `GENIE` using Bartol fluxes at Soudan (DUNE) and Kamioka (Super-K/Hyper-K)

Barr et. al.: PRD70:023006,2004

DUNE Thresholds



- Charged particles: cross 10 wires
- Unstable particles: energetic decay products

Water Cherenkov Thresholds

- Charged & heavy: require $\beta > 1/n$ for Cherenkov radiation
- e & γ: 3.5 MeV

  Super-Kamiokande: PRD94, 052010 (2016)
- Unstable particles: energetic decay products
- $\mu^{\pm}$ vs. $\pi^{\pm}$: challenging to distinguish
  For Cherenkov: assume no distinction

A bit crude... but need experimental input for more!