Searching for New Physics at Neutrino Experiments

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Dark Interactions

New Perspectives from Theory and Experiment

16th November 2022

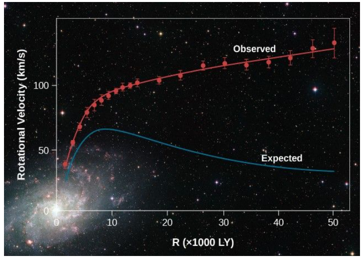
Fermilab U.S. DEPARTMENT OF ENERGY | Office of Science

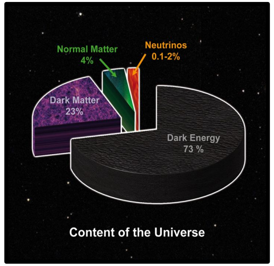
Evidence for New Physics

We know that there is **new physics** (see all previous talks)

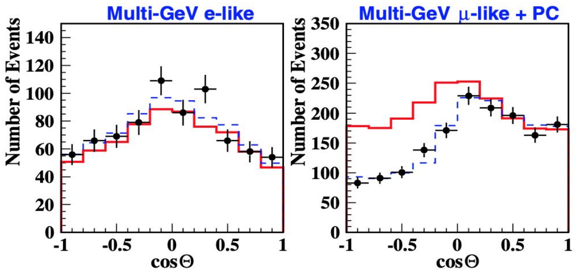
evidence includes e.g.

Dark Matter

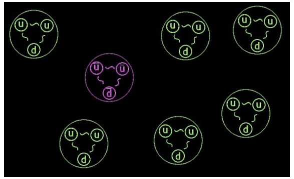




Neutrino Masses



Baryon asymmetry?



$$\eta_B = (n_B - n_{\bar{B}})/n_\gamma \simeq (6.09 \pm 0.06) \times 10^{-10}$$

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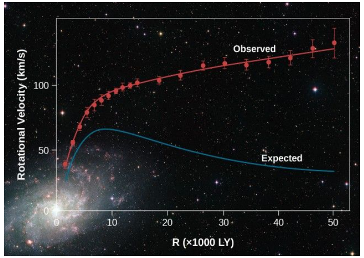

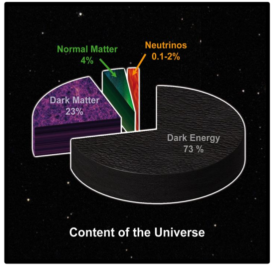

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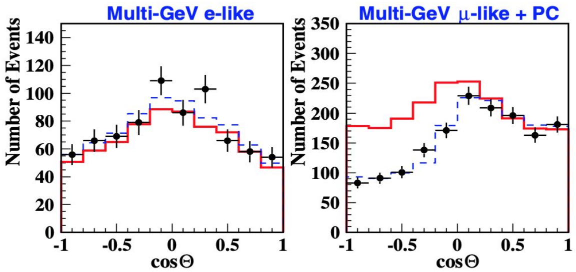

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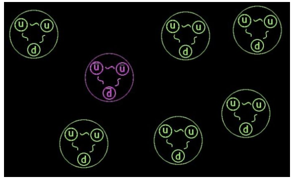
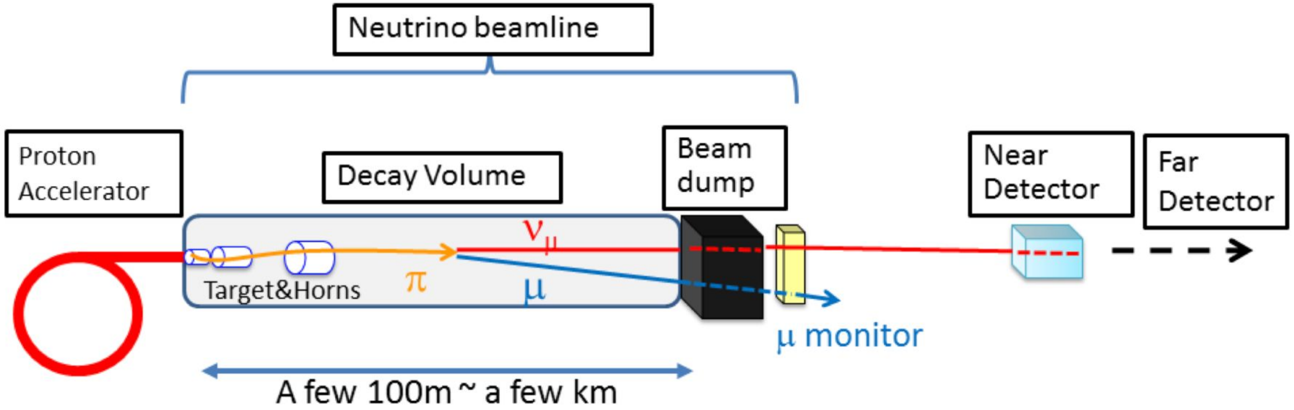


$$\eta_B = (n_B - n_{\bar{B}})/n_\gamma \simeq (6.09 \pm 0.06) \times 10^{-10}$$

How can neutrino experiments help us in finding the new physics?

Searching for New Physics

Typical setup for a pion decay-in-flight accelerator neutrino experiment



Searching for New Physics

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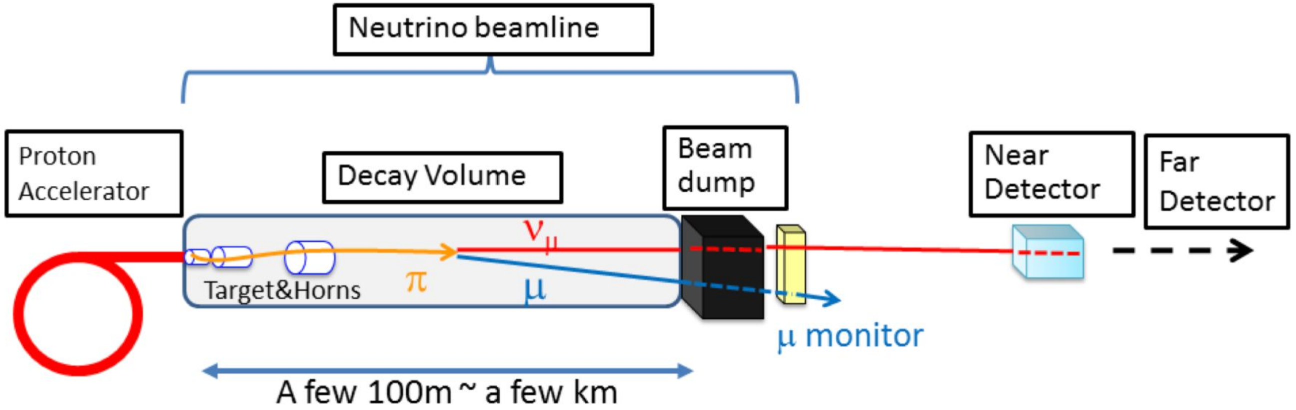
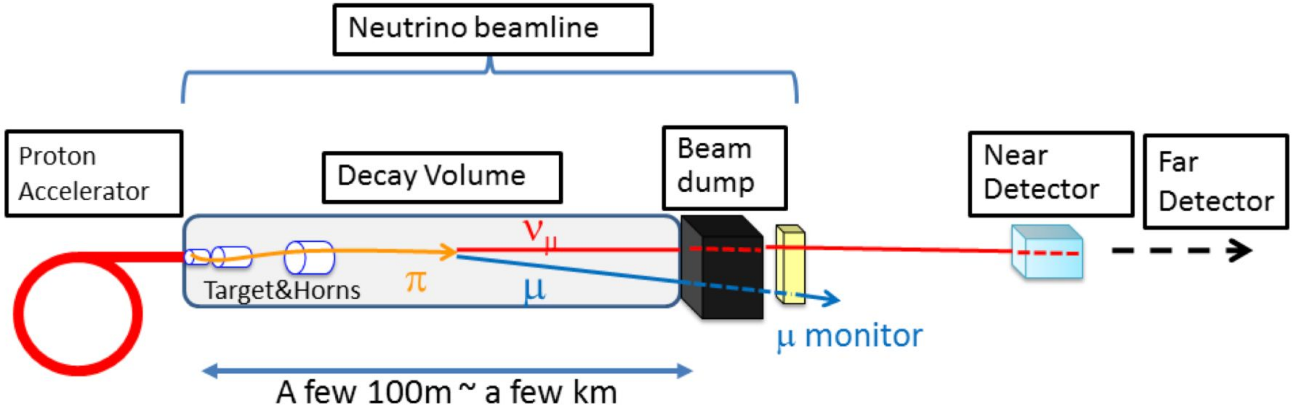


Possible search strategies

1. **Direct production of new particles and mediators**

Searching for New Physics

Typical setup for a pion decay-in-flight accelerator neutrino experiment

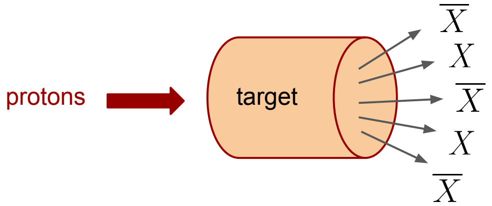


Possible search strategies

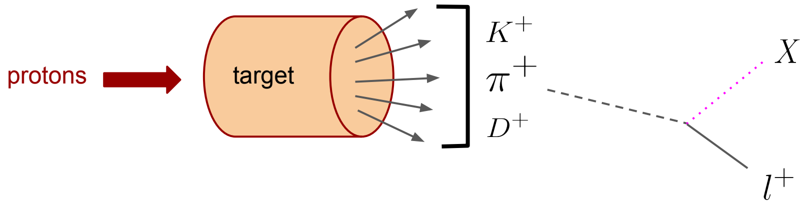
1. **Direct production of new particles and mediators**
2. **Indirect effects on e.g. neutrino oscillation**

Searching for NP: Direct production

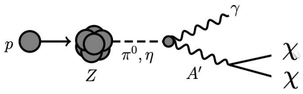
1. **Drell-Yan/Bremmstrahlung in the proton target**

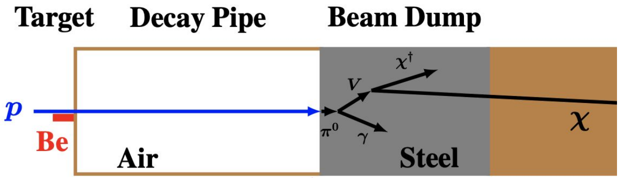


2. **Meson decay-in-flight**

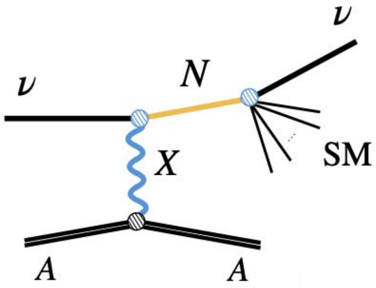


3. **Beam dump mode**





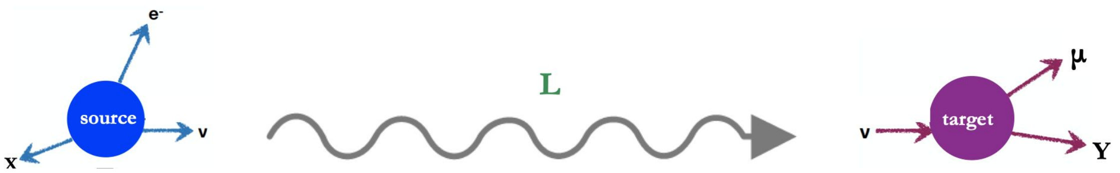
4. **In-detector neutrino scattering**

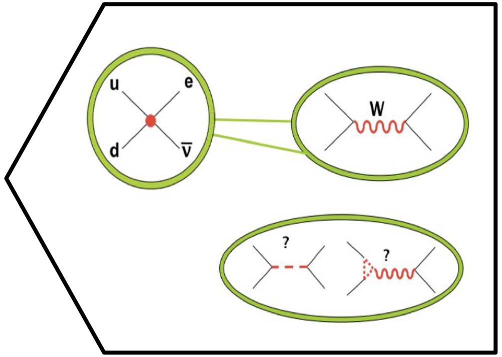


Searching for NP: Indirect effects

Examples of indirect NP include e.g. NSIs, EFTs **(see arXiv: 1901.04553, 1910.02971)**

Heavy new physics can modify **neutrino production**, **propagation** and **detection** leading to modified oscillation probabilities





by Martín González-Alonso

Modifications can be computed in the presence of **EFT** and measurements of low-energy observables translated into constraints on higher-dimension SMEFT operators

Why Neutrino Experiments?

1. High POT (~1e21) → **large flux of charged and neutral mesons**

2. Large detector masses ~ O(1e2) tonnes

3. Good PID (p, μ, e, γ reconstructed)

4. Good calorimetry

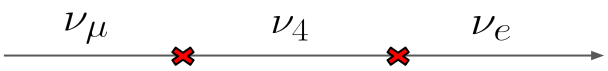
5. High cosmic rejection

6. Parasitic: cost shared with neutrino projects

See talk by Richard Van de Water, U.S. Cosmic Visions 2017
“Future possibilities at Proton fixed target experiments”

New Physics Searches at *Current* and *Future* Neutrino Experiments

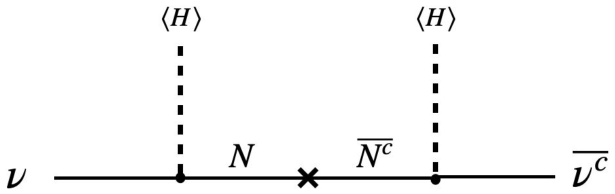
Neutrino Oscillations: Steriles



Among the simplest extensions of the SM that predict neutrino masses

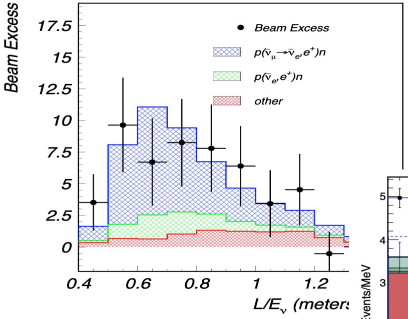
Type-I seesaw: $\mathcal{L}_{\nu-\text{mass}} \supset -Y_{\alpha i}\overline{L_\alpha}\widetilde{H}N_j - \frac{M_{ij}}{2}\overline{N_i^c}N_j + \text{h.c.}$

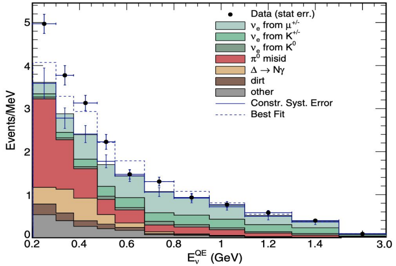
$$M_\nu \simeq -\frac{v^2}{2}Y^T M^{-1} Y$$



neutrino portal to a neutral hidden sector

Observation of what appears to be SBL oscillation has motivated the existence of a ~ eV scale sterile neutrino





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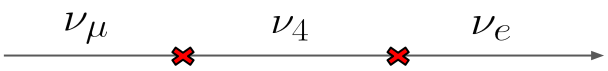
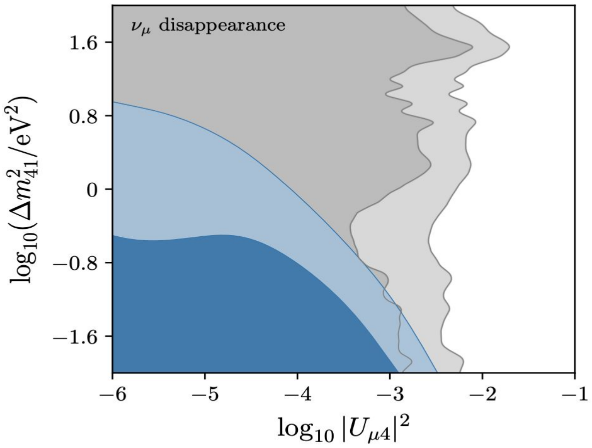


The 3+1 sterile solution to SBL anomalies is now disfavoured

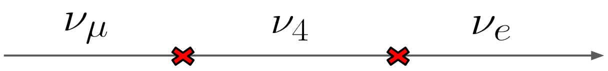
S. Hagstotz et al, arXiv:2003.02289



Light sterile neutrino is relativistic at early times and contributes to Neff

strong constraints from CMB+LSS

Neutrino Oscillations: Steriles



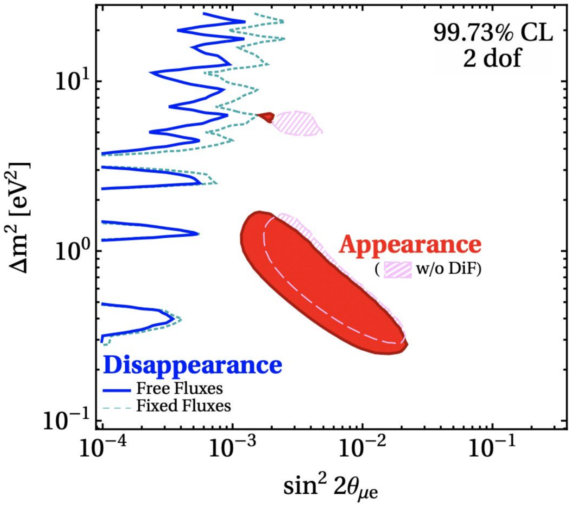
The 3+1 sterile solution to SBL anomalies is now disfavoured

Furthermore, strong tensions between appearance and disappearance data

$$P_{\mu\mu}^{\rm SBL} = 1-4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P_{\mu e}^{\rm SBL} = 4|U_{\mu 4}|^2|U_{e4}|^2\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

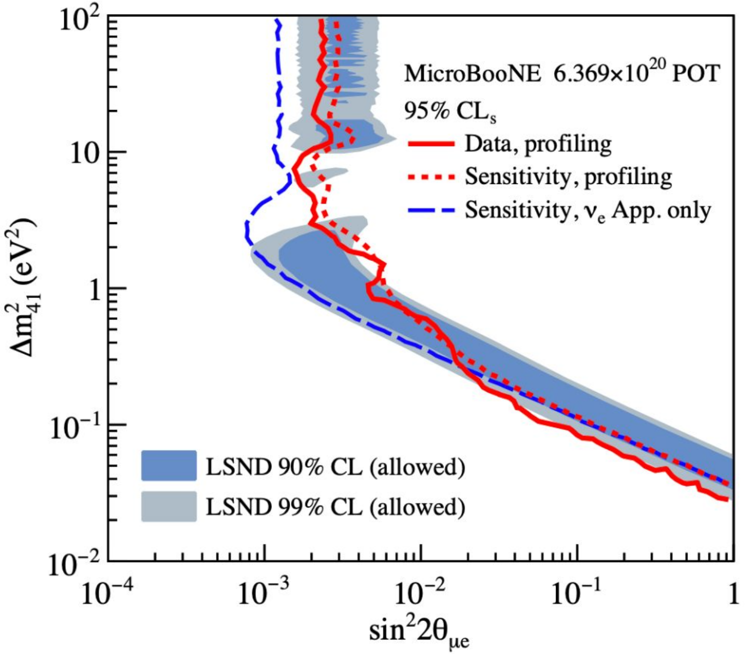
M. Dentler et al, JHEP 08 (2018) 010

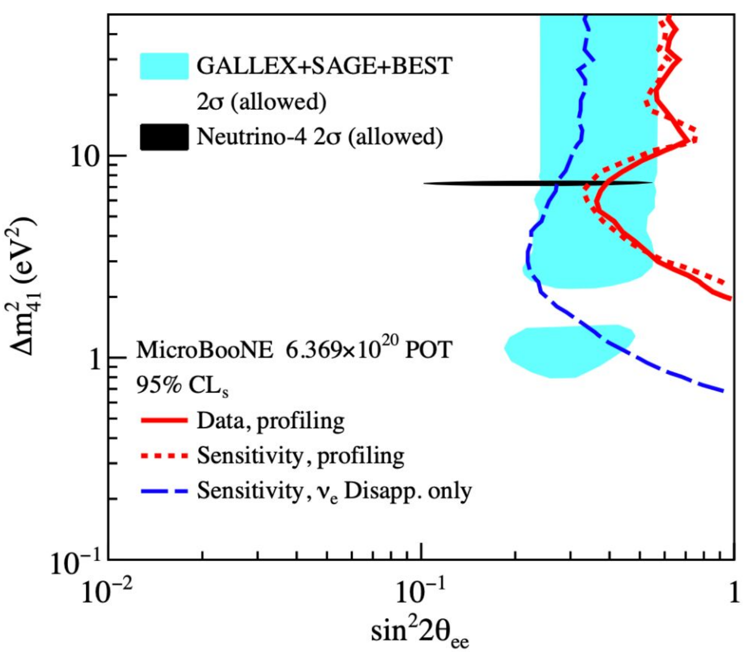


Neutrino Oscillations: Steriles

Most recent sterile search comes from MicroBooNE which does not exclude the full LSND (and MiniBooNE) preferred regions

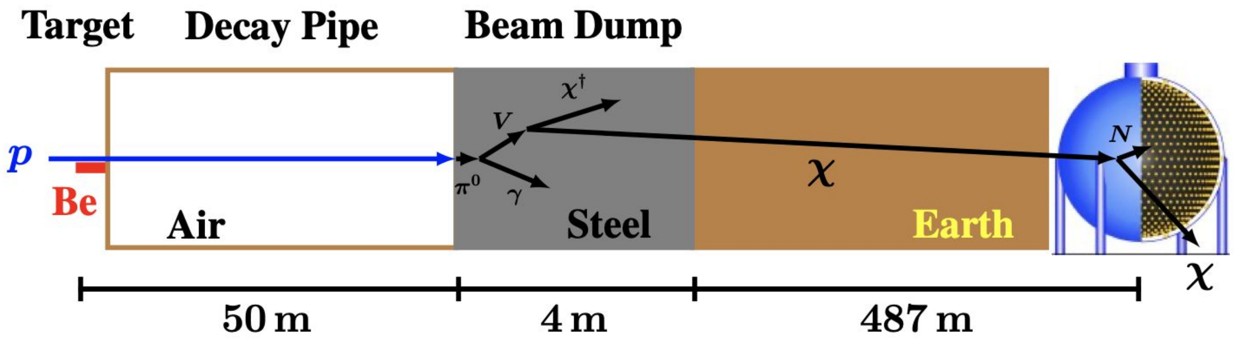
P. Abratenko et al, arXiv:2210.10216



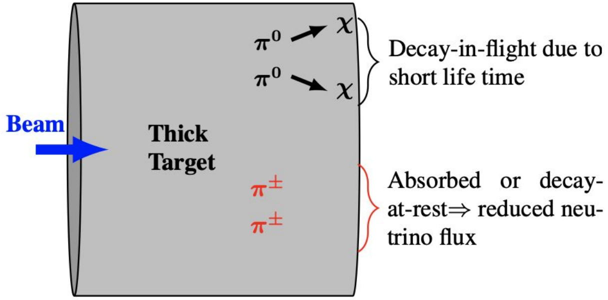


Beam Dump Mode

BSM searches at neutrino experiments suffer large neutrino bkgs and the NP can be hard to detangle



If protons impinge directly on the beam dump target, charged pions are absorbed or decay at rest → neutrino flux suppressed!



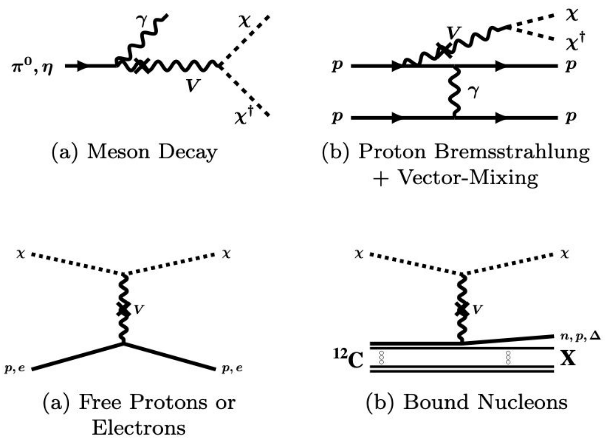
MiniBooNE-DM collab. arXiv: 1807.06137

Beam Dump: Light Dark Matter

MiniBooNE was the first accelerator neutrino experiment to perform a dark matter search in beam dump mode

Vector portal LDM

$$\mathcal{L}_V = \mathcal{L}_\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\epsilon}{2}F_{\mu\nu}V^{\mu\nu}$$



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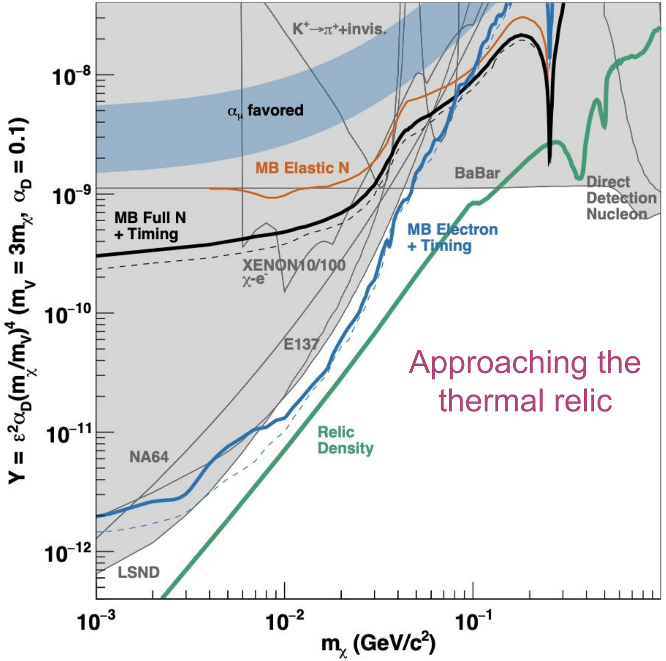


Approaching the thermal relic

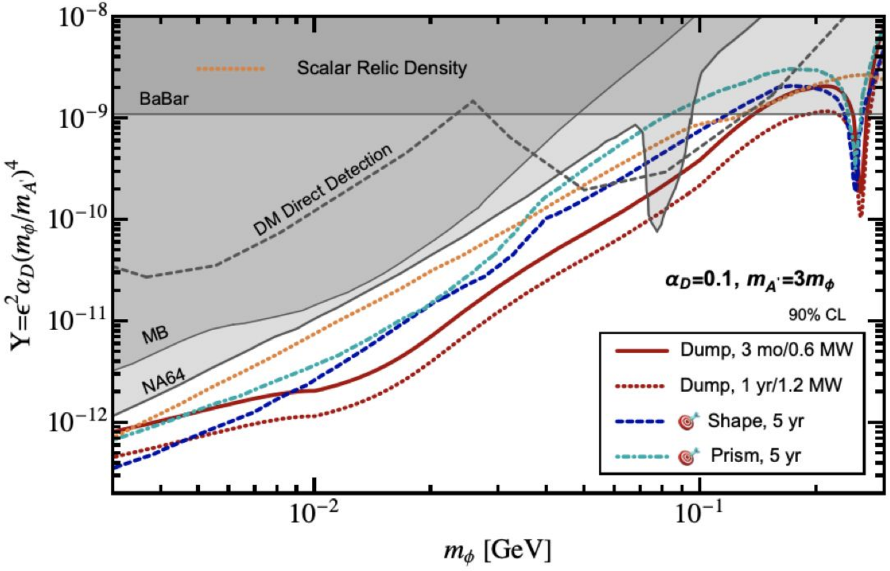
LDM at a "target-less" DUNE

Recently been proposed that running in beam dump mode at DUNE for < 3 months at half the expected initial beam intensity could give competitive limits on LDM!

Light scalar dark matter coupled to a dark photon

$$\mathscr{L}_{\rm DM} \supset -\frac{1}{2}\epsilon F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu + |D_\mu \phi|^2 - m_\phi^2|\phi|^2$$

see Brdar et al, arXiv: 2206.06380
BSM Targets at a "Target-less DUNE"

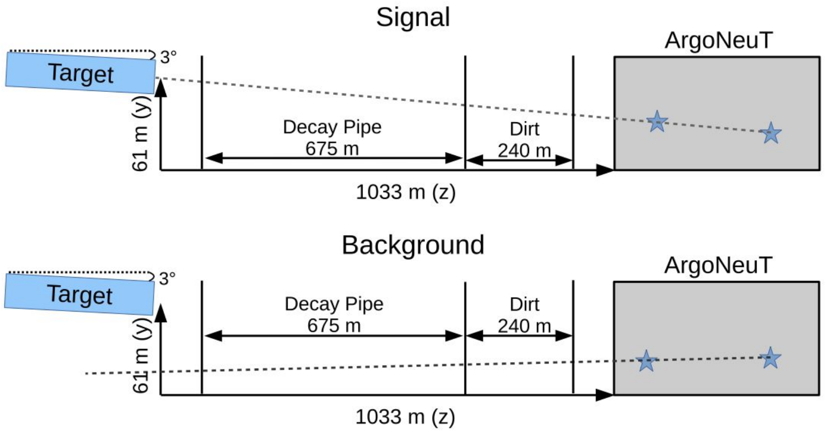


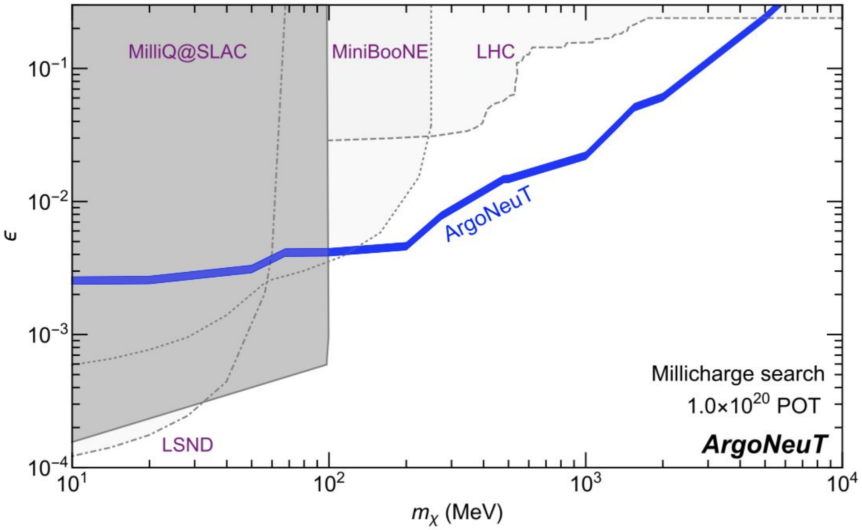
BSM searches at ArgoNeuT

Search for Millicharged particles (MCP)

Flux of MCPs from neutral meson decays or Drell-Yan at target scatter off electrons

Signal: two soft energy depositions aligned with target direction





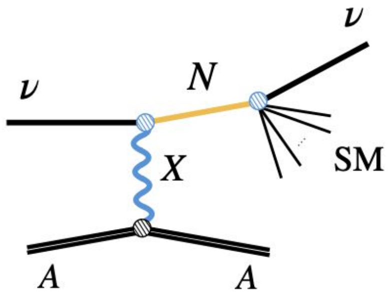
PHYSICAL REVIEW LETTERS 124, 131801 (2020)

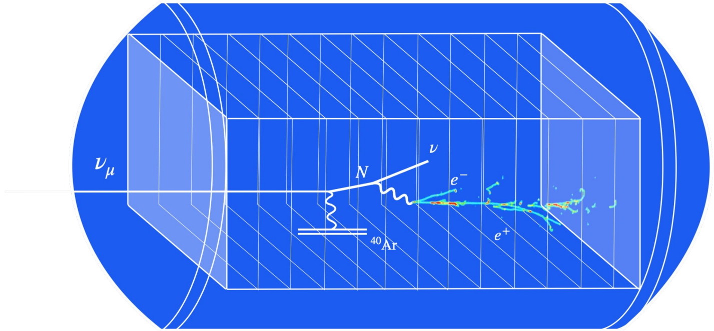
New Particles in Neutrino Scattering

New particles and mediators may be produced in the scattering of neutrinos on the detector material

Distinguishing these processes from SM interactions requires excellent PID and reconstruction → **LArTPC detectors**

e.g. ArgoNeuT, MicroBooNE (running)
+ ICARUS, SBND, DUNE (upcoming)





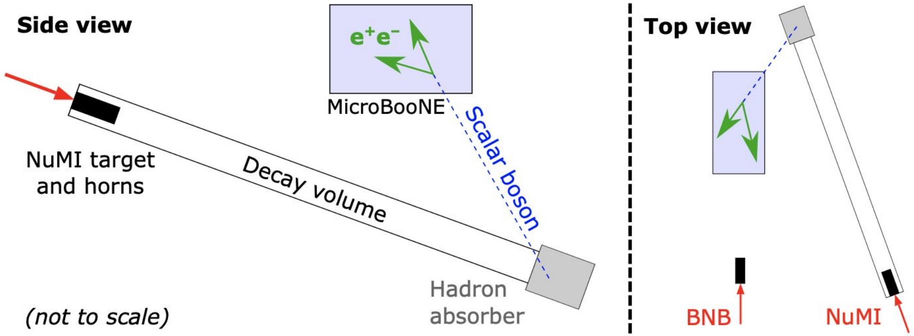
Schematic of MicroBooNE TPC and cryotank

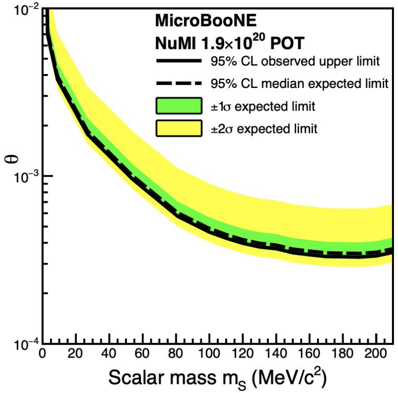
1. Improved hadronic vertex ID
2. Better spatial resolution
3. Improved calorimetry

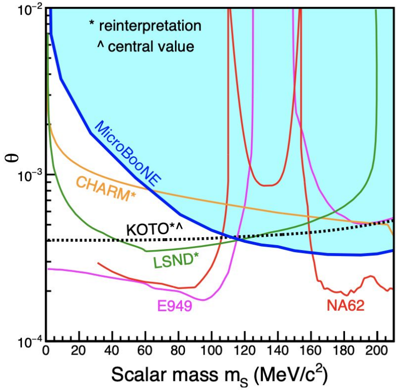
BSM searches at MicroBooNE

Higgs portal scalar decaying to e^+e^- pair (first search for an e^+e^- final state)

Scalars produced in KDAR at the NuMI* hadron absorber travel to MicroBooNE detector and produce e^+e^- pairs







Leading constraint between 130 - 160 MeV

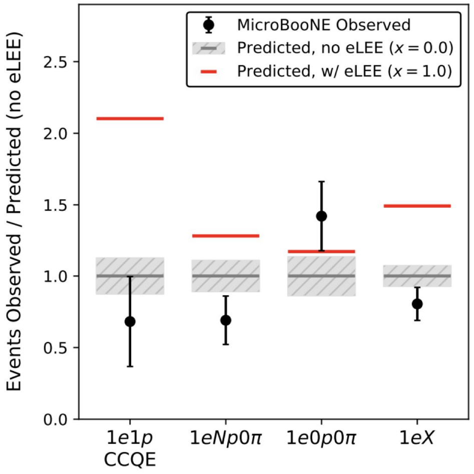
*MicroBooNE is located 8 deg. off-axis with respect to the NuMI target

MicroBooNE LEE search

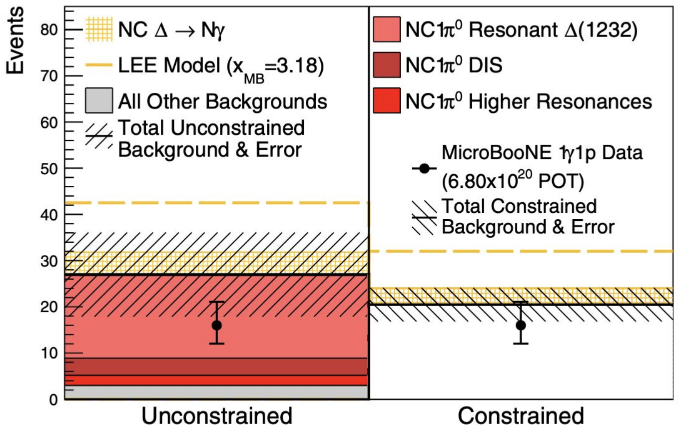
Among MicroBooNE's main physics goals is to determine the origin of the MiniBooNE LEE

Searches for an eLEE and gLEE have already been performed

Search for excess e^- (PRL 128, 241801 2022)



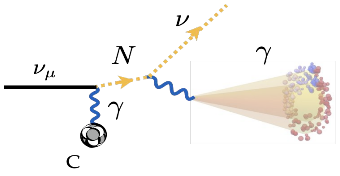
Search for SM NC $\Delta \rightarrow N\gamma$ (PRL 128, 111801 2022)



No electron or single photon excess observed compatible with MiniBooNE!

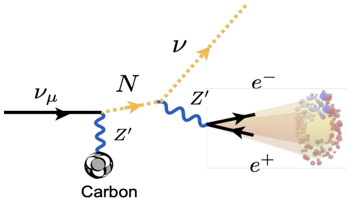
MicroBooNE LEE search

A number of new physics models which predict EM final states (e^-, γ, e^+e^-) have been proposed as alternatives to a SM LEE, e.g.



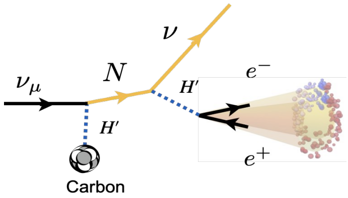
transition magnetic moment

$$F^{\mu\nu}\left(\frac{\mu_\nu^{\alpha j}}{2}\overline{\nu_\alpha}\sigma_{\mu\nu}N_j + \frac{\mu_\nu^{ij}}{2}\overline{N_i}\sigma_{\mu\nu}N_j\right)$$



dark photon

$$Z'_\mu\left(V^{\alpha j}\overline{\nu_\alpha}\gamma^\mu N_j + V^{ij}\overline{N_i}\gamma^\mu N_j + d_V^\ell\,\overline{\ell}\gamma^\mu\ell\right)$$

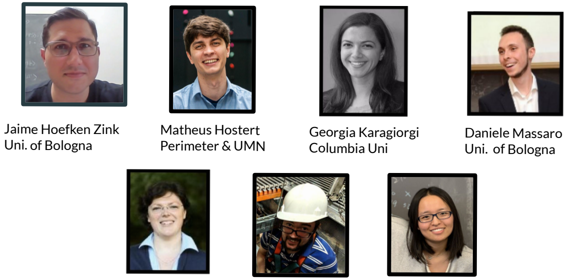


dark scalar

$$h'\left(S^{\alpha j}\overline{\nu_\alpha}N_j + S^{ij}\overline{N_i}N_j + d_S^\ell\,\overline{\ell}\ell\right)$$

While MicroBooNE is yet to perform dedicated searches for these models, we may already be able to constrain them using MicroBooNE public data

**** work-in-progress ****



Jaime Hoefken Zink, Uni. of Bologna
Matheus Hostert, Perimeter & UMN
Georgia Karagiorgi, Columbia Uni
Daniele Massaro, Uni. of Bologna
Silvia Pascoli, Uni. of Bologna
Mark Ross-Lonergan, LANL
Guanqun Ge, Columbia Uni.

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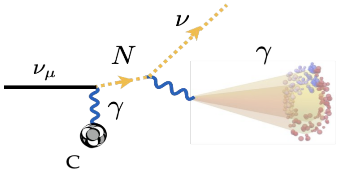

transition magnetic moment

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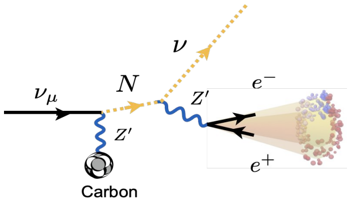
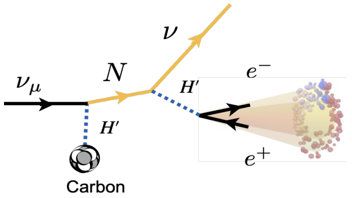


dark photon

$$Z'_\mu\left(V^{\alpha j}\overline{\nu_\alpha}\gamma^\mu N_j + V^{ij}\overline{N_i}\gamma^\mu N_j + d_V^\ell\,\overline{\ell}\gamma^\mu\ell\right)$$



dark scalar

$$h'\left(S^{\alpha j}\overline{\nu_\alpha}N_j + S^{ij}\overline{N_i}N_j + d_S^\ell\overline{\ell}\ell\right)$$

Simulation of neutrino-nuclear scattering at MicroBooNE using

DarkNews is a light-weight Python generator for neutrino-nucleus upscattering to heavy neutrinos.

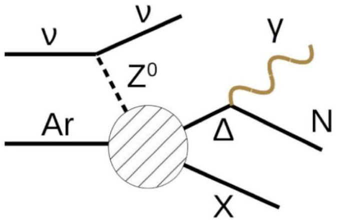
`pip install DarkNews`

Public and documented

Paper: arxiv.org/abs/2207.04137
GitHub: github.com/mhostert/DarkNews-generator
PyPI: pypi.org/project/DarkNews/

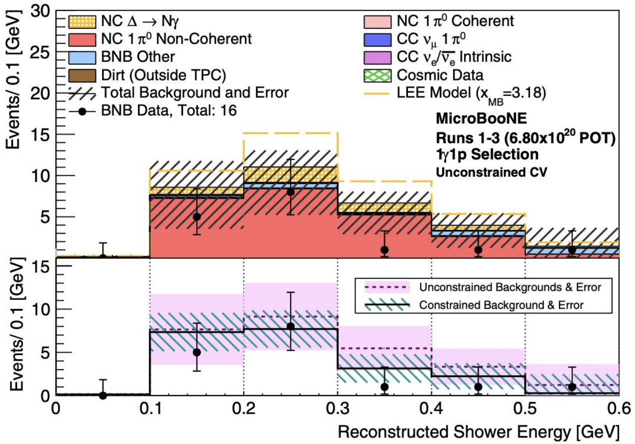
gLEE: NC Δ → Nγ search

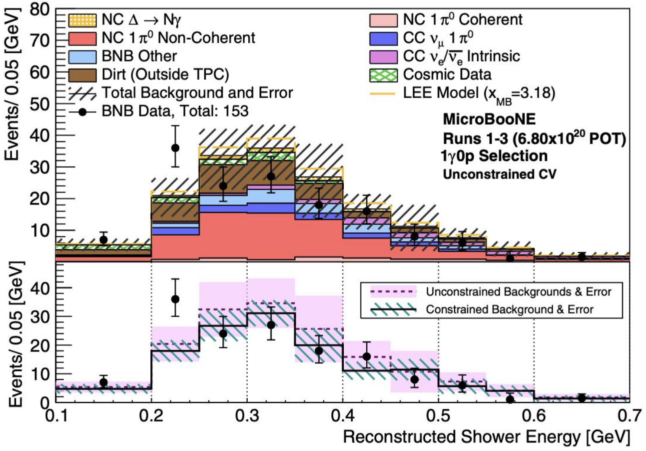
MicroBooNE constrain two topologies in the gLEE (γLEE) search:



1. $\Delta^+ \rightarrow p\,\gamma \rightarrow 1\gamma\,1p$

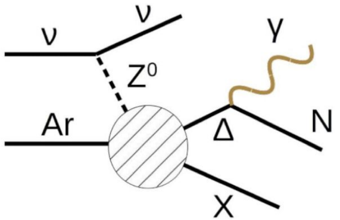
2. $\Delta^0 \rightarrow n\,\gamma \rightarrow 1\gamma\,0p$



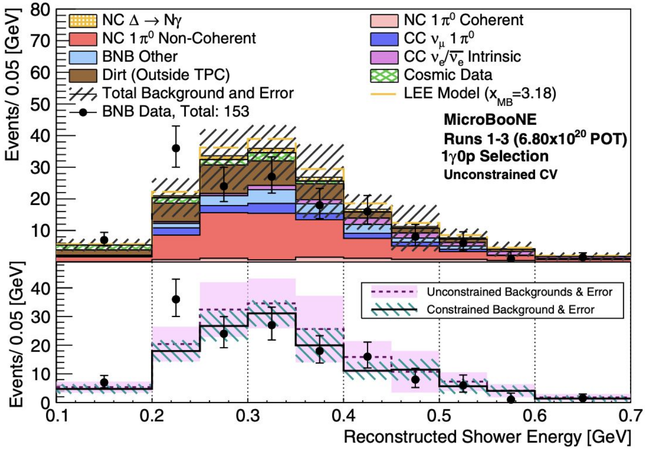


gLEE: NC Δ → Nγ search

MicroBooNE constrain two topologies in the gLEE (γLEE) search:



2. $\Delta^0 \rightarrow n\,\gamma \rightarrow 1\gamma\ 0p$



While our models do contribute to both topologies, we **consider only the 1γ 0p topology** to avoid issues with nuclear modelling

caveat: 1γ 0p selection has larger bkg, as proton kinematics cannot be leveraged for bkg rejection

gLEE 1γ 0p selection

Impossible to apply official MicroBooNE selection and so we make some educated guesses

Selection Stages
Topological cut
Pre-selection cuts
Cosmic BDT
BNB Other BDT
NC π^0 BDT

One reconstructed shower and no reconstructed tracks

Reconstructed shower energy

Shower start position from SCB

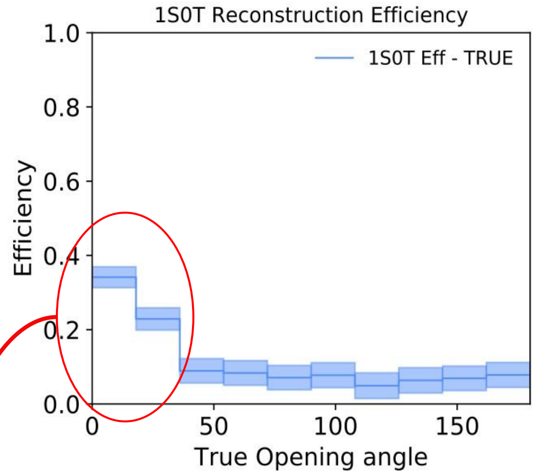
More involved set of cuts, e.g. second shower veto

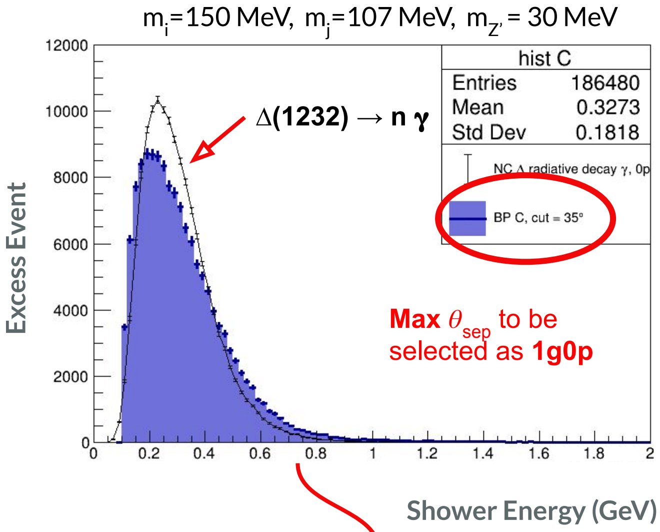
We can use our knowledge of e+e- reconstruction to make a pseudo-topological cut

As well as information about the energy distribution of the true NC delta decay photons

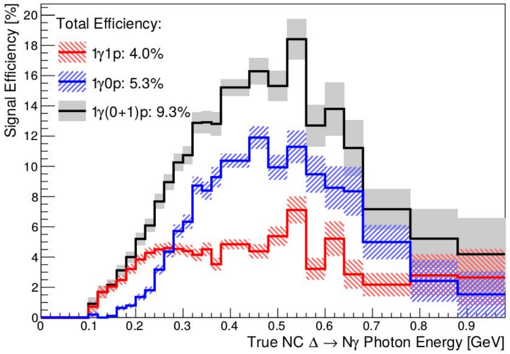
pseudo-1γ 0p selection

Pairs of uniformly distributed e^+e^- are passed through MicroBooNE reconstruction and topological reconstruction efficiencies derived





We can then apply 1g0p efficiency to our remaining events

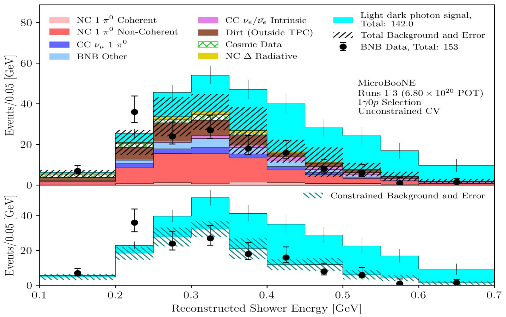


Efficiency to reconstruct a single shower highest for e^+e^- separation angle **< 35 deg.**

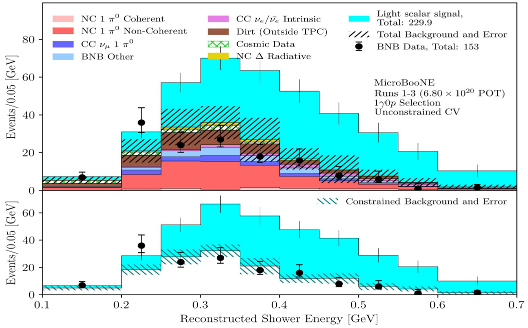
Comparison of truth-level energy distributions for benchmark model suggest it is valid to apply single photon selection efficiency

Preliminary selection

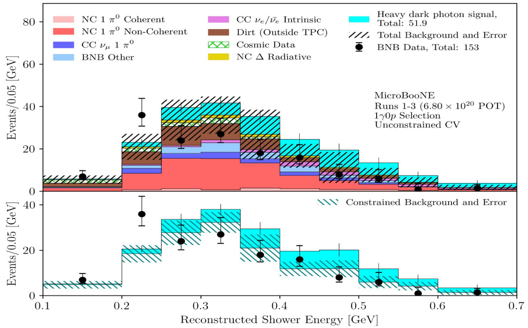
Light dark photon BP



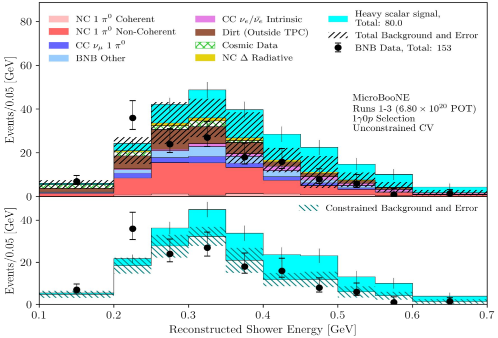
Light scalar BP



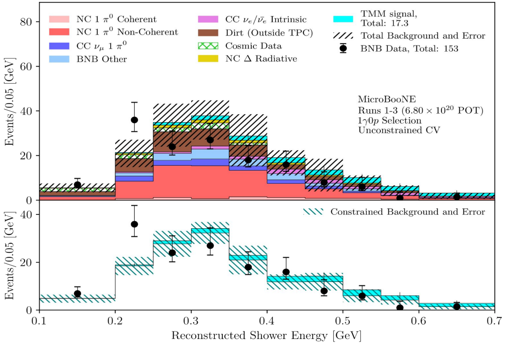
Heavy dark photon BP



Heavy scalar BP



TMM BP



Takeaways: Why Neutrino Experiments?

1. High POT O(1e21) → **large flux of charged and neutral mesons** that can decay to new particles which leave signal in the detector

2. Can take advantage of **potential to run in beam dump mode** to search for broader dark sector models

3. Strong **PID** (p, μ, e, γ), **spatial** and **energy resolution** (esp. LArTPC-based detectors) make distinguishing NP from SM more possible

4. **Parasitic**: Cost burden is shared with on-going neutrino projects and greater goal of elucidating oscillation parameters

Thank you for your attention!