MicroBooNE in 10 Minutes

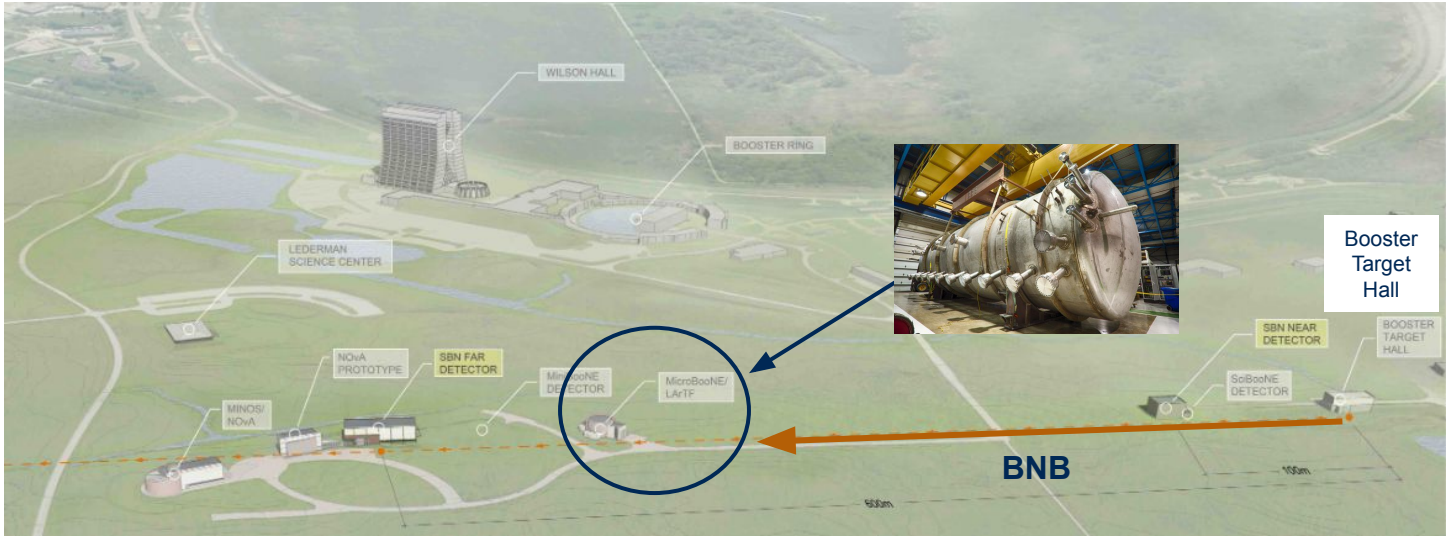
Kate Pletcher on behalf of the MicroBooNE Collaboration

New Perspectives 2024

July 8, 2024

What is MicroBooNE?

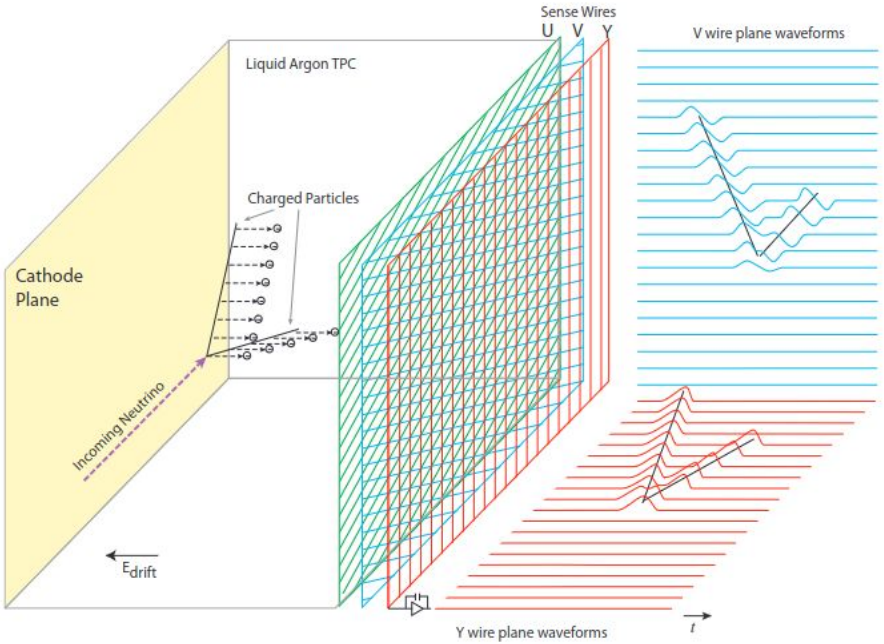
The **Micro Boo**ster **N**eutrino **E**xperiment is an 85-tonne liquid argon time projection chamber (LArTPC) experiment part of the Fermilab Short Baseline Neutrino (SBN) program with ~190 collaborators



→ On-axis to the booster neutrino beam (BNB), 470 m from target

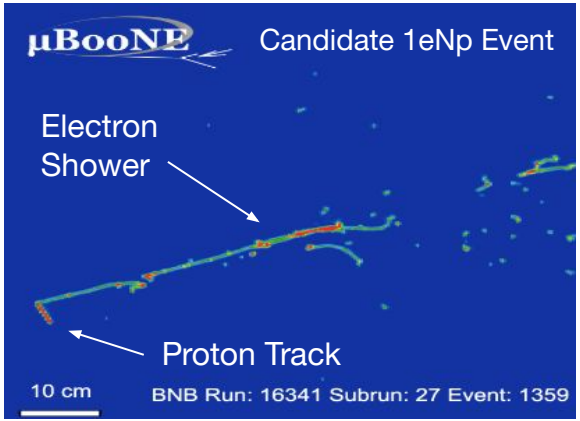
→ Off-axis from neutrinos at the main injector (NuMI) beam by 8°, ~680 m downstream from target

The MicroBooNE Detector: LArTPCs



R. Acciarri *et al* 2017 *JINST* **12** P02017

- The light readout system behind the anode plane uses photomultiplier tubes (PMTs) to detect scintillation photons, giving a start time for the neutrino interaction
- The Cosmic Ray Tagger (CRT), a plastic scintillator detector, was installed around the cryostat for improved cosmic ray rejection



LArTPC Capabilities

- Calorimetry for measuring particle energy
- Millimeter-scale spatial resolution
- Particle identification

MicroBooNE Physics Goals: Detector Physics and Calibrations

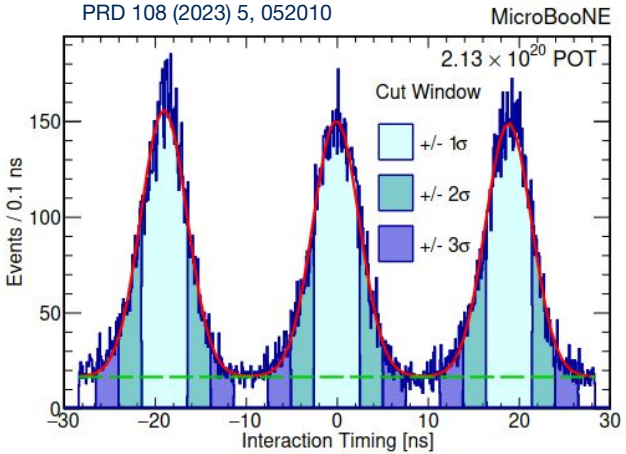
Detector Physics & Calibrations

Investigating the MiniBooNE Low Energy Excess and other Beyond the Standard Model Physics

Neutrino-Argon Cross Sections

Detector Physics and Analysis Methods

- MeV-Scale Reconstruction
  - Used for radiopurity measurement of radon effects
    - PRD 109 (2024), 092007
- Nanosecond Timing
  - Reconstruct neutrino interaction times at O(1 ns)
  - Helpful for cosmic rejection and BSM particle searches
    - PRD 108 (2023) 5, 052010
- Neutron Identification
  - Novel detection technique applicable to any LArTPC
    - arXiv:2406.10583



Fraction of cosmic background events to neutrino events across ns-scale interaction timing

→ Lots of data from 5 years of data taking & dedicated detector R&D runs!

MicroBooNE Physics Goals: MiniBooNE LEE & BSM Physics

Detector Physics & Calibrations

Investigating the MiniBooNE Low Energy Excess and other Beyond the Standard Model Physics

Neutrino-Argon Cross Sections

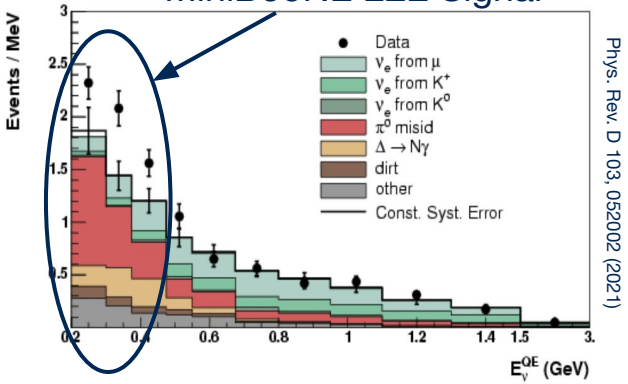
MiniBooNE Low Energy Excess (LEE)

MiniBooNE (**Mini Boo**ster **N**eutrino **E**xperiment)

- Observed 4.8σ excess (LEE) of shower events at low energy
- Predicted to be produced by *electron* or *photon* events

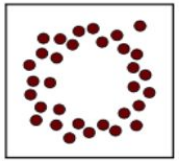
As a mineral oil Cherenkov detector, MiniBooNE cannot distinguish between electrons and photons…but MicroBooNE can!

MiniBooNE LEE Signal

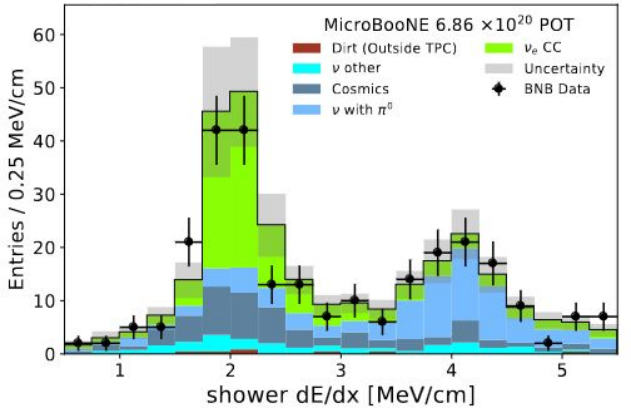


Phys. Rev. D 103, 052002 (2021)

MiniBooNE e/γ Event Display



MicroBooNE e/γ Separation

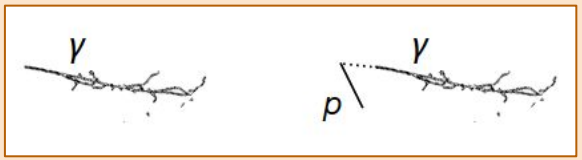


Phys. Rev. D105, 112004 (2022)

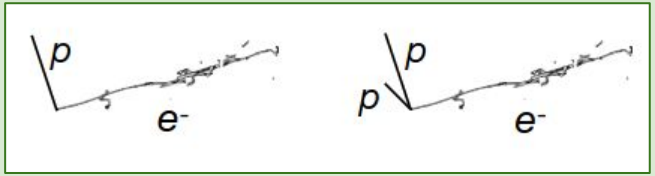
Probing the MiniBooNE LEE Anomaly

Final State Searches:

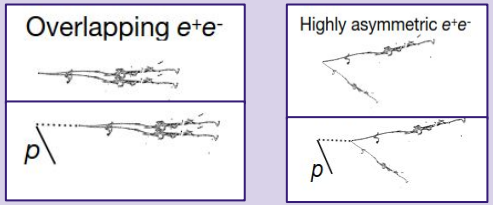
Single Photons



Electrons



Dark Sector e^+e^- Pairs



Diagrams courtesy of Matt Toups

New Results: Semi-Inclusive Search for Pionless ν_e Events

2022 results disfavor electron-like explanation (Phys. Rev. D105, 112004 (2022), Phys. Rev. Lett. 128, 241801 (2022), Phys. Rev. Lett. 128, 241801 (2022))

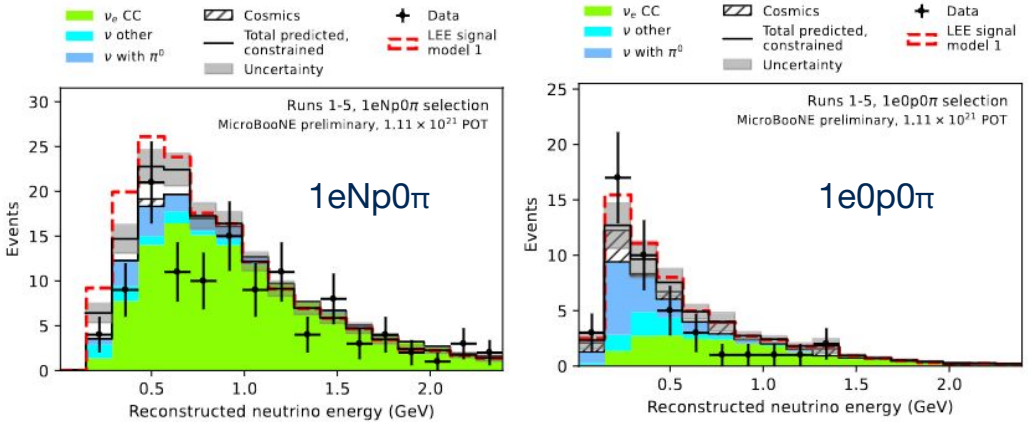
This 2024 analysis:

→ **First analysis using full MicroBooNE data set of 1.11×10^{21} POT** (previous result uses 6.86×10^{20} POT)

→ Test in reconstructed neutrino energy and with new model in shower energy and angle kinematics

→ Use of additional constraint samples: 1μNp0π, 1μ0p0π, and ν NC π^0

→ Use of the cosmic ray tagger (CRT) in the 1e0p0π selection



Data is consistent with nominal ν interaction model with p-values ranging from 5.2% - 71.7% across both signal channels and all kinematic variables

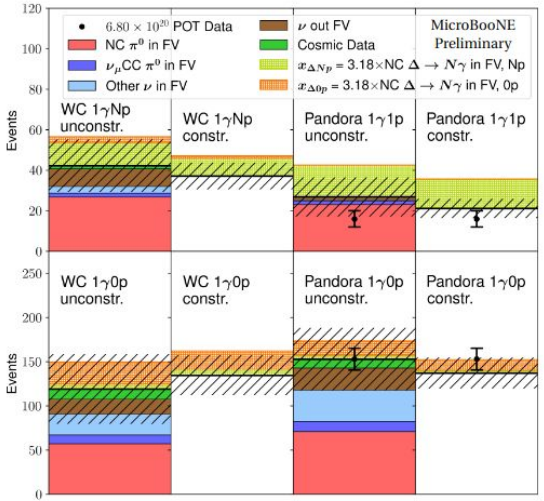
Excludes the ν_e interpretation of the MiniBooNE LEE at ≥ 99% CL in all kinematic variables

MICROBOONE-NOTE-1127-PUB

The MiniBooNE LEE: Single Photon Final States

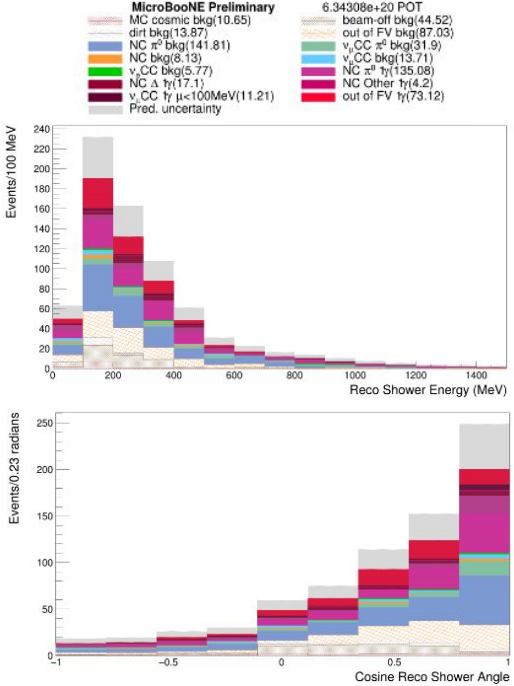
Neutral-Current Delta radiative decay NC $\Delta \rightarrow N\gamma$

Final States: 1γNp and 1γ0p



MICROBOONE-NOTE-1126-PUB

Inclusive single photon search

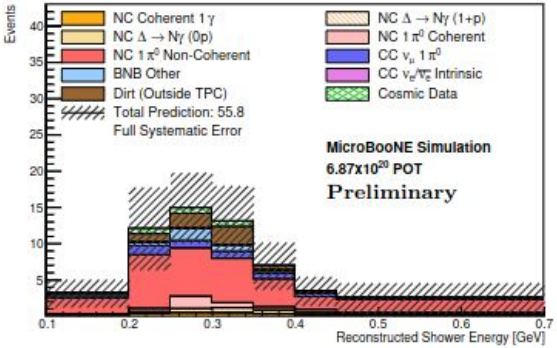


MICROBOONE-NOTE-1125-PUB

Coherent single photon search

$$\nu(\overline{\nu}) + \mathrm{Ar}_{gs} \rightarrow \nu(\overline{\nu}) + \mathrm{Ar}_{gs} + \gamma$$

First search of its kind!

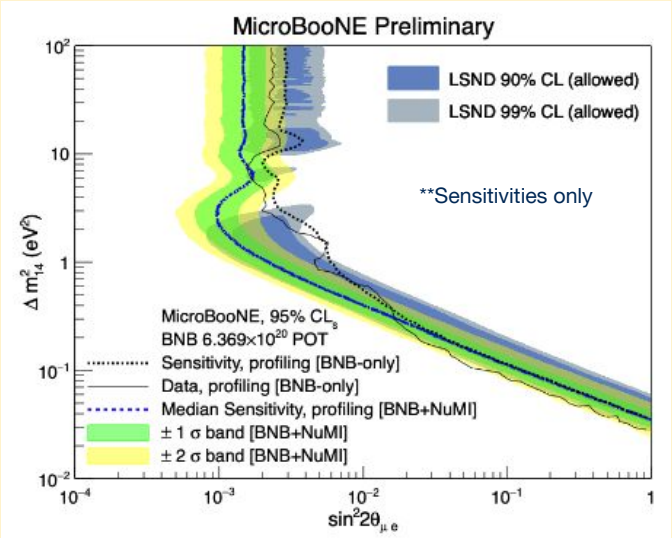


MICROBOONE-NOTE-1131-PUB

Further Anomaly Exploration and BSM Searches

3+1 Oscillation Measurement

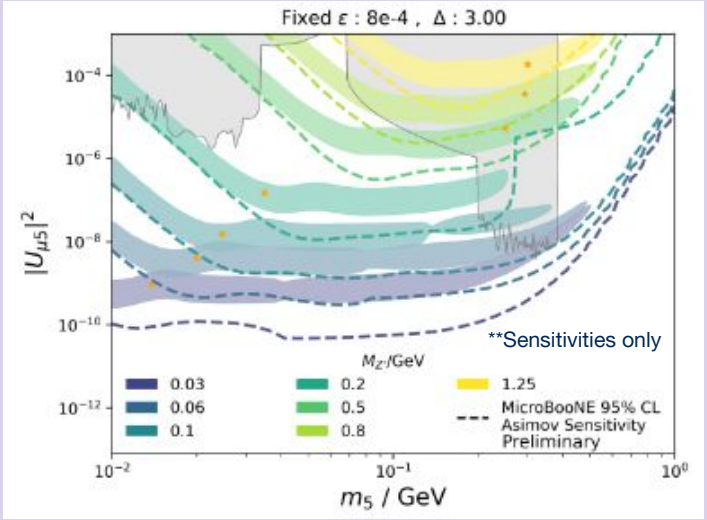
- Utilizes BNB and NuMI beam data, each with a distinct ν_μ / ν_e ratio to mitigate degeneracy in oscillation parameters



MICROBOONE-NOTE-1132-PUB

Dark Sector e^+e^- Final States

- Sufficiently overlapping or asymmetric e^+e^- pairs could match the MiniBooNE signal



95% CLs sensitivity for broad analysis with heavy and light Z'

MICROBOONE-NOTE-1124-PUB

MicroBooNE Physics Goals: Cross Sections

Detector Physics & Calibrations

Investigating the MiniBooNE Low Energy Excess and other Beyond the Standard Model Physics

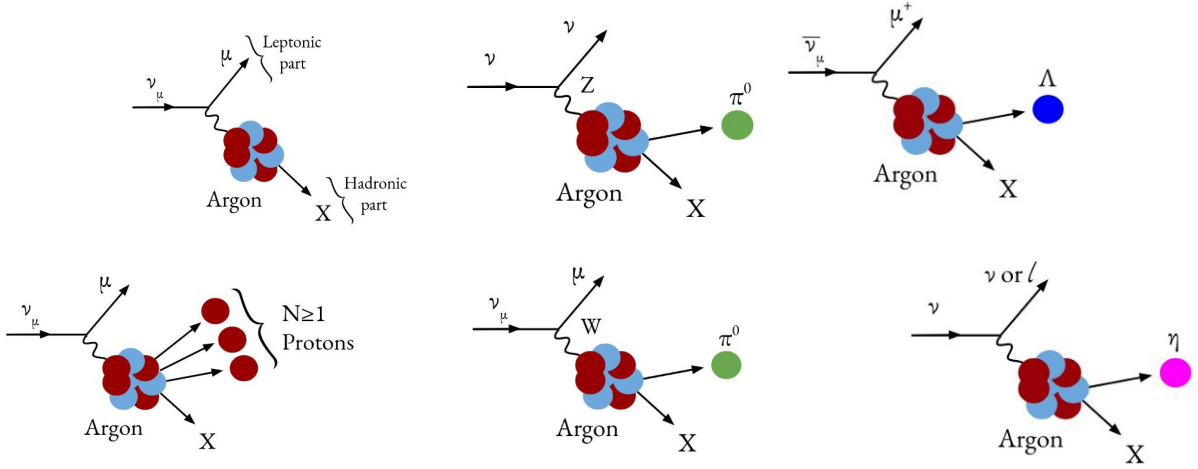
Neutrino-Argon Cross Sections

Neutrino Interaction Cross Sections

→ MicroBooNE has collected O(500k) neutrino-Argon interactions in 5 years of data taking, the largest ν-Ar dataset in the world, paving the way in ν-Ar measurements

→ MicroBooNE can accurately measure energy reconstruction for lepton and hadron kinematics

Types of cross section measurements:



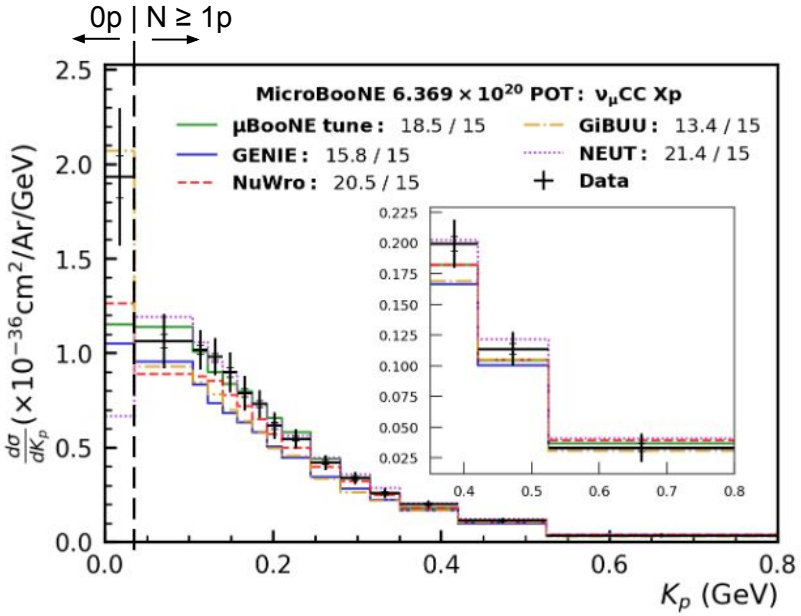
Images from Afroditi Papadopoulou's talk at Neutrino '24

MicroBooNE has published >20 ν-Ar cross sections!

…and more!

Cross Sections: Hadronic Modeling

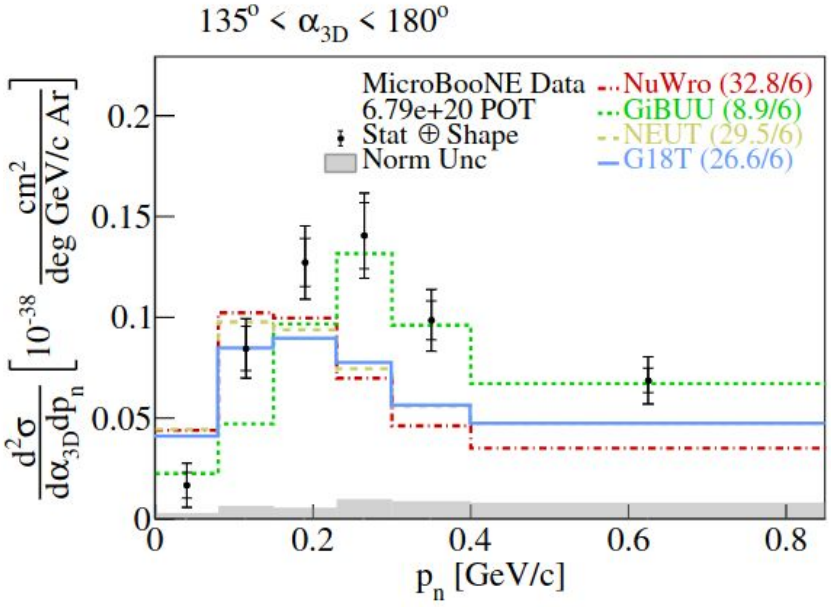
CC ν_μ-Ar for final states with and without protons



Accepted into PRD: arXiv:2402.19216

Accepted into PRL: arXiv:2402.19281

Nuclear effects in ν-Ar interactions using generalized kinematic imbalance variables

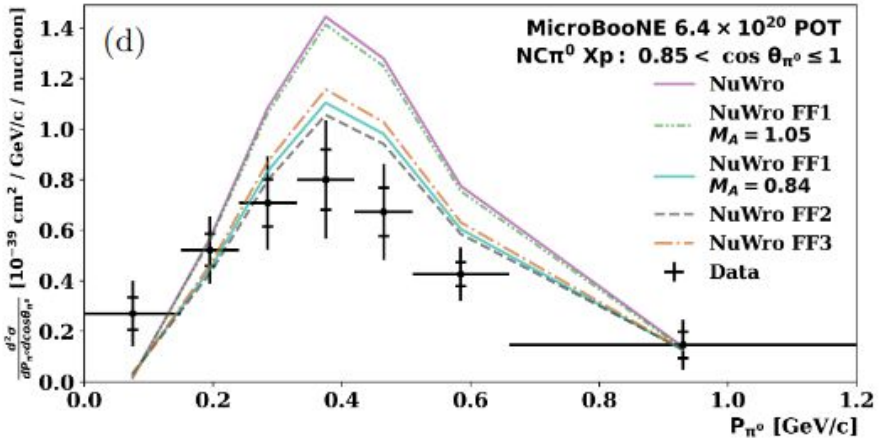


Phys. Rev. D 109, 092007 (2024)

First Differential Cross Section Measurements of π^0 Production

NC π^0 Production

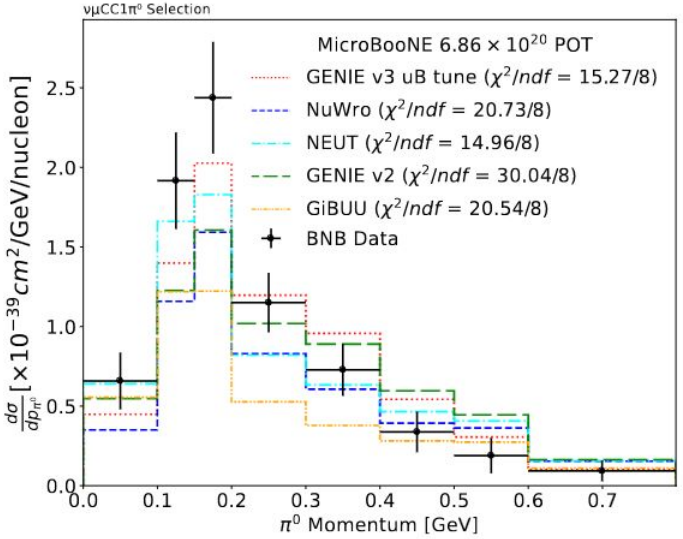
$$\nu_l + \mathrm{Ar} \rightarrow \nu_l + \pi^0 + X$$



arXiv:2404.10948

CC π^0 Production

$$\nu_\mu + \mathrm{Ar} \rightarrow \mu^- + \pi^0 + 0\pi^\pm + \mathrm{X},$$



arXiv:2404.09949

Summary

- ★ MicroBooNE is a liquid argon time projection chamber neutrino experiment at Fermilab, part of the SBN program
- ★ It currently has the most neutrino-Argon interaction data in the world!
- ★ We are a very active collaboration, paving the way for neutrino-Argon cross section measurements, investigating the MiniBooNE LEE, pioneering LArTPC detector physics studies, and developing novel analysis methods

Thank you!

MicroBooNE Collaboration Meeting at Michigan State University, May ‘24

Backup Slides

LSND and MiniBooNE Anomalies

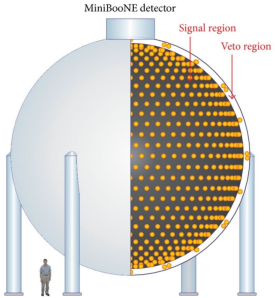
Liquid Scintillator Neutrino Detector (LSND)

- 1993-1998: LSND takes data at Los Alamos National Laboratory
- 2001: Reported excess of anti-ν_ep → e$^+$n events at 3.8σ, experimental evidence for anti-ν_μ → anti-ν_e oscillation with Δm^2 ~ 1 eV^2 scaling
- This Δm^2 limit, when considered alongside much smaller Δm^2 limits from other experiments, disfavors the three-neutrino mass eigenstate model

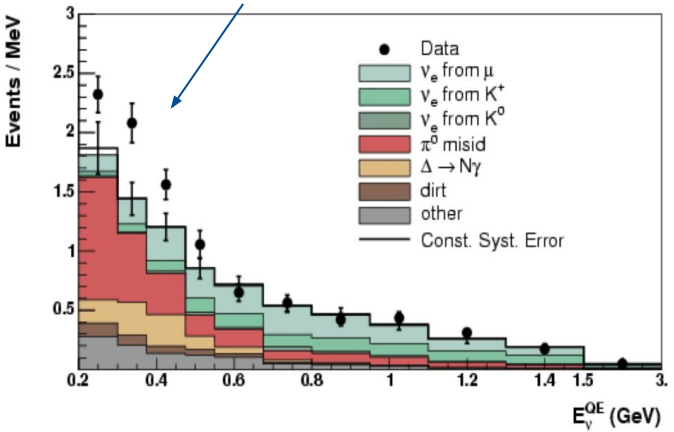
MiniBooNE (**Mini Boo**ster **N**eutrino **E**xperiment)

- 2002-2017: Mineral oil Cherenkov detector takes data at FNAL, measuring ν_e and anti-ν_e appearance
- 2009: Observed excess of electron-like events in their low energy region at 4.8σ, known as the Low Energy Excess (LEE)
- Predicted to be produced by
  - Electron events
  - Photon events

MiniBooNE cannot distinguish between electrons and photons as final state particles in its detector…but MicroBooNE can!



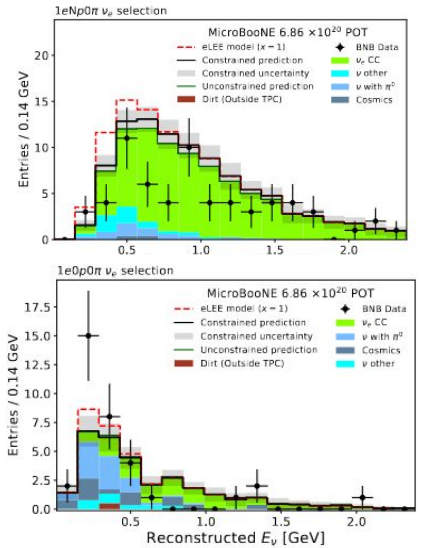
MiniBooNE LEE Signal



The MiniBooNE LEE: Electron-like Final States (2022 Results)

Semi-inclusive search for pionless ν_e events

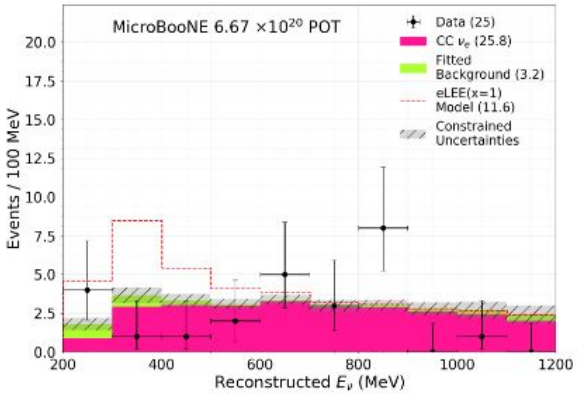
Signal Channels: 1eNp0π and 1e0p0π



Phys. Rev. D105, 112004 (2022)

Search for two-body ν_e CCQE scattering

Signal Channel: 1e1p0π

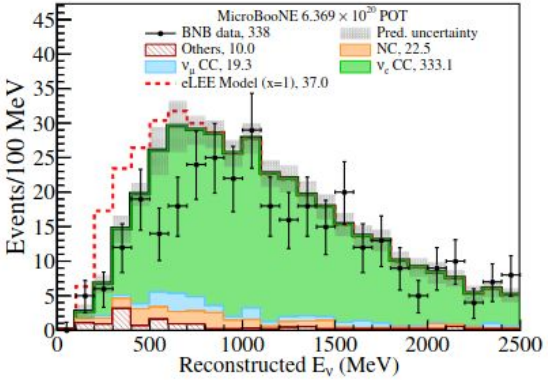


Phys. Rev. Lett. 128, 241801 (2022)

Inclusive ν_e search with any hadronic final state

Wire-Cell Reconstruction

Signal Channel: 1eX



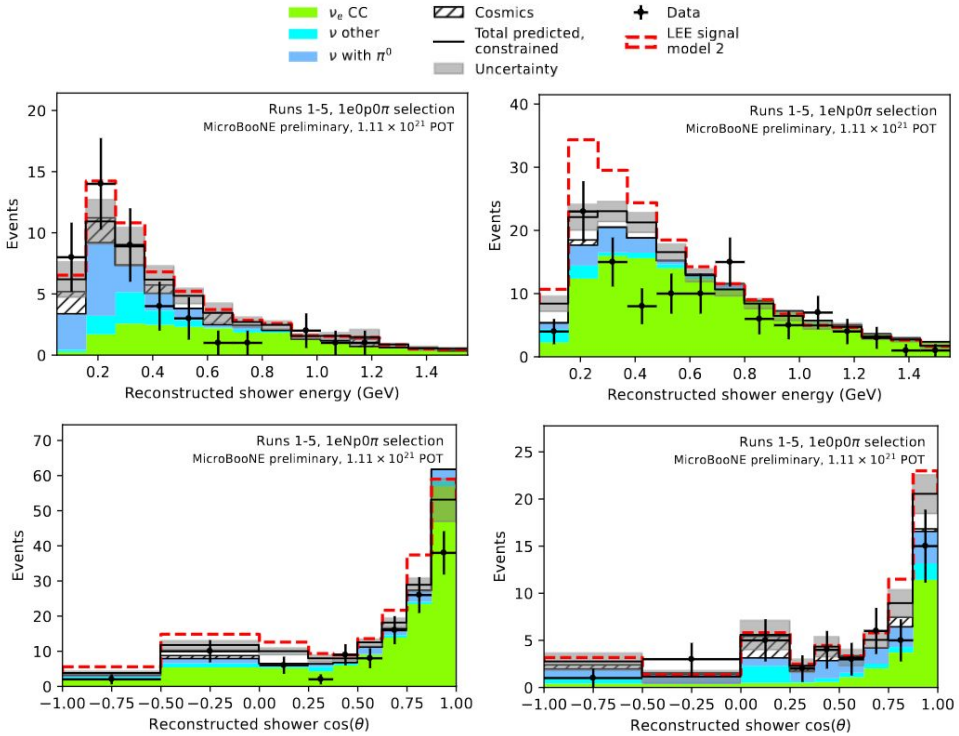
Phys. Rev. Lett. 128, 241801 (2022)

New Results: Semi-Inclusive Search for Pionless ν_e Events

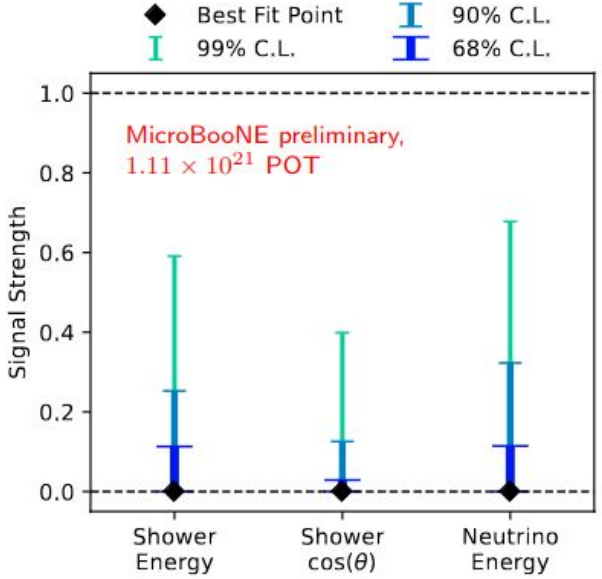
New Signal Model Results

Shower Energy

Shower cos(θ)



Confidence Intervals

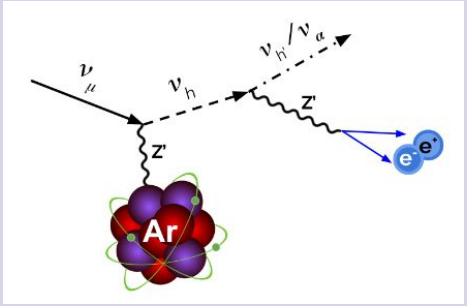


MICROBOONE-NOTE-1127-PUB

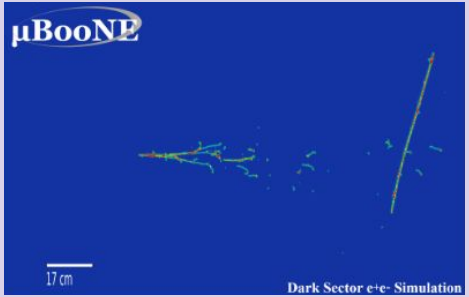
The MiniBooNE LEE Anomaly: e^+e^- Pair Searches, Detailed

Searches for dark sector e^+e^- pairs

→ Sufficiently overlapping or asymmetric e^+e^- pairs could match the MiniBooNE signal



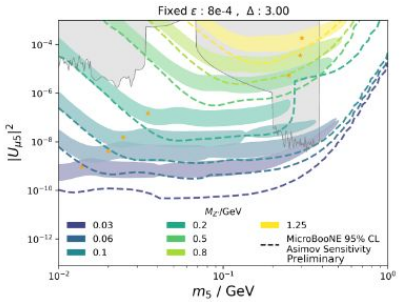
Active neutrinos upscatter off Argon nuclei via a dark photon (Z') to produce heavy, unstable sterile neutrinos (N) which decay into e^+e^- pairs. This final state could also match the MiniBooNE anomalous signal



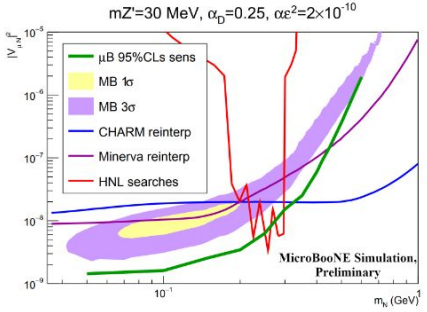
Simulated event display for an e^+e^- pair with a small opening angle. The shower is indistinguishable from a photon

Two approaches:

1. Broad analysis with heavy and light dark gauge bosons with one (3+1) or two (3+2) heavy sterile neutrinos
   Uses Pandora reconstruction
2. Focused analysis with a light dark gauge boson
   Uses Wire-Cell reconstruction



95% CLs sensitivity for broad analysis with heavy and light Z'



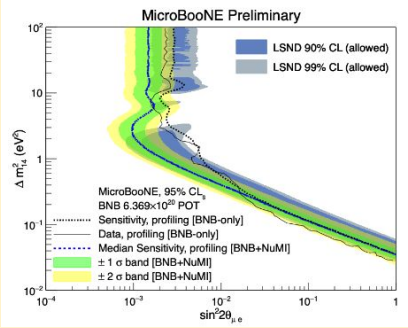
95% CLs sensitivity for focused 3+1 analysis with light Z'

Further Anomaly Exploration and Other BSM Searches

3+1 Oscillation Measurement

- Utilizes BNB and NuMI beam data, each with a distinct ν_μ / ν_e ratio to mitigate degeneracy in oscillation parameters
- Adding NuMI data makes this analysis sensitive to the LSND allowed region

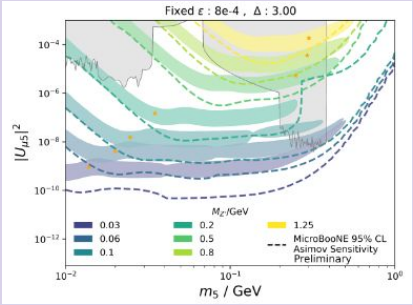
MICROBOONE-NOTE-1132-PUB



Constraining dark sector e^+e^- solutions to the MiniBooNE LEE

- Sufficiently overlapping or asymmetric e^+e^- pairs could match the MiniBooNE signal
- Sensitivity results for two approaches:
  - Broad analysis with heavy and light dark gauge bosons with one (3+1) or two (3+2) heavy sterile neutrinos
  - Focused analysis with a light dark gauge boson

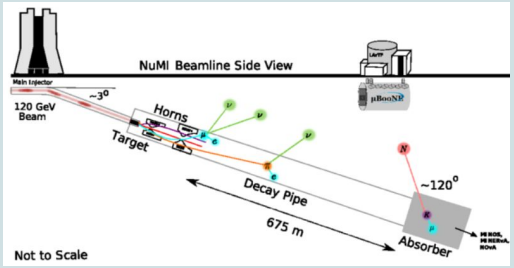
MICROBOONE-NOTE-1124-PUB



95% CLs sensitivity for broad analysis with heavy and light Z'

Astro Particle and Exotics Searches

- Kaons decaying at rest (KDARs) in NuMI absorber could produce HPS/HNLs that reach the MicroBooNE detector
- π^0 or η meson decays could produce dark matter particles in the target



Dark sector searches include:

- Heavy Neutral Leptons (HNL)
  - Phys. Rev. Lett. 132 (2024) 4, 04180
  - Phys. Rev. D 106 (2022) 9, 092006
- Higgs Portal Scalars (HPS)
  - Phys. Rev. Lett. 127 (2021) 15, 151803
- Dark Tridents
  - Phys. Rev. Lett. 132, 241801

3+1 Oscillation Measurement, Detailed

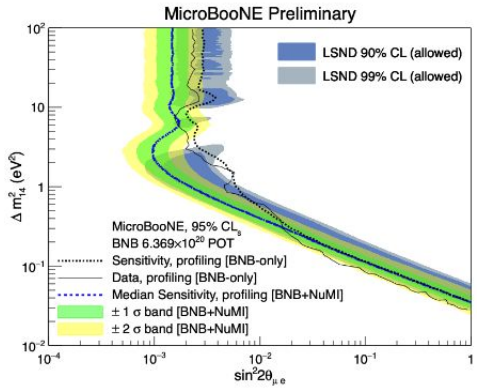
MicroBooNE utilizes BNB and NuMI data to perform a light sterile neutrino search → 3 active, 1 sterile (3+1) neutrino framework

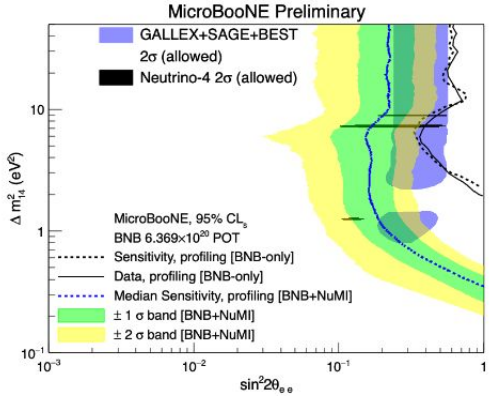
$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} + (-1)^{\delta_{\alpha\beta}} \cdot \sin^2 2\theta_{\alpha\beta} \cdot \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$\nu_\mu \to \nu_e$ appearance oscillations cancelling with ν_e disappearance leads to degeneracy in oscillation parameters

BNB: 99.5% ν_μ / 0.5% ν_e
NuMI: 95% ν_μ / 5% ν_e

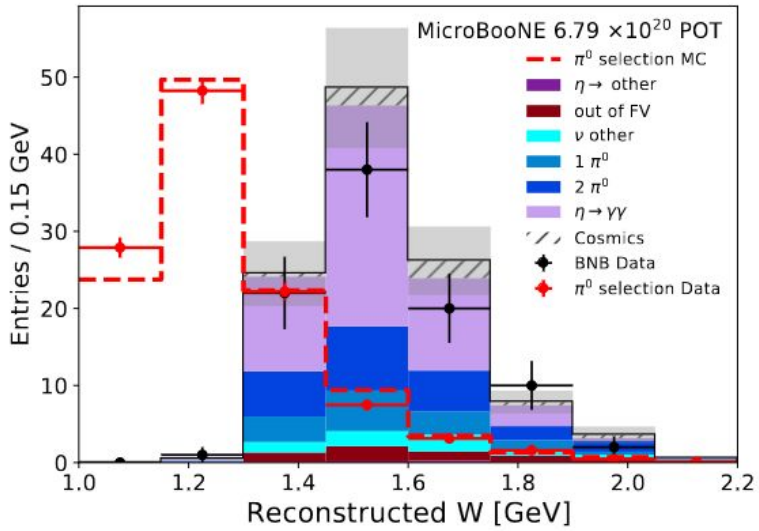
} The different ν_μ / ν_e ratios mitigate this degeneracy





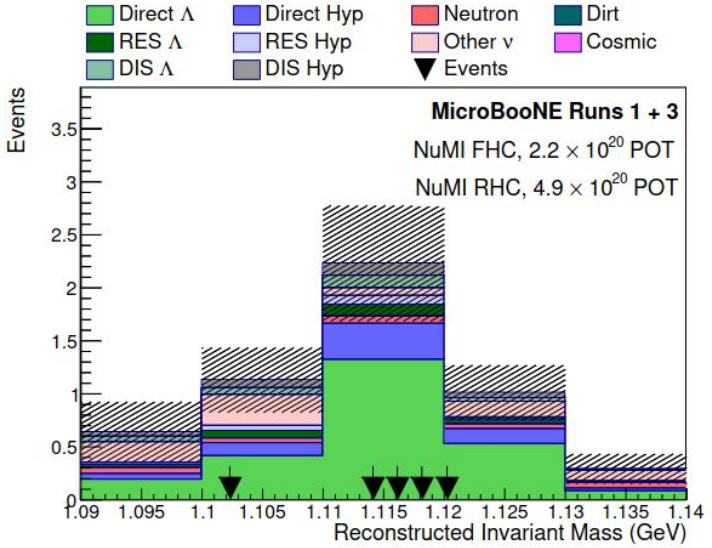
Cross Sections: Novel Identification Techniques

η Meson Production



Phys. Rev. Lett. 132, 151801 (2024)

Λ Baryon Production



Five candidates identified

Phys. Rev. Lett. 130, 231802