

43rd International Symposium on Physics in Collision

PIC 2024



22-25 October 2024

NCSR "Demokritos", Athens, Greece



Recent results from MicroBooNE

Holly Parkinson

(on behalf of the [MicroBooNE Collaboration](#))

University of Edinburgh

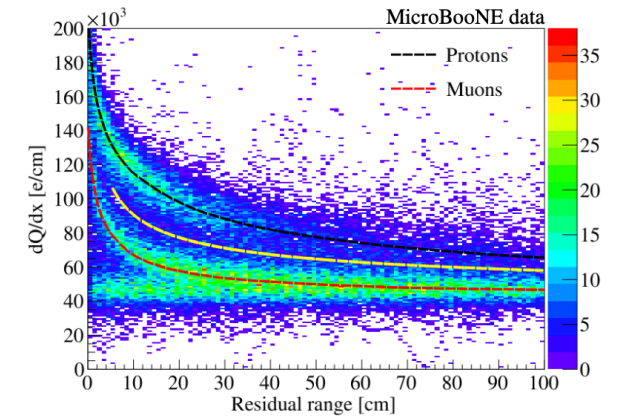
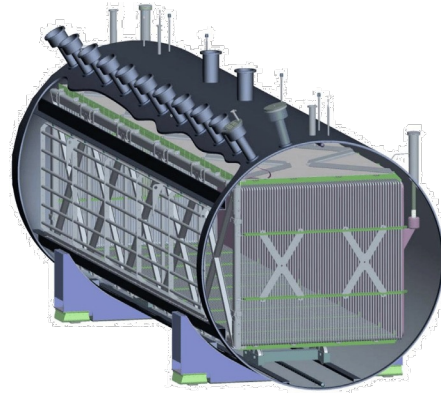
23rd October 2024



THE UNIVERSITY
of EDINBURGH

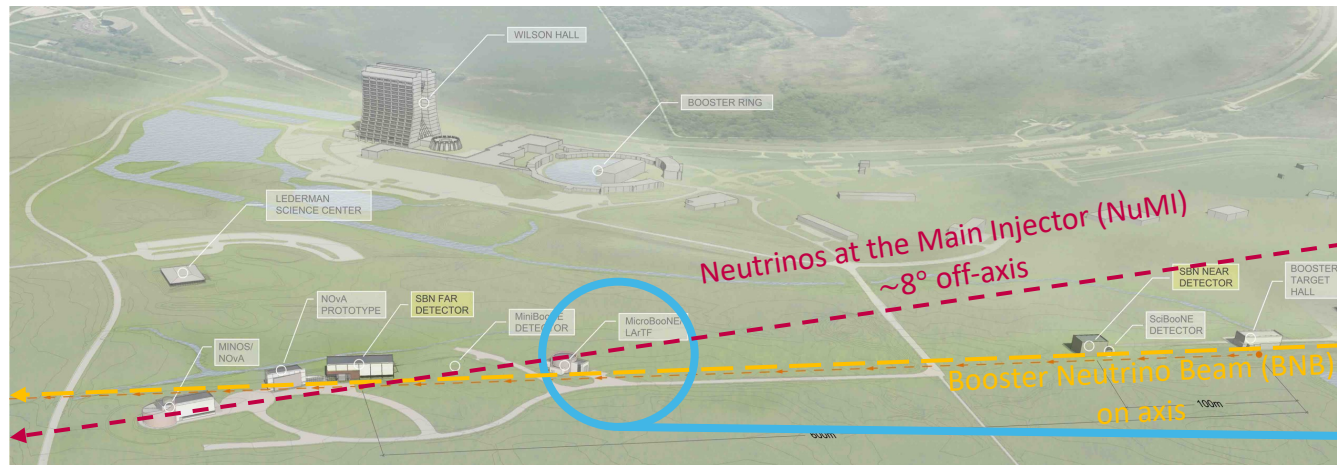
Outline

- The MicroBooNE detector
- Analysis techniques
- Physics at MicroBooNE
 - MiniBooNE LEE
 - BSM Searches
 - Cross sections
- Future analyses



The MicroBooNE Detector

- The **Micro Booster Neutrino Experiment** is part of the Fermilab SBN (Short Baseline Neutrino) Program



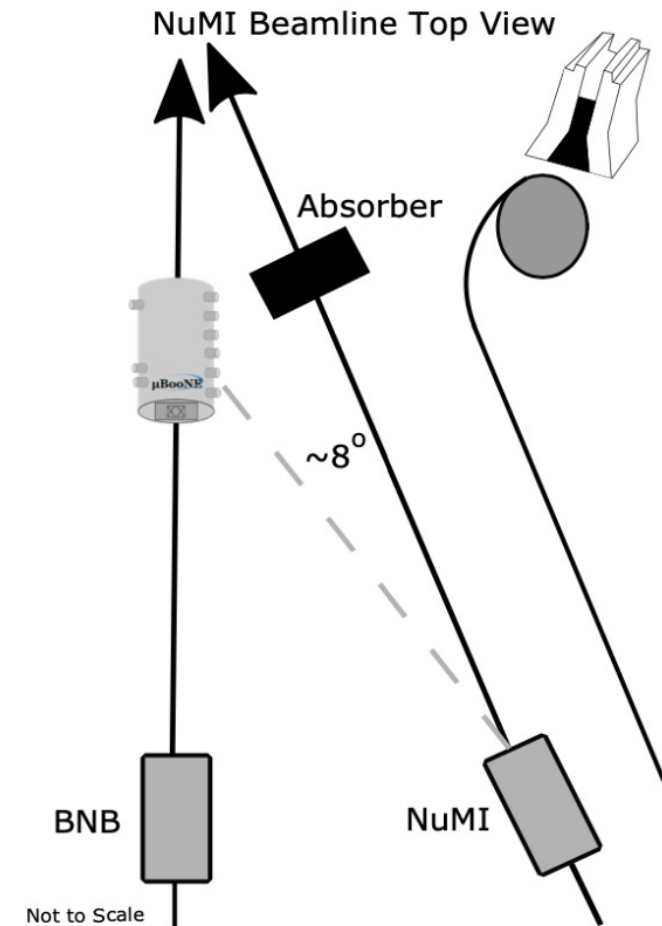
MicroBooNE
470 m from BNB target
~680 m from NuMI target



- Operated from 2015 – 2021
 - Large, well-understood dataset of neutrino-argon interactions

One detector, two beams

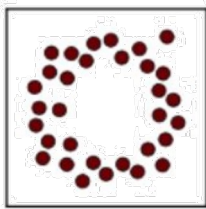
- MicroBooNE receives neutrinos from two beams:
 - **Booster Neutrino Beam (BNB)**
 - target 470 m from MicroBooNE, **on axis**
 - 8 GeV protons, Be target
 - $\langle E_{\nu_\mu} \rangle = 800$ MeV
 - **0.5% ν_e and $\bar{\nu}_e$** , 99.5% ν_μ and $\bar{\nu}_\mu$
 - **Neutrinos at the Main Injector (NuMI)**
 - target ~ 680 m from MicroBooNE, **off axis** (8°)
 - 120 GeV protons, C target
 - $\langle E_{\nu_e} \rangle = 650$ MeV
 - **4.5% ν_e and $\bar{\nu}_e$** , 95.5% ν_μ and $\bar{\nu}_\mu$



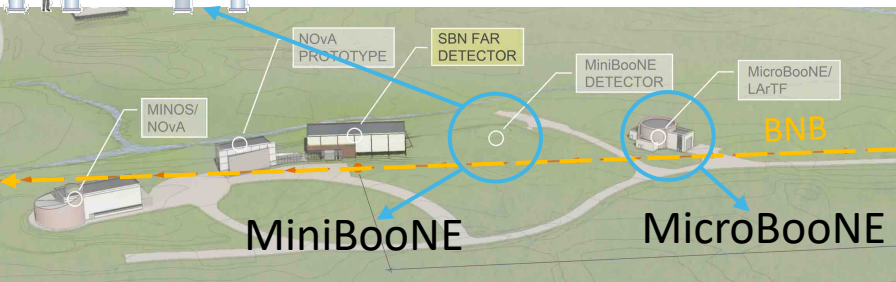
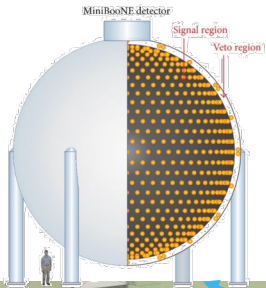
The MiniBooNE Low Energy Excess (LEE)

Phys. Rev. D 103, 052002

Cherenkov signal for electron or photon



e/γ

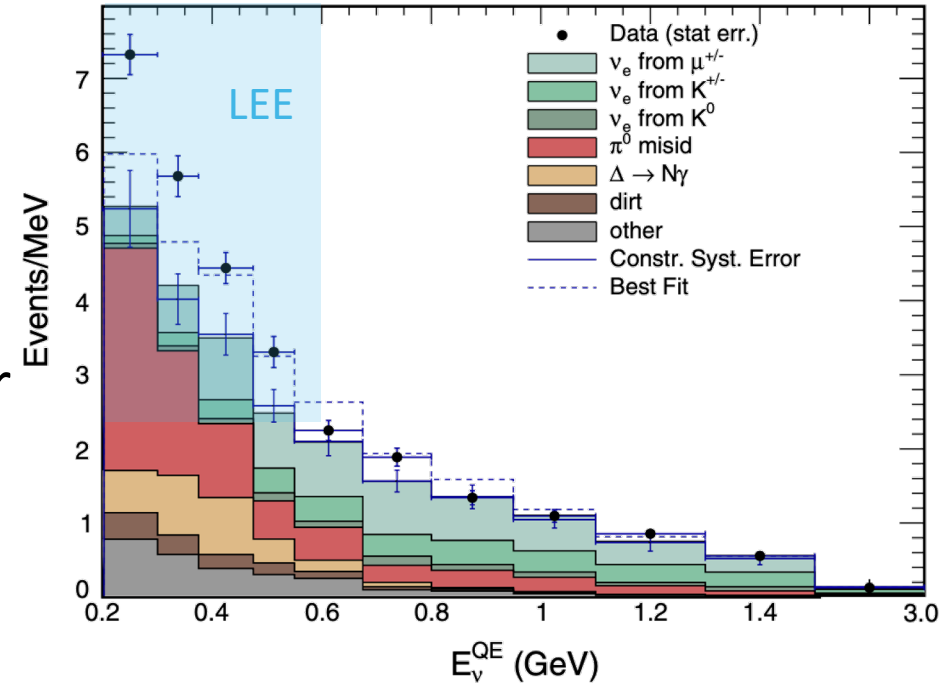


- One of MicroBooNE's investigation goals
- The **Mini Booster Neutrino Experiment** saw a **4.8 σ excess of electron neutrino-like events at low energies** compared to prediction
- **3.8 σ excess of $\bar{\nu}_e$** seen earlier by Liquid Scintillator Neutrino Detector (LSND)

- photon or electron events?
- something else- *new physics*?

sterile neutrinos?
hypothetical neutrino flavour, only interact via gravity

dark sector?
hypothetical particles, possible DM candidates

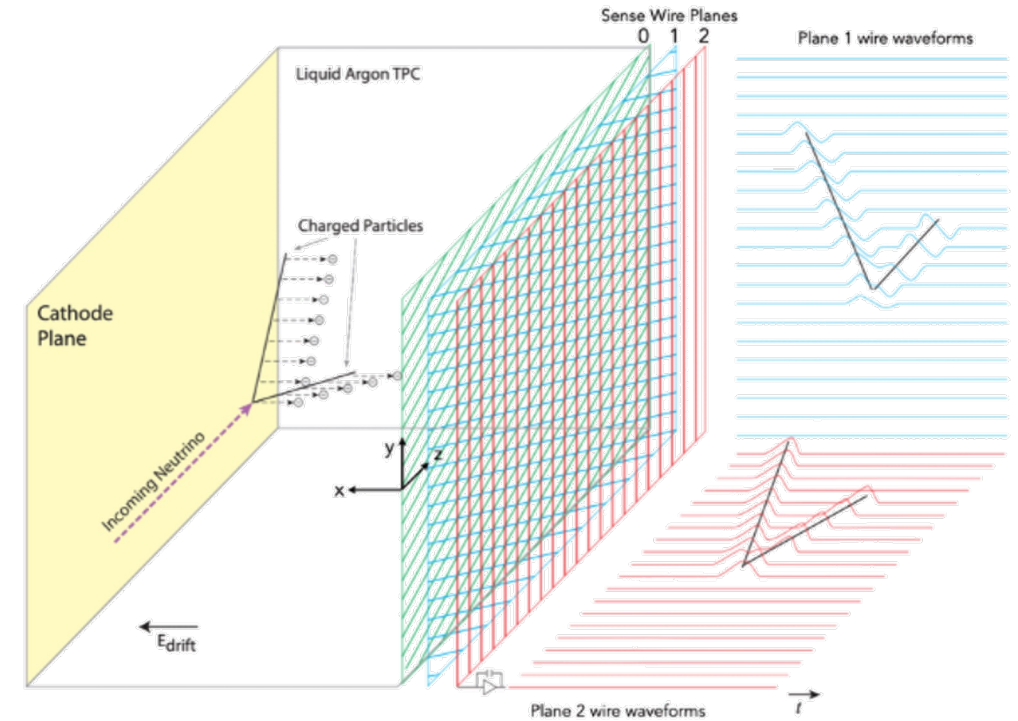


MiniBooNE and LSND could not distinguish between electrons and photons, **but a LArTPC can!**

LArTPCs

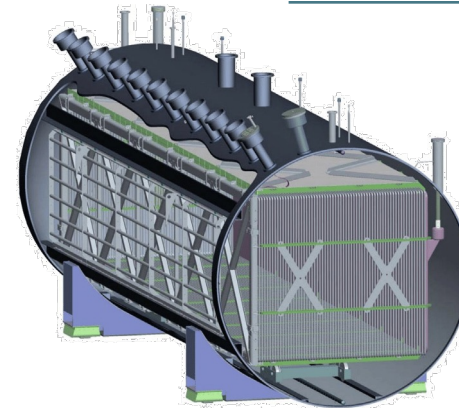
DUNE will use this technology!

- **Liquid Argon Time Projection Chambers**
 - Charge drifted and collected to precisely reconstruct track positions and calorimetry
 - Light used to identify times and reject non-beam background
- MicroBooNE has...
 - **85 tonne** active volume
 - **3 planes of wires** (vertical, $+60^\circ$, -60°), 3 mm spacing, for charge collection
 - **32 PMTs** to detect scintillation photons



Operational principle of the MicroBooNE LArTPC

[R. Acciarri et al 2017 JINST 12 P02017](#)

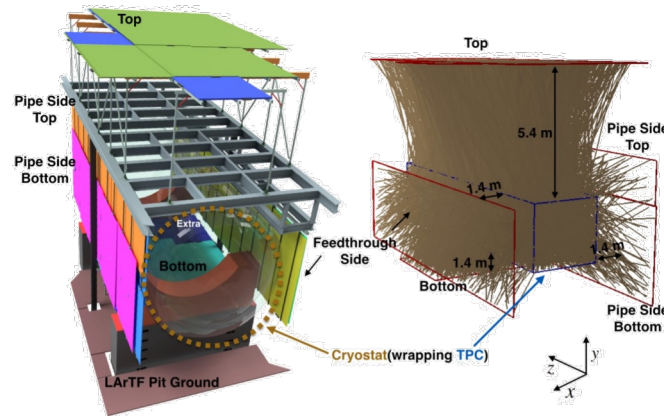


A schematic drawing of the MicroBooNE LArTPC as installed inside the cryostat

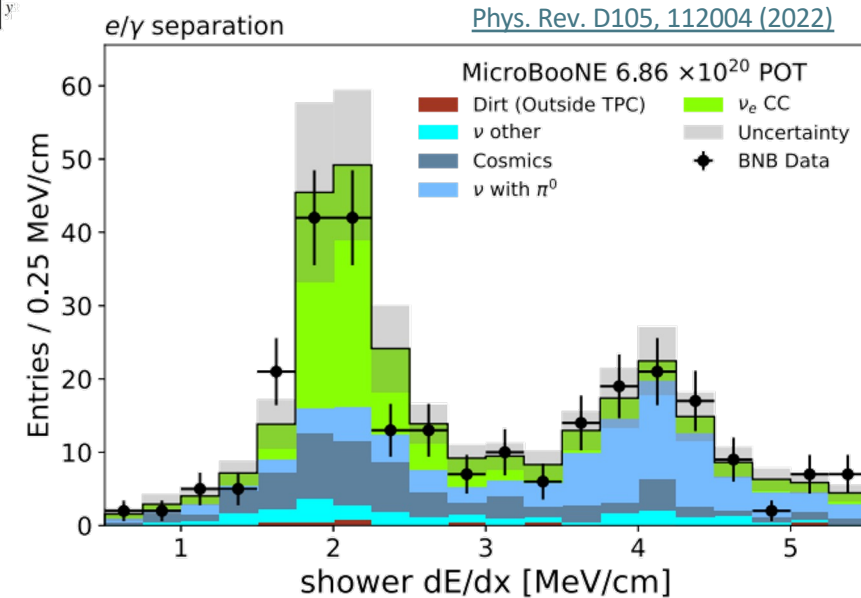
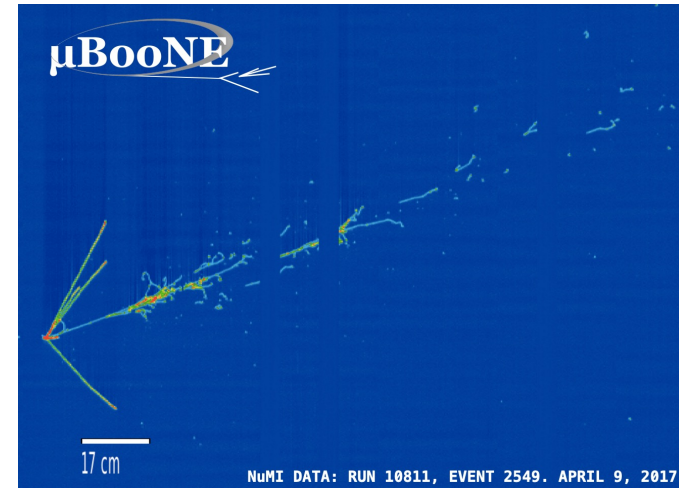
[P. Abratenko et al 2020 Physical Review D 102](#)

MicroBooNE's LArTPC Capabilities

- mm-level spatial resolution
 - 3D interaction images
- Fully active tracking calorimeter: precise energy resolution
- Excellent particle identification
 - Including distinguishing electrons from photons
- Cosmic Ray Tagger (CRT) installed around cryostat to improve cosmic background rejection

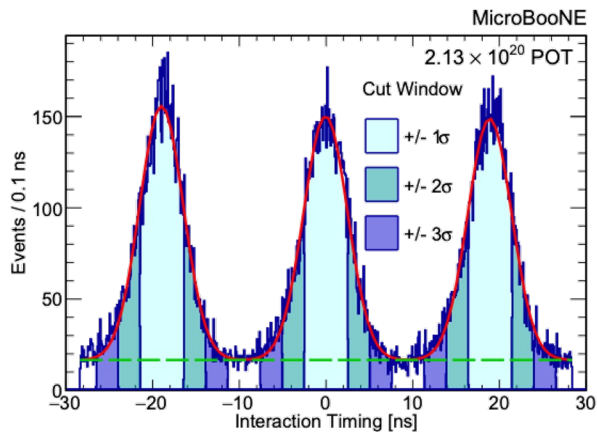


C. Adams et al 2019 JINST 14 P04004



Analysis techniques

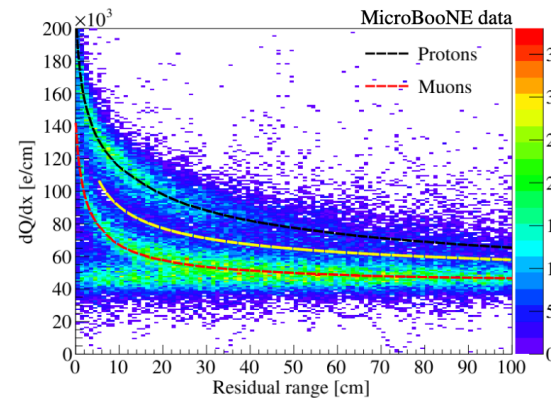
Our latest developments in LArTPC physics:



ns timing resolution

helpful for BSM searches

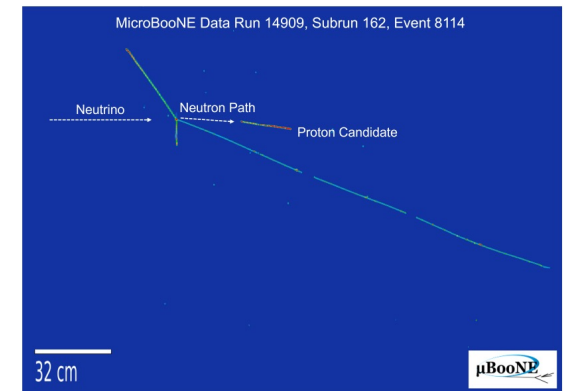
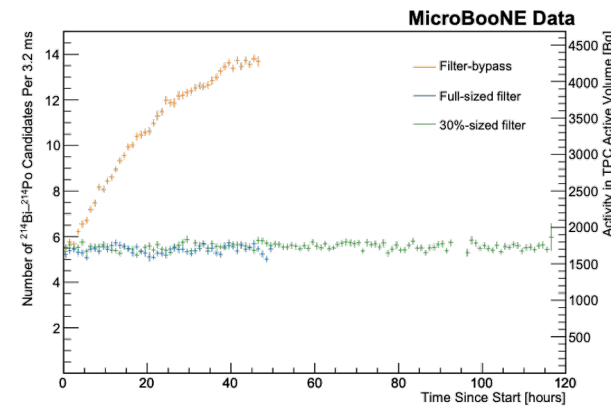
[Phys.Rev.D108,052010 \(2023\)](#)



reconstruction advancement

MeV-scale reconstruction: aids low-energy calorimetry

[arXiv:2203.10147, *JINST* **17** P01037 \(2022\)](#)



neutron identification

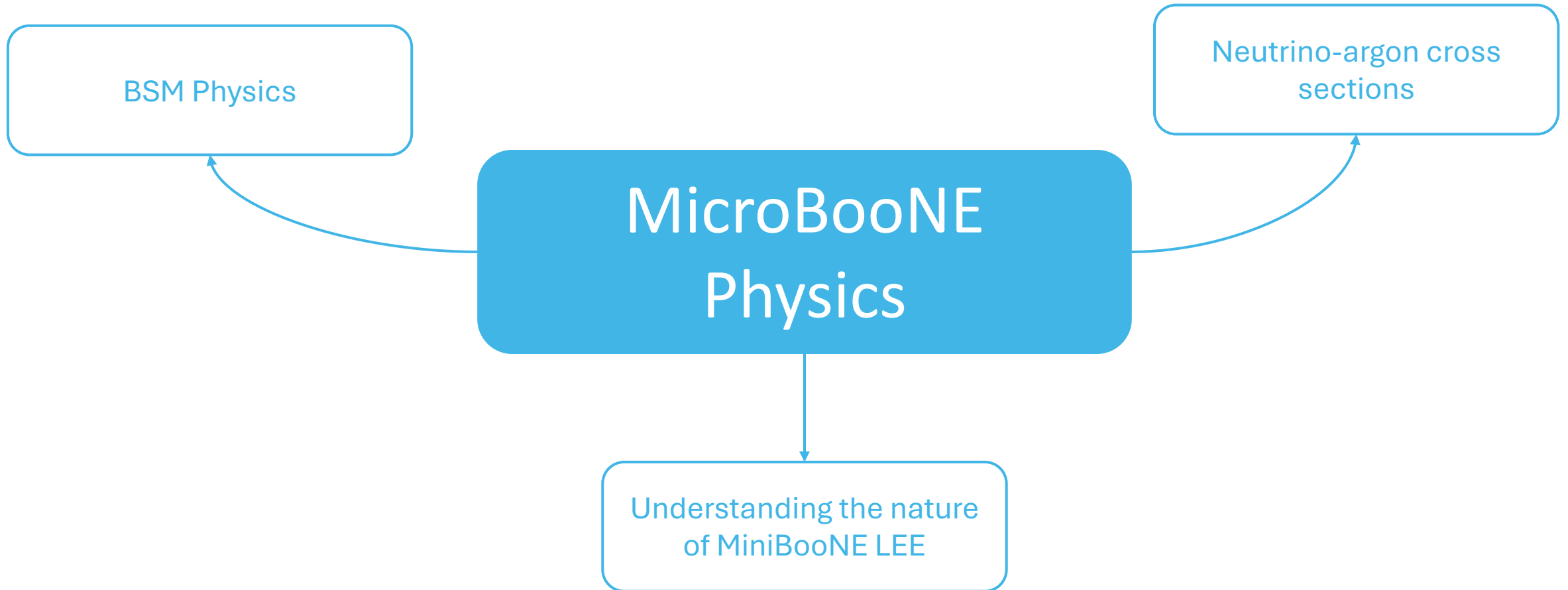
technique applicable to any

LArTPC

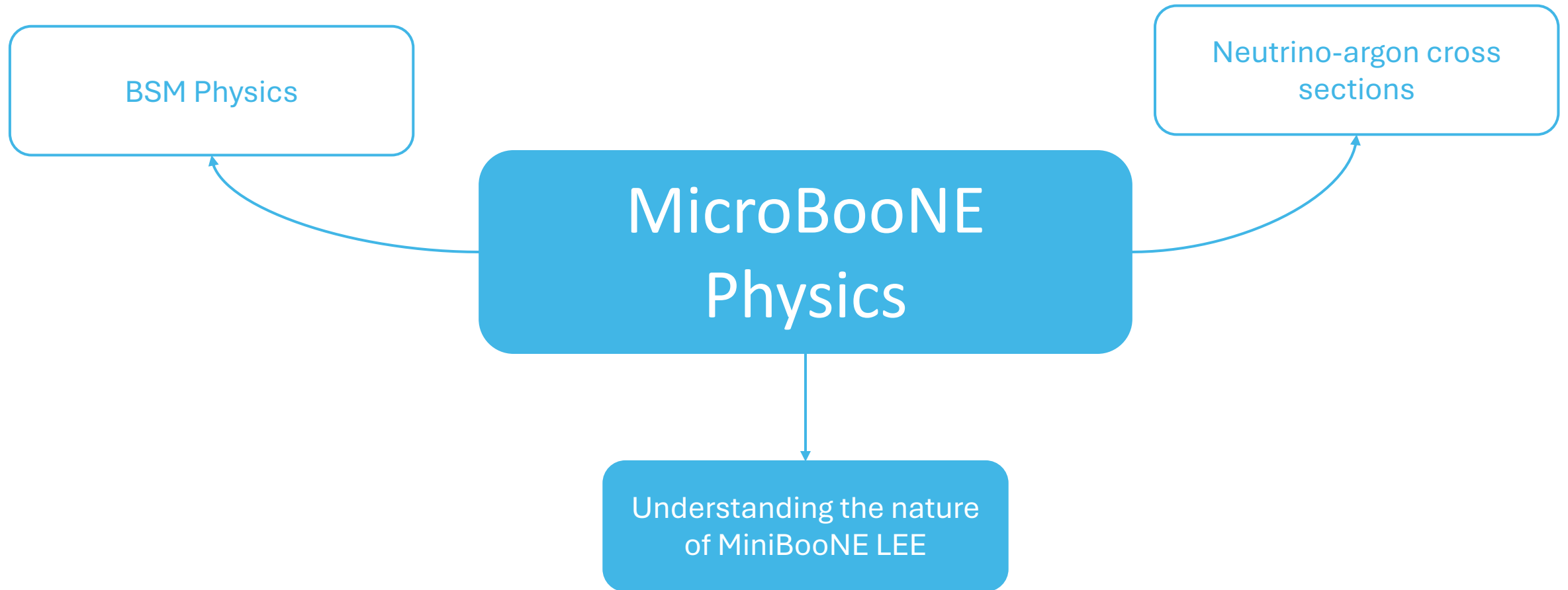
[Eur. Phys. J. C **84**, 1052 \(2024\)](#)

We have a history of developing physics analysis tools, and post-operation R&D studies are currently ongoing

Physics with MicroBooNE



Physics with MicroBooNE



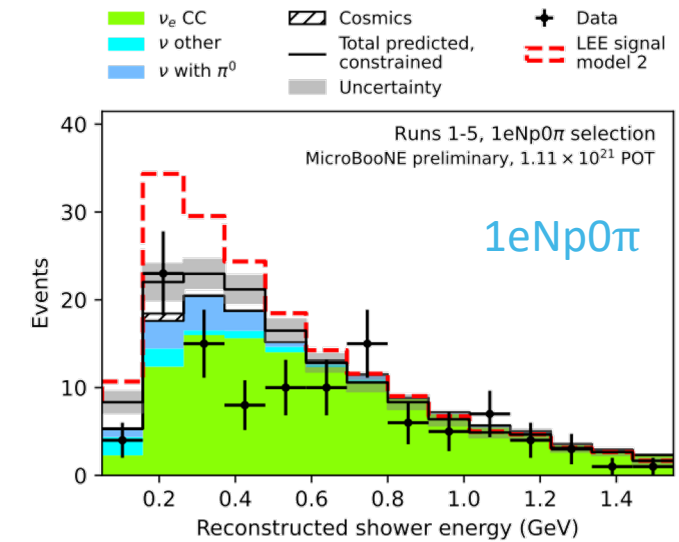
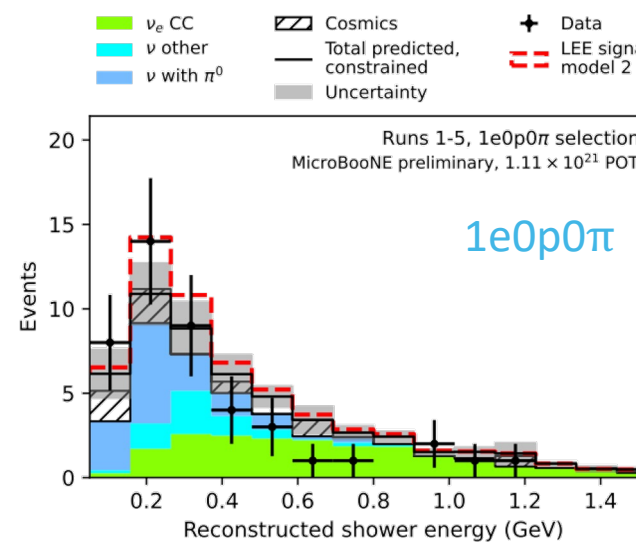
The MiniBooNE Low Energy Excess (LEE)

2022 results disfavoured an electron-like explanation for the LEE → Electron excess rejected at > 97% CL

([Phys. Rev. D105, 112004 \(2022\)](#), [Phys. Rev. Lett. 128, 241801 \(2022\)](#))

- New 2024 analysis uses **full MicroBooNE dataset: 1.11×10^{21} POT**
 - Uses CRT, new LEE model, represents LEE as a function of shower energy and angle

Excludes the ν_e interpretation of the MiniBooNE LEE at $\geq 99\%$ CL in all investigated variables (inc. electron angle and energy variables)

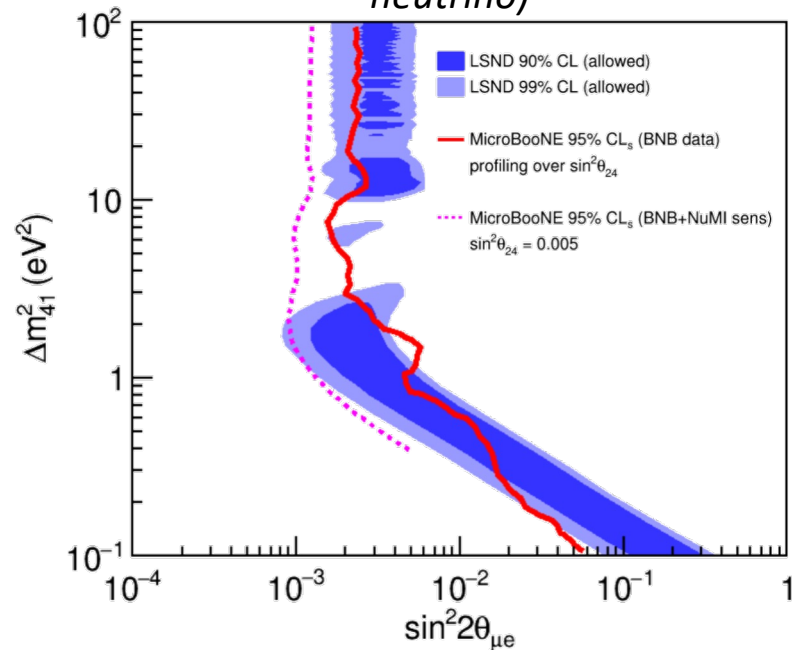


[MICROBOONE-NOTE-1127-PUB](#)

BSM as LEE exploration

3+1 Sterile Neutrinos

Excess may be due to oscillation to new neutrino flavour (sterile neutrino)

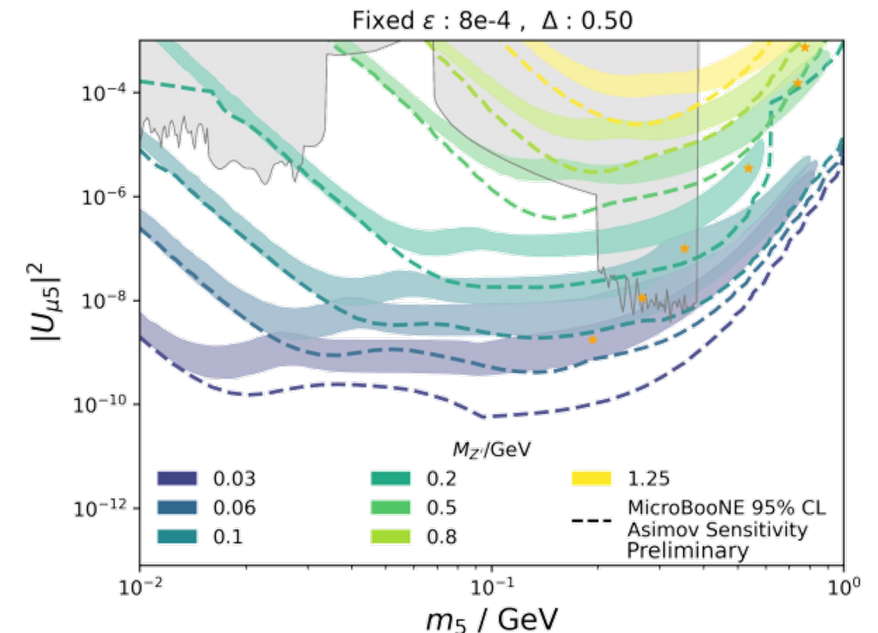


significantly improved sensitivity by combining BNB and NuMI data:
new analysis will be sensitive to more LSND parameter space

[MICROBOONE-NOTE-1116-PUB](#), [MICROBOONE-NOTE-1132-PUB](#)

Dark Sector e^+e^- Final States

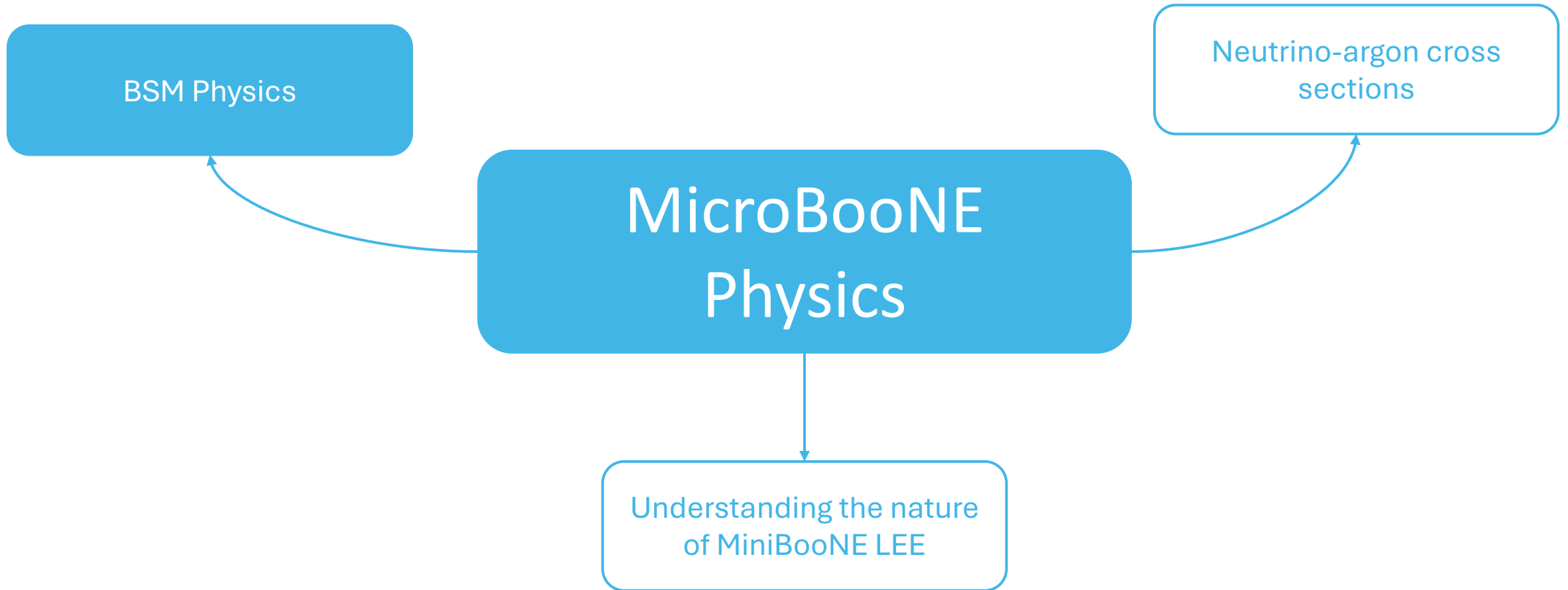
Dark sector neutrinos decaying into overlapping/asymmetric e^+e^- could lead to excess



substantial improvements in efficiency, exploring new dark sector parameter space

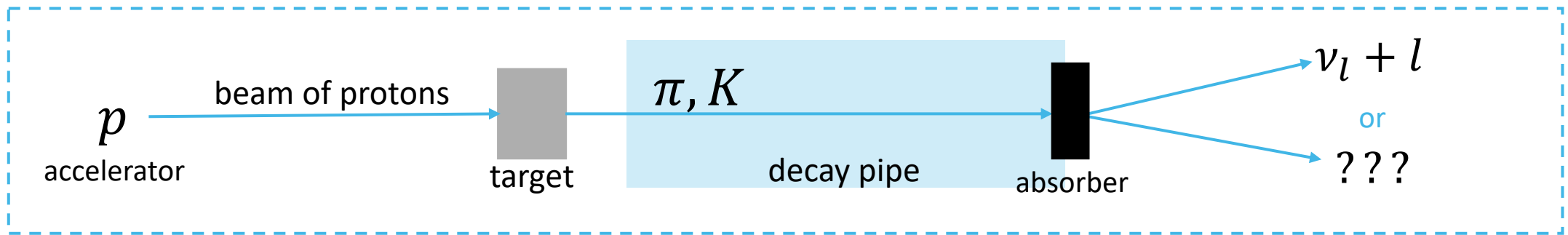
[MICROBOONE-NOTE-1124-PUB](#)

Physics with MicroBooNE



BSM: searches for new physics

- Beyond the Standard Model
- In a neutrino beamline, we produce many kaons and pions
 - These decay producing neutrinos, but could produce something else...



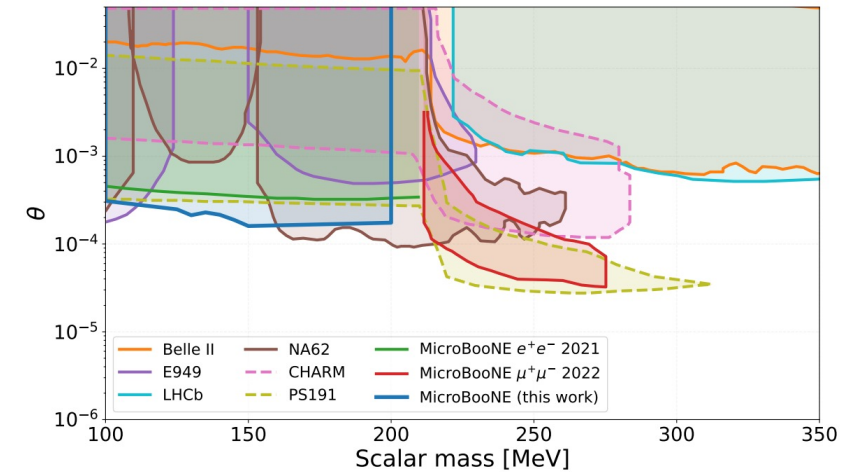
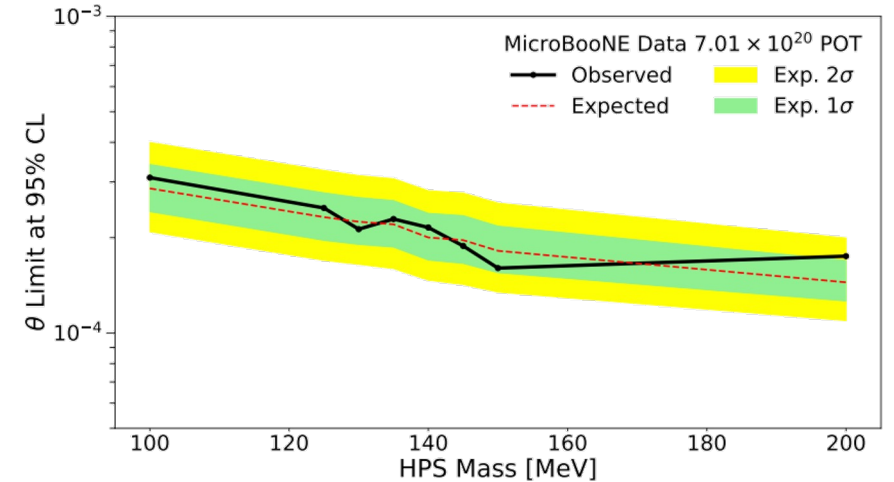
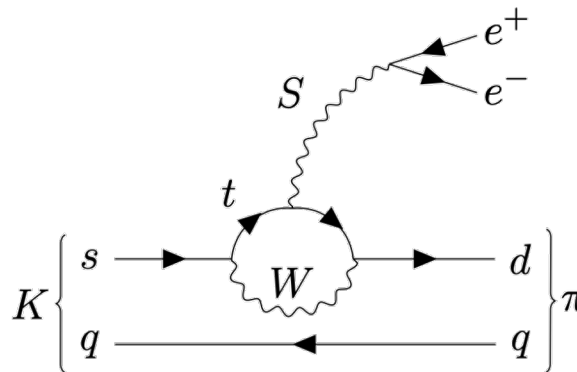
- MicroBooNE has **world leading limits in searches for new particles** in $\mathcal{O}(10 \text{ MeV}) - 300 \text{ MeV}$ range under several phenomenological models

BSM: searches for new physics

Higgs portal scalar (HPS) decays

- **Strongest limits to date** on mixing angle θ for new scalar particle, S , mixing with the Higgs field
 - $\theta < 2.48 \times 10^{-4}$ ($\theta < 1.60 \times 10^{-4}$) at the 95% confidence level at $m_S = 125$ MeV ($m_S = 150$ MeV)

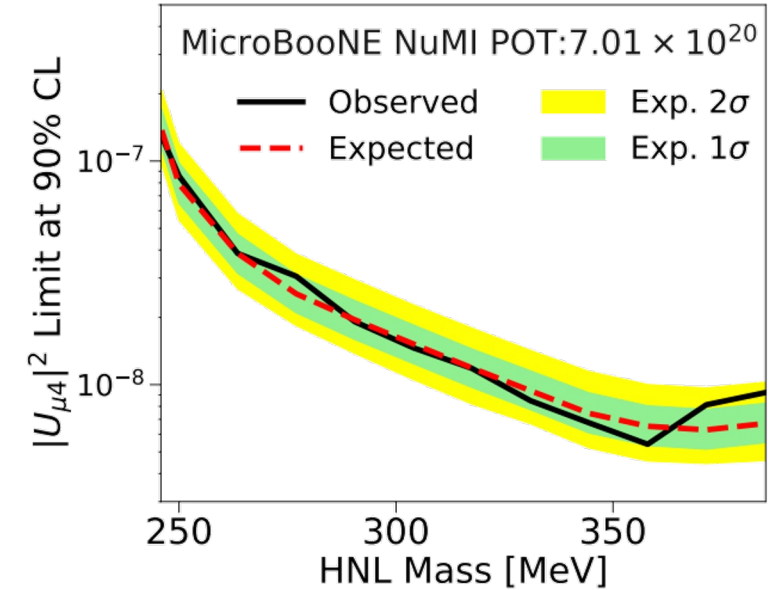
[MicroBooNE Public Note](#)



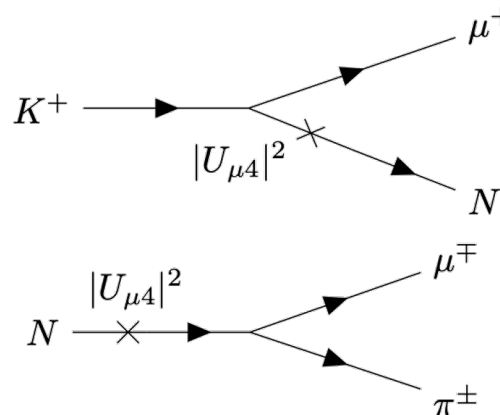
BSM: searches for new physics

Heavy neutral leptons (HNLs)

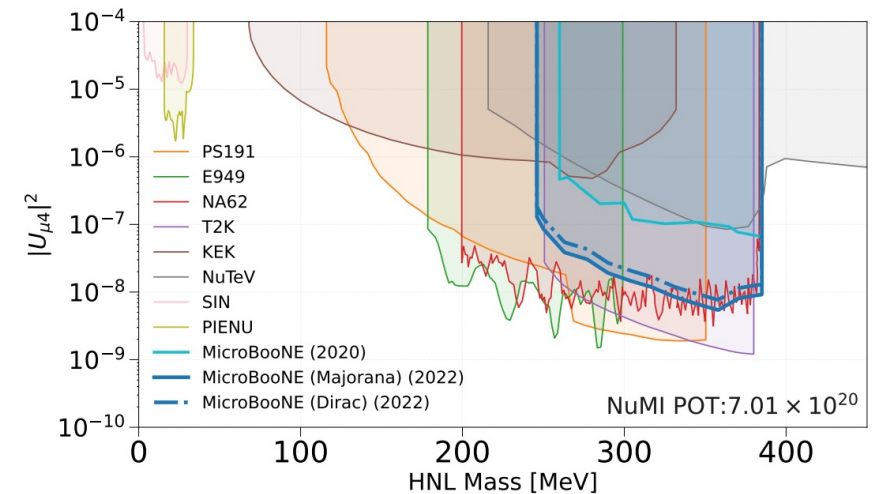
- Search for HNL decays to $\mu^\pm \pi^\mp$ pairs
 - order of magnitude improvement on previous MicroBooNE results: similar sensitivity to NA62



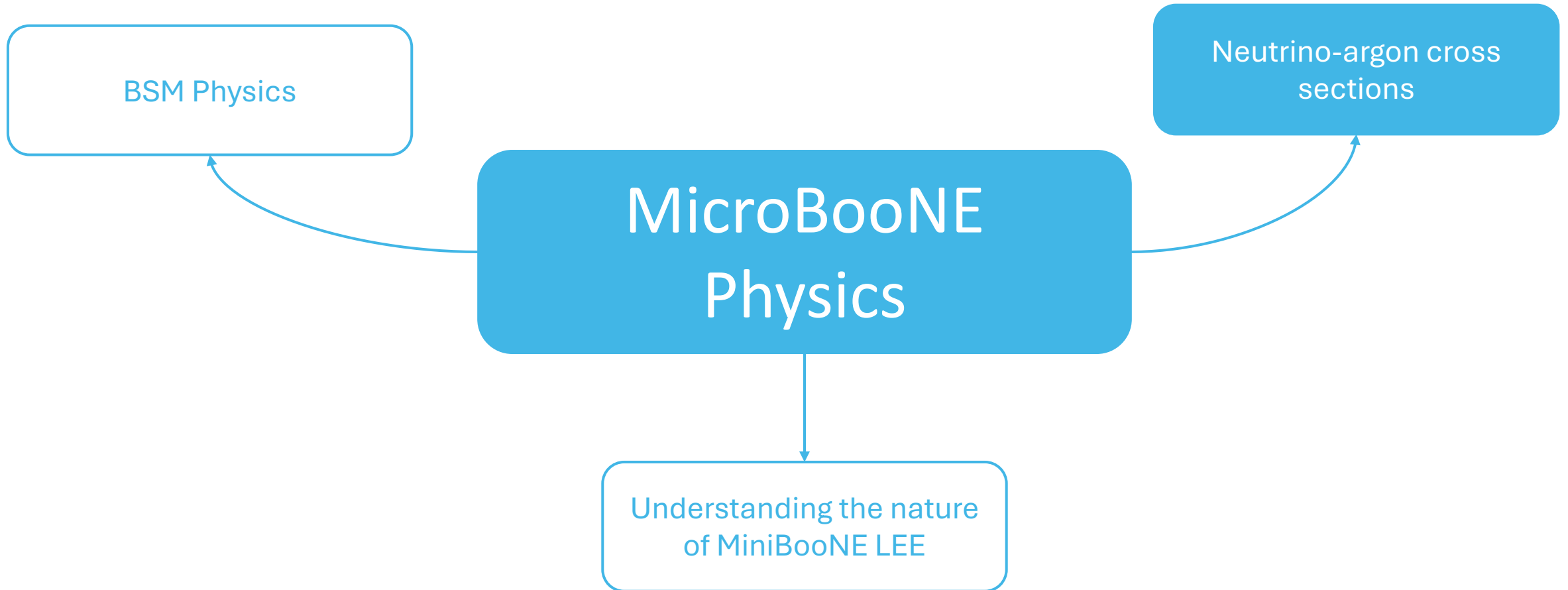
Majorana HNL mass (MeV)	Upper limit on mixing parameter $ U_{\mu 4} ^2$
246	12.9×10^{-8}
385	0.92×10^{-8}



[Phys. Rev. D **106**, 092006](#)

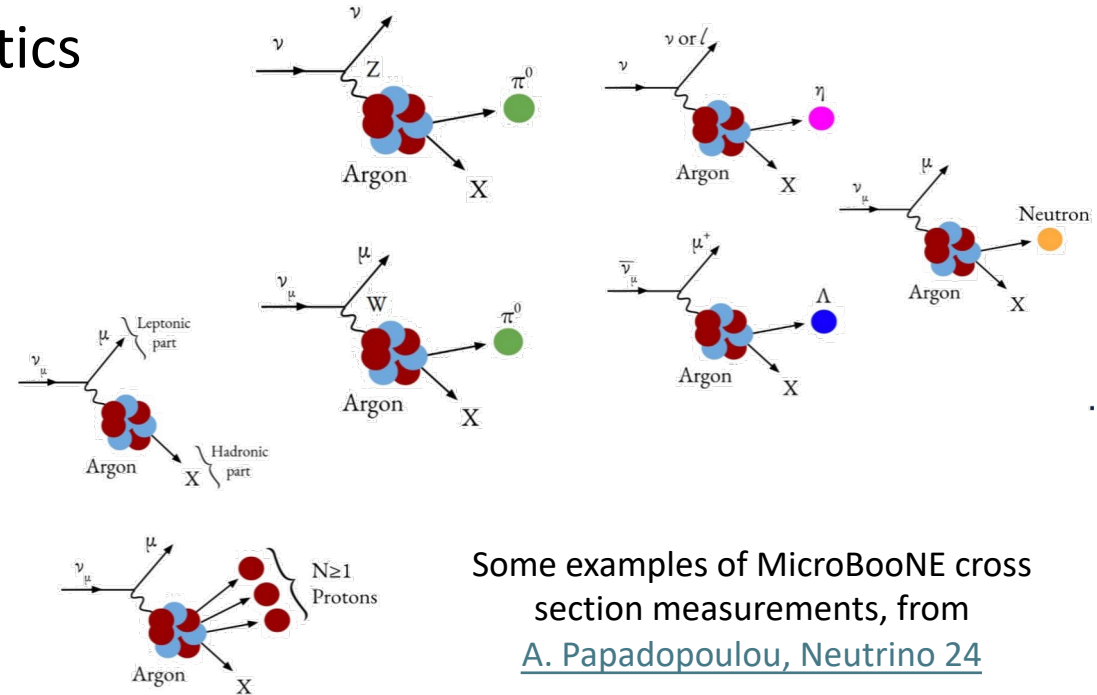


Physics with MicroBooNE



Cross sections

- MicroBooNE possesses a **large , well-understood neutrino-argon interaction dataset** after 5 years of data taking
 - Accurate energy reconstruction for kinematics
- **Over 20 ν -Ar** cross sections published
- Important to further our understanding of neutrino-argon interactions for future liquid argon experiments, such as **DUNE**

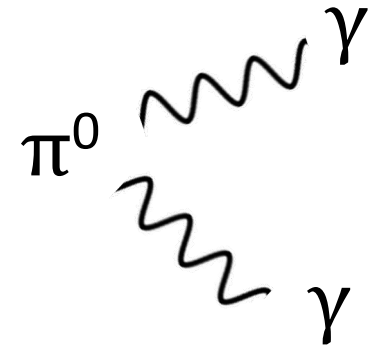


First $CC\pi^0/NC\pi^0$ differential cross sections

- π^0 are an **important background in ν_e searches**
 - A π^0 interaction produces **2 showers**, but if 1 is missed, it can **look like a ν_e interaction**

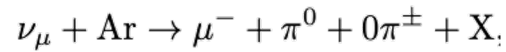
This could be because...

- energy is too low (less common in MicroBooNE: low thresholds)
- one shower has left the detector
- showers may be on top of each other



First $CC\pi^0/NC\pi^0$ differential cross sections

$CC\pi^0$

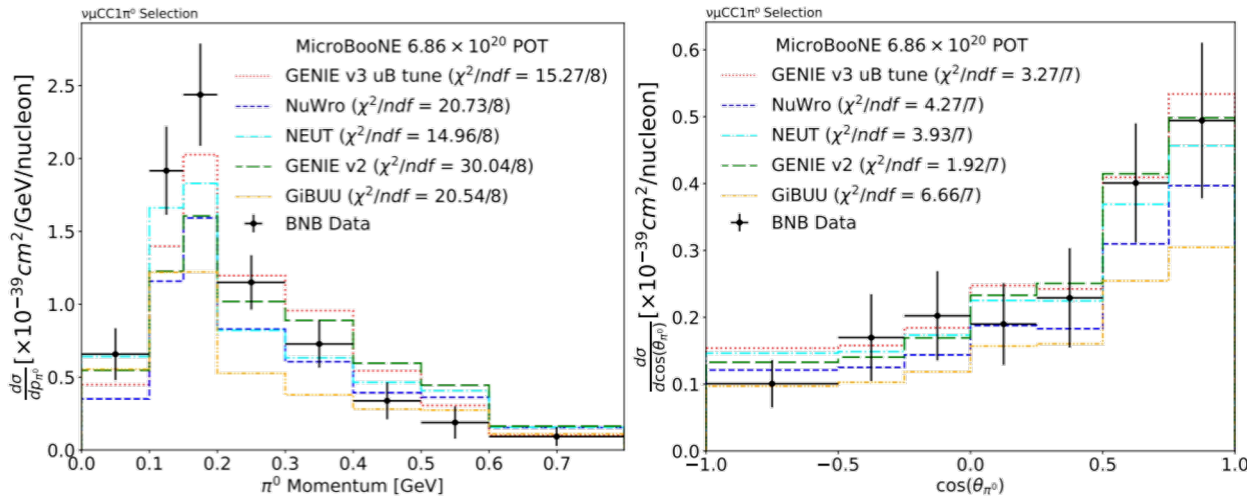


$NC\pi^0$

0 protons

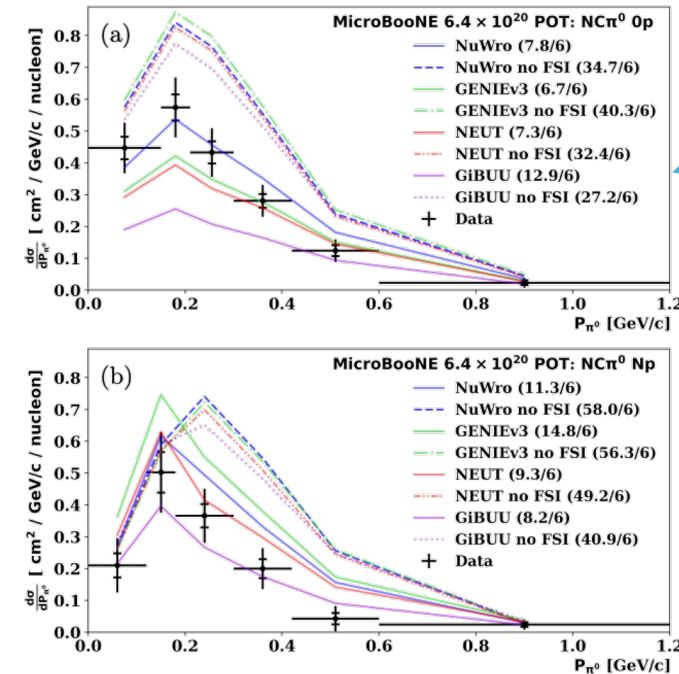


1 proton



Differential cross sections in muon momentum, neutrino-muon scattering angle, and muon-pion opening angle

[arXiv:2404.09949](https://arxiv.org/abs/2404.09949)

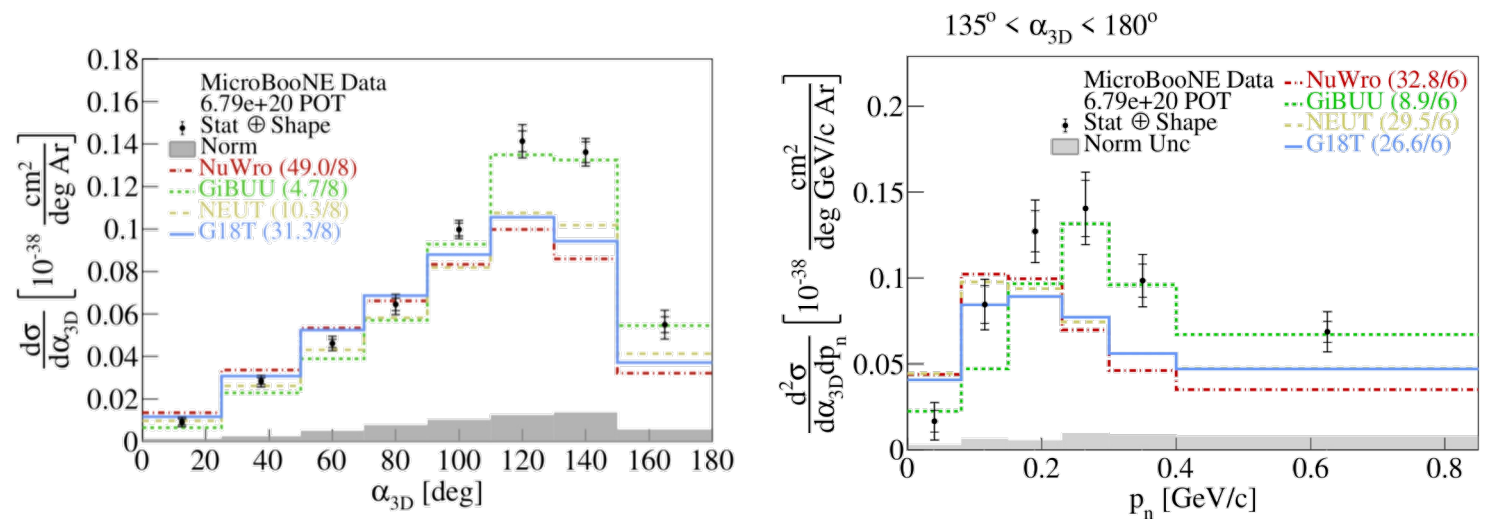
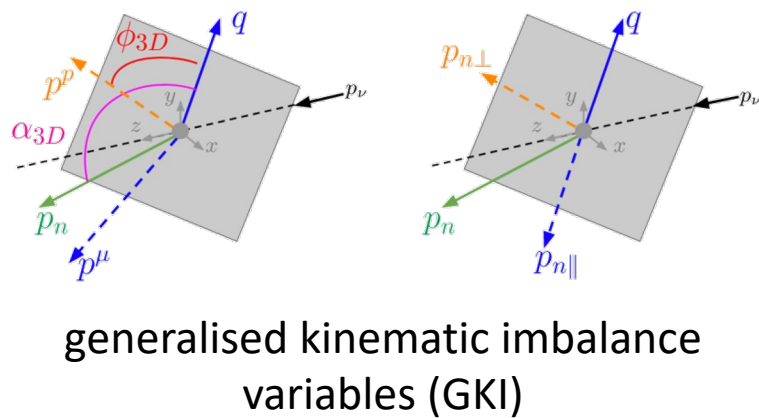


Double-differential cross section in $\cos(\theta_{\pi^0})$ and P_{π^0} also published

[arXiv:2404.10948](https://arxiv.org/abs/2404.10948)

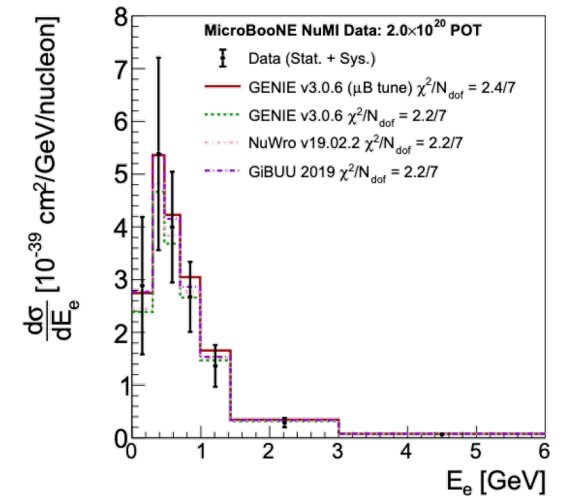
CC1p cross sections using kinematic imbalance

- first flux-integrated single and double-differential cross section measurements in these variables using ν_μ -Ar CC1p0 π interactions



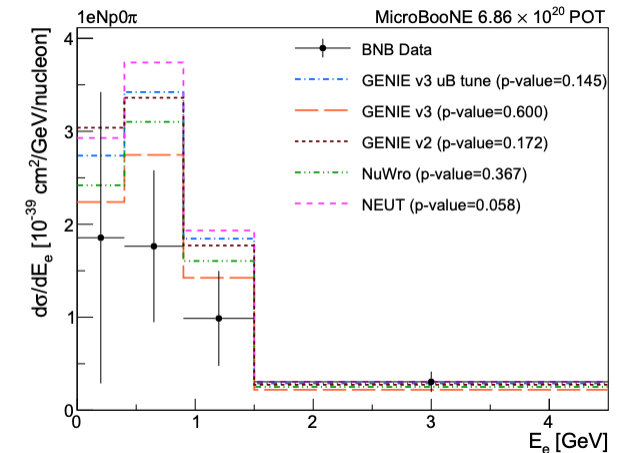
$\nu_e/\bar{\nu}_e$ cross sections

- Due to being off-axis, NuMI provides MicroBooNE a **higher flux of ν_e and $\bar{\nu}_e$**
 - Neutrino cross sections probe nuclear effects, needed for DUNE oscillation experiments
- **Inclusive** measurements of $\nu_e + \bar{\nu}_e$, performed; **exclusive ν_e and $\bar{\nu}_e$** measurements in progress
- BNB has smaller ν_e content, but exclusive measurements are possible!
- Currently measurements of $\nu_e/\bar{\nu}_e$ cross sections using the **full MicroBooNE dataset** are in progress



Unfolded inclusive ν_e and $\bar{\nu}_e$ charged current differential cross section

[Phys. Rev. D 105, L051102 \(2022\)](#)



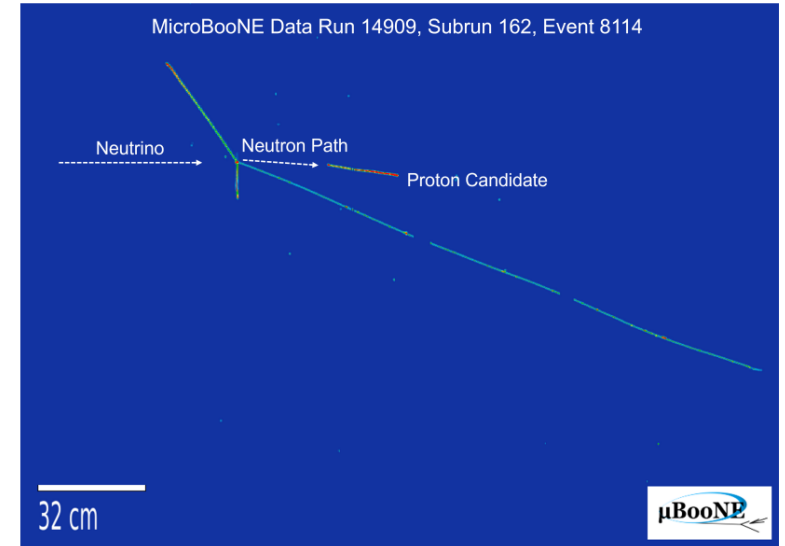
Unfolded differential exclusive ν_e cross section (1eNp0 π)

[Phys. Rev. D 106, L051102 \(2022\)](#)

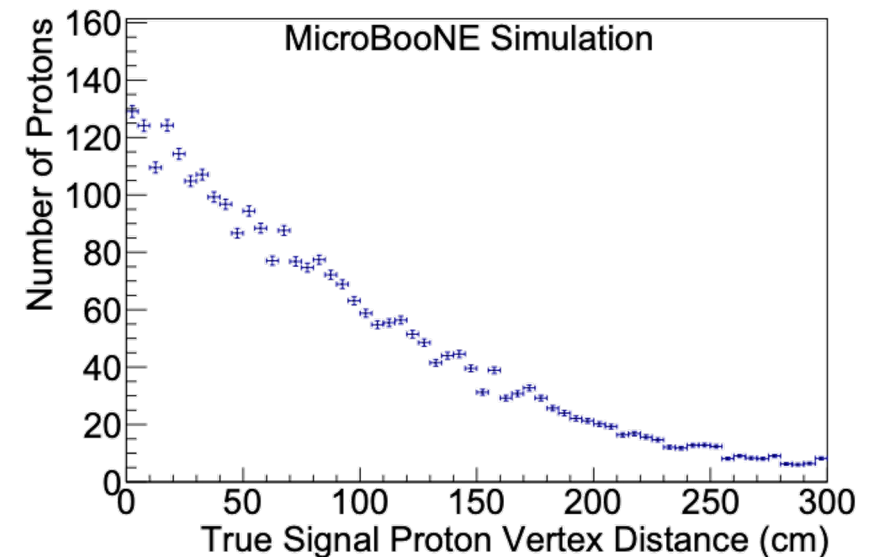
Neutron identification

Newest paper at time of making these slides!

- Neutrons found using **secondary protons** separated from neutrino vertex
 - Applicable to any LArTPC
 - **Measures neutron production** from neutrinos; could provide statistical **separation between neutrinos and antineutrinos**
- Prospects for efficiency improvement



[Eur. Phys. J. C **84**, 1052 \(2024\)](#)



MicroBooNE's accomplishments

2017 ↓ 2018 ↓ 2019 ↓ 2020 ↓ 2021 ↓ 2022 ↓ 2023 ↓ 2024 ↓

70 papers
(and counting!)

- Demonstration of neutron identification in neutrino interactions in the MicroBooNE liquid argon time projection chamber
- Improving neutrino energy estimation of charged-current interaction events with recurrent neural networks in MicroBooNE
- First double-differential cross section measurement of neutral-current π^0 production in neutrino-argon scattering in the MicroBooNE detector
- Measurement of the differential cross section for neutral pion production in charged-current muon neutrino interactions on argon with the MicroBooNE detector
- Measurement of double-differential cross sections for mesonless charged-current muon neutrino interactions on argon with final-state protons using the MicroBooNE detector
- Inclusive cross section measurements in final states with and without protons for charged-current ν_μ -Ar scattering in MicroBooNE
- First simultaneous measurement of differential muon-neutrino charged-current cross sections on argon for final states with and without protons using MicroBooNE data
- First search for dark-radiant processes using the MicroBooNE detector
- Search for heavy neutral leptons in electron-positron and neutral-pion final states with the MicroBooNE detector
- Measurement of nuclear effects in neutrino-argon interactions using generalised kinetic imbalance variables with the MicroBooNE detector
- First demonstration for a LArTPC-based search for intranuclear neutron-antineutron transitions and annihilation in ^{40}Ar using the MicroBooNE detector
- Measurement of triple-differential inclusive muon-neutrino charged-current cross section on argon with the MicroBooNE detector
- Measurement of ambient radon daughter decay rates and energy spectra in liquid argon using the MicroBooNE detector
- First measurement of η production in neutrino interactions on argon with MicroBooNE
- First demonstration of $O(1\text{ ns})$ timing resolution in the MicroBooNE liquid argon time projection chamber
- Multi-differential cross section measurements of muon-neutrino-argon quasielastic-like reactions with the MicroBooNE detector
- First double-differential measurement of kinematic imbalance in neutrino interactions with the MicroBooNE detector
- First measurement of quasi-elastic Λ baryon production in muon antineutrino interactions in the MicroBooNE detector
- First measurement of differential cross sections for muon neutrino charged current interactions on argon with a two-proton final state in the MicroBooNE detector
- First constraints on light sterile neutrino oscillations from combined appearance and disappearance searches with the MicroBooNE detector
- Differential cross section measurements of charged current ν_e interactions without final-state pions in MicroBooNE
- Search for long-lived heavy neutral leptons and Higgs portal scalars decaying in the MicroBooNE detector
- Measurement of neutral current single π^0 production on argon with the MicroBooNE detector
- Observation of radon mitigation in MicroBooNE by a liquid argon filtration system
- Cosmic ray muon clustering for the MicroBooNE liquid argon time projection chamber using sMask-RCNN
- Novel approach for evaluating detector-related uncertainties in a LArTPC using MicroBooNE data
- First measurement of energy-dependent inclusive muon neutrino charged-current cross sections on argon with the MicroBooNE detector
- Search for an anomalous excess of inclusive charged-current ν_e interactions without pions in the final state with the MicroBooNE experiment
- Search for an anomalous excess of charged-current quasi-elastic ν_e interactions with the MicroBooNE experiment using deep-learning-based reconstruction
- New theory-driven GENIE tune for MicroBooNE
- Search for an anomalous excess of inclusive charged-current ν_e interactions in the MicroBooNE experiment using Wire-Cell reconstruction
- Search for an excess of electron neutrino interactions in MicroBooNE using multiple final state topologies
- Wire-Cell 3D pattern recognition techniques for neutrino event reconstruction in large LArTPCs
- Electromagnetic shower reconstruction and energy validation with Michel electrons and π^0 samples for the deep-learning-based analyses in MicroBooNE
- Search for neutrino-induced NC Δ radiative decay in MicroBooNE and a first test of the MiniBooNE low-energy excess under a single-photon hypothesis
- First measurement of inclusive electron-neutrino and antineutrino charged current differential cross sections in charged lepton energy on argon in MicroBooNE
- Calorimetric classification of track-like signatures in liquid argon TPCs using MicroBooNE data
- Search for a Higgs Portal Scalar Decaying to Electron-Positron Pairs in the MicroBooNE Detector
- Measurement of the Longitudinal Diffusion of Ionization Electrons in the Detector
- Cosmic Ray Background Rejection with Wire-Cell LAr TPC Event Reconstruction in the MicroBooNE Detector
- Measurement of the Flux-Averaged Inclusive Charged Current Electron Neutrino and Antineutrino Cross Section on Argon using the NuMI Beam in MicroBooNE
- Measurement of the Atmospheric Muon Rate with the MicroBooNE Liquid Argon TPC
- Semantic Segmentation with a Sparse Convolutional Neural Network for Event Reconstruction in MicroBooNE
- High-performance Generic Neutrino Detection in a LAr TPC near the Earth's Surface with the MicroBooNE Detector
- Neutrino Event Selection in the MicroBooNE LAr TPC using Wire-Cell 3D Imaging, Clustering, and Charge-Light Matching
- A Convolutional Neural Network for Multiple Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
- Vertex-Finding and Reconstruction of Contained Two-track Neutrino Events in the MicroBooNE Detector
- The Continuous Readout Stream of the MicroBooNE Liquid Argon Time Projection Chamber for Detection of Supernova Burst Neutrinos
- Measurement of Differential Cross Sections for Muon Neutrino CC Interactions on Argon with Protons and No Pions in the Final State
- Measurement of Space Charge Effects in the MicroBooNE LAr TPC Using Cosmic Muons
- First Measurement of Differential Charged Current Quasi-Elastic-Like Muon Neutrino Argon Scattering Cross Sections with the MicroBooNE Detector
- Search for heavy neutral leptons decaying into muon-pion pairs in the MicroBooNE detector
- Reconstruction and Measurement of $O(100)$ MeV Electromagnetic Activity from Neutral Pion to Gamma Gamma Decays in the MicroBooNE LArTPC
- A Method to Determine the Electric Field of Liquid Argon Time Projection Chambers Using a UV Laser System and its Application in MicroBooNE
- Calibration of the Charge and Energy Response of the MicroBooNE Liquid Argon Time Projection Chamber Using Muons and Protons
- First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at Enu ~ 0.8 GeV with the MicroBooNE Detector
- Design and Construction of the MicroBooNE Cosmic Ray Tagger System
- Rejecting Cosmic Background for Exclusive Neutrino Interaction Studies with Liquid Argon TPCs: A Case Study with the MicroBooNE Detector
- First Measurement of Muon Neutrino Charged Current Neutral Pion Production on Argon with the MicroBooNE detector
- A Deep Neural Network for Pixel-Level Electromagnetic Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
- Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions
- Ionization Electron Signal Processing in Single Phase LArTPCs II: Data/Simulation Comparison and Performance in MicroBooNE
- Ionization Electron Signal Processing in Single Phase LArTPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation
- The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector
- Measurement of Cosmic Ray Reconstruction Efficiencies in the MicroBooNE LAr TPC Using a Small External Cosmic Ray Counter
- Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC
- Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LAr TPC
- Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved Model of Multiple Coulomb Scattering
- Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber
- Design and Construction of the MicroBooNE Detector



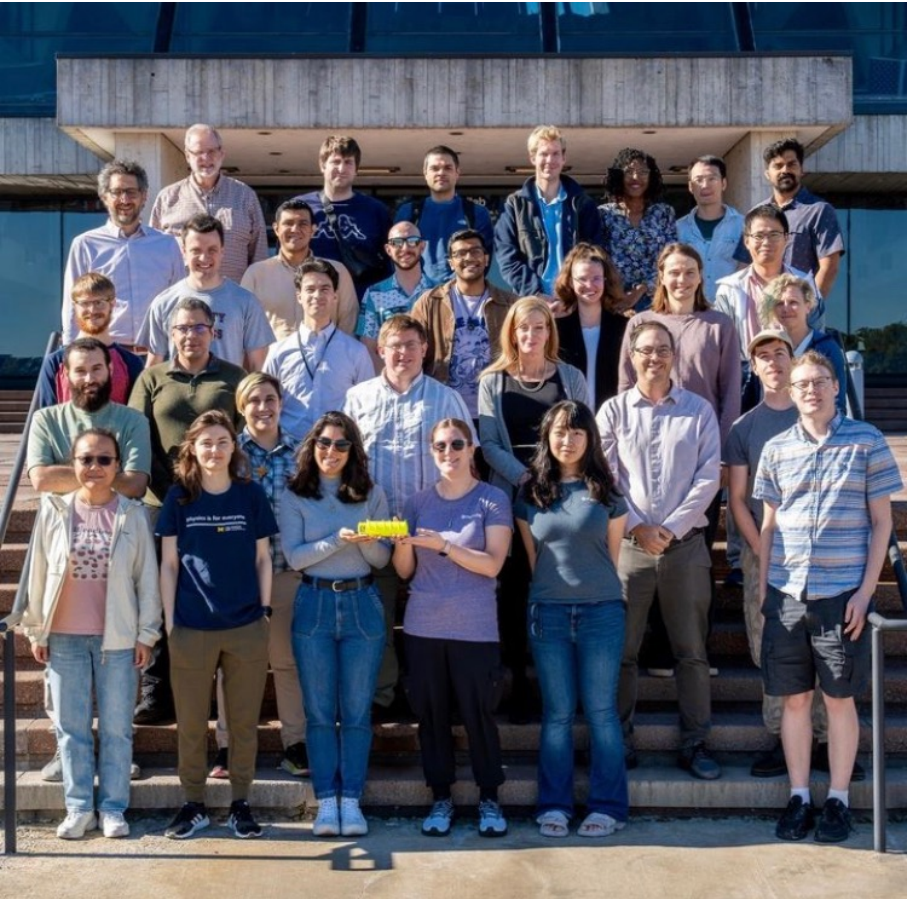
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Summary

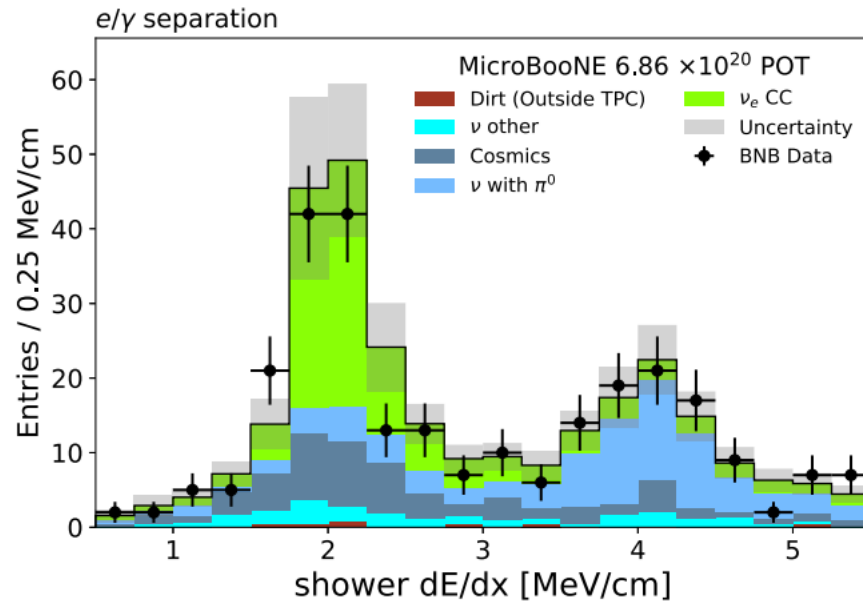
- MicroBooNE is a LArTPC neutrino detector based at Fermilab
 - Large, well-understood neutrino-argon interaction dataset
- We are a very active collaboration with recent results in several areas of physics!
- Further analyses aim to utilise the full dataset, incorporate NuMI and BNB data together, and implement updated NuMI flux
- The detector is currently in a decommissioning R&D phase, results to come soon

Thank you!



Backup

Electron-photon separation



“ Two key features are used to achieve electron-photon separation: the calorimetric measurement of dE/dx at the start of the shower and the displacement of the electromagnetic shower’s start position from the primary vertex in neutrino interactions with hadronic activity. To evaluate dE/dx , reconstructed showers are fit using a Kalman filter [59] based procedure to identify the main shower trunk and reject hits that are transversely or longitudinally displaced. ”

[Phys. Rev. D105, 112004 \(2022\)](#)

MicroBooNE's cross section papers

Already Public Results



CC inclusive

- 1D ν_{μ} CC inclusive @ BNB, [Phys. Rev. Lett. 123, 131801](#)
- 1D ν_{μ} CC E _{ν} @ BNB, [Phys. Rev. Lett. 128, 151801](#)
- 3D CC E _{ν} @ BNB, [arXiv:2307.06413](#)
- 1D ν_e CC inclusive @ NuMI, [Phys. Rev. D104, 052002](#)
[Phys. Rev. D105, L051102](#)
- 2D ν_{μ} CC0pNp inclusive @ BNB, [arXiv:2402.19216](#), [arXiv:2402.19281](#)

Pion production

- ν_{μ} NC π^0 @ BNB, [Phys. Rev. D 107, 012004](#)
- 2D ν_{μ} NC π^0 @ BNB, [arXiv:2404.10948](#)
- ν_{μ} CC π^0 @ BNB, [arXiv:2404.09949](#)

CC0 π

- 1D ν_e CCNp0 π @ BNB, [Phys. Rev. D 106, L051102](#)
- 1D & 2D ν_{μ} CC1p0 π transverse imbalance @ BNB, [Phys. Rev. Lett. 131, 101802](#)
[Phys. Rev. D 108, 053002](#)
- 1D & 2D ν_{μ} CC1p0 π generalized imbalance @ BNB, [Phys. Rev. D 109, 092007](#)
- 1D ν_{μ} CC1p0 π @ BNB, [Phys. Rev. Lett. 125, 201803](#)
- 1D ν_{μ} CC2p @ BNB, [arXiv:2211.03734](#)
- 1D ν_{μ} CCNp0 π @ BNB, [Phys. Rev. D102, 112013](#)
- 2D ν_{μ} CCNp0 π @ BNB, [arXiv:2403.19574](#)

Rare channels & novel identification techniques

- η production @ BNB, [Phys. Rev. Lett. 132, 151801](#)
- Λ production @ NuMI, [Phys. Rev. Lett. 130, 231802](#)
- Neutron identification, [arXiv:2406.10583](#)

28

A. Papadopoulou, Neutrino 24

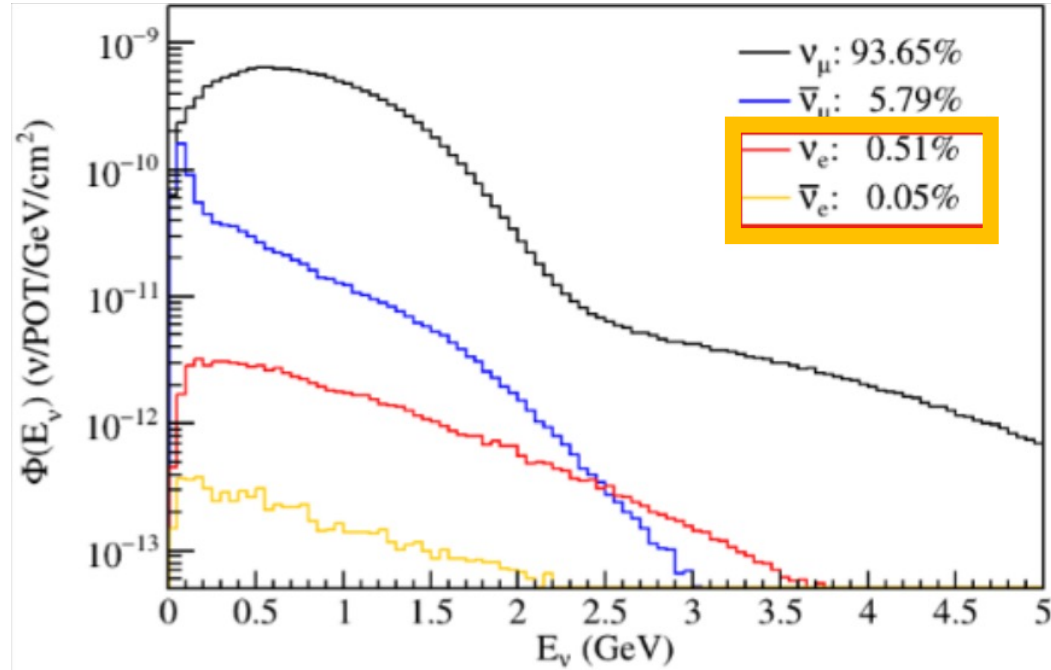


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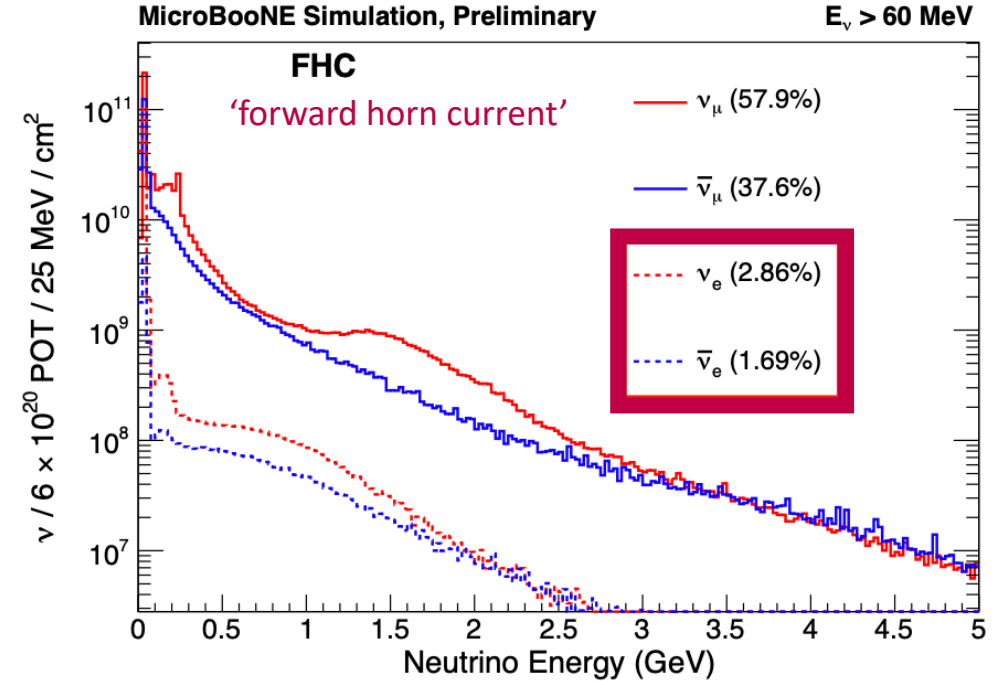
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28

Beam fluxes

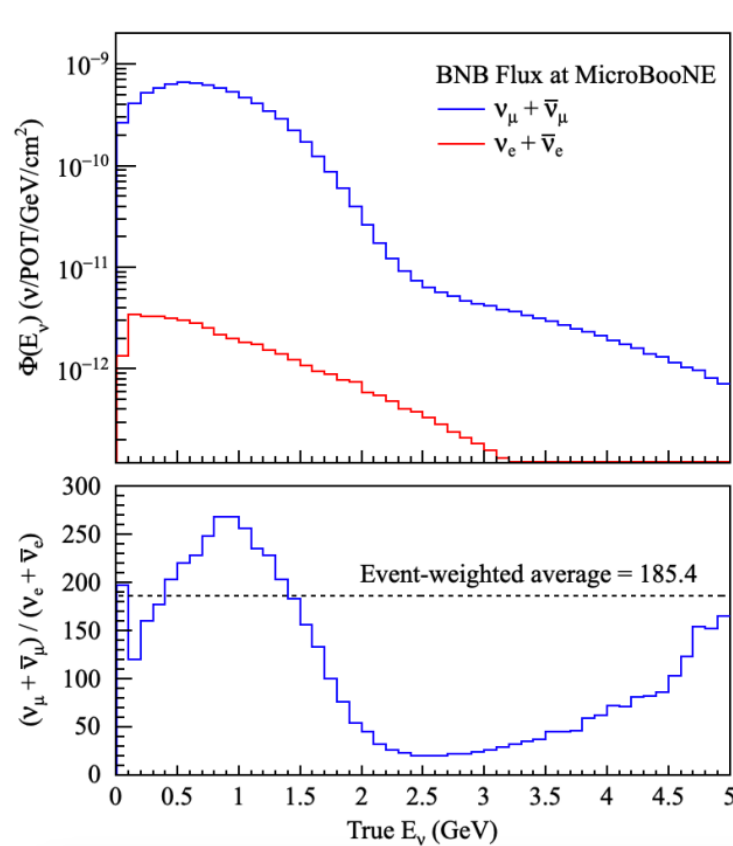


BNB

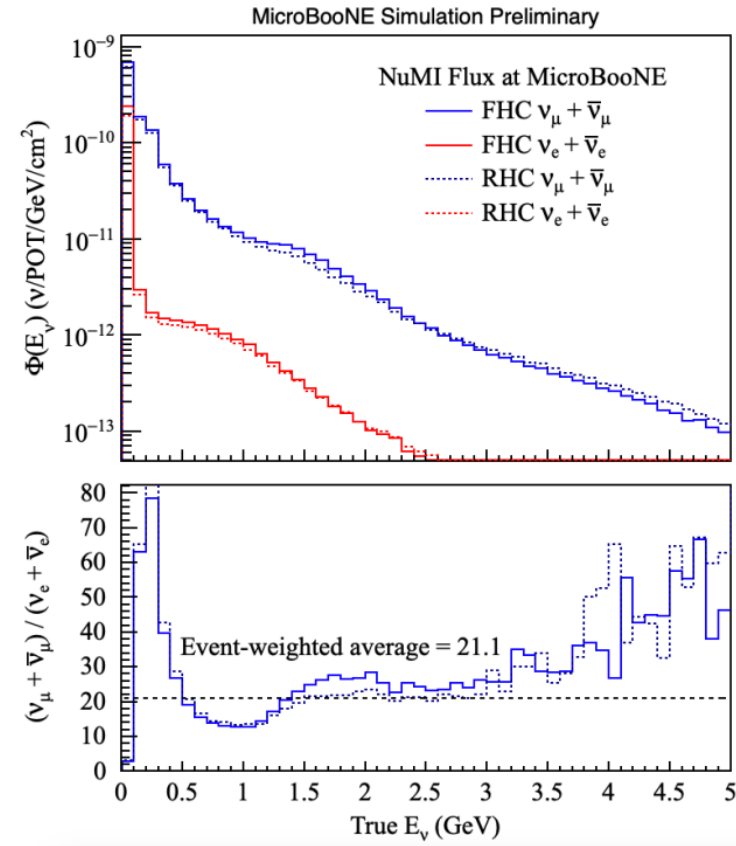


NuMI

Beam fluxes



(a) BNB flux



(b) NuMI flux

[MICROBOONE-NOTE-1132-PUB](#)