Recent results from MicroBooNE

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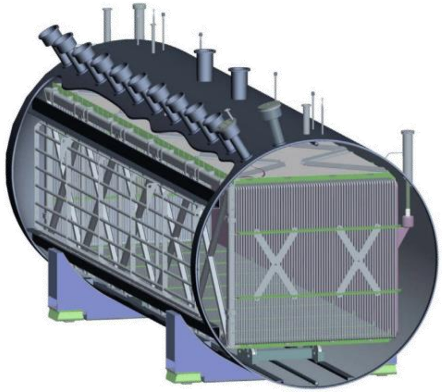
(on behalf of the MicroBooNE Collaboration)
University of Edinburgh
23rd October 2024

μBooNE

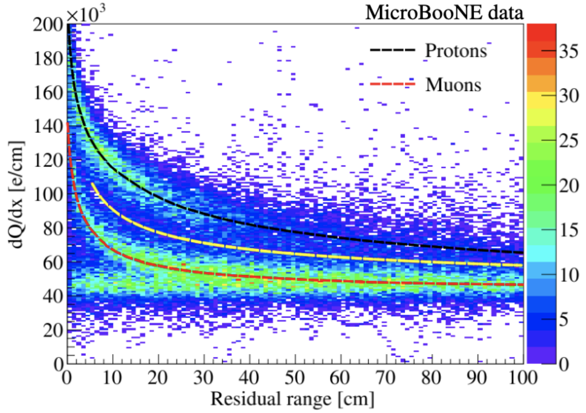
THE UNIVERSITY of EDINBURGH

Outline

- The MicroBooNE detector



- Analysis techniques

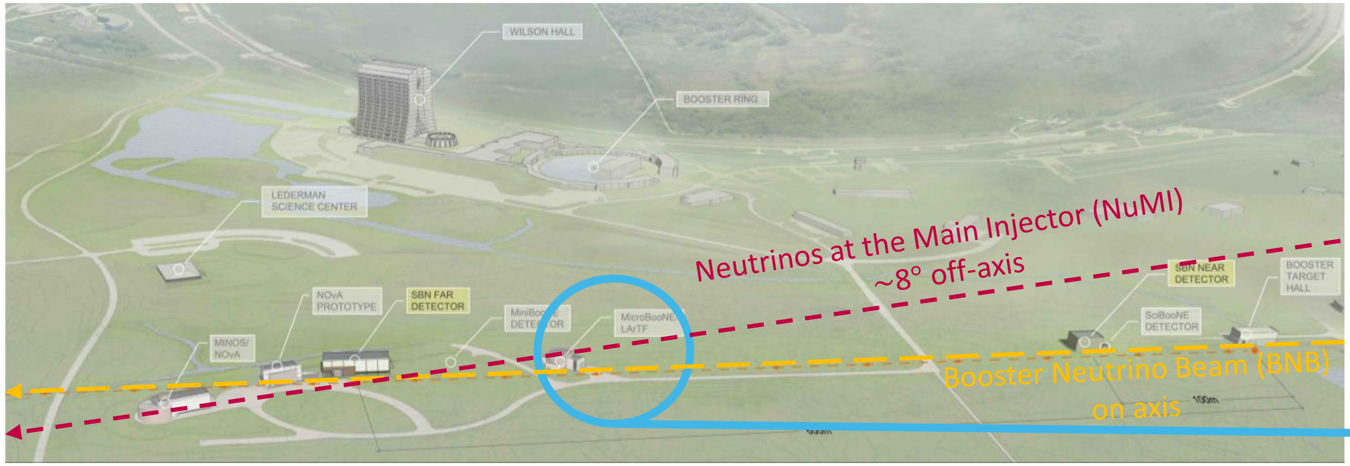


- Physics at MicroBooNE
    - MiniBooNE LEE
    - BSM Searches
    - Cross sections

- Future analyses

The MicroBooNE Detector

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

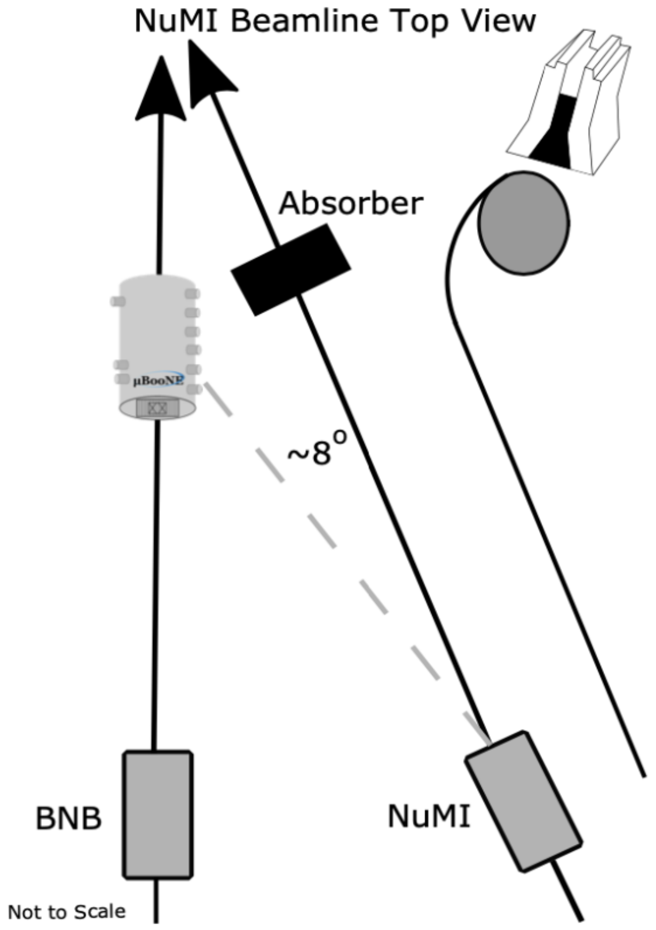


MicroBooNE
470 m from BNB target
~680 m from NuMI target

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

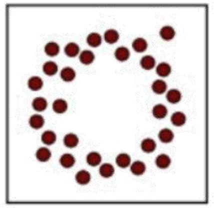
One detector, two beams

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

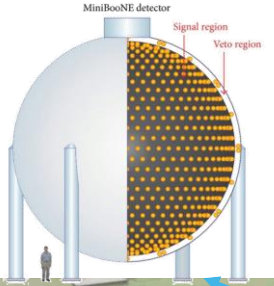


The MiniBooNE Low Energy Excess (LEE)

Cherenkov signal for electron or photon



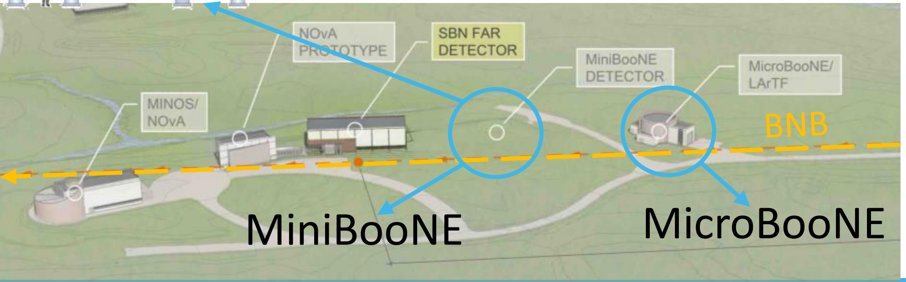
e/γ



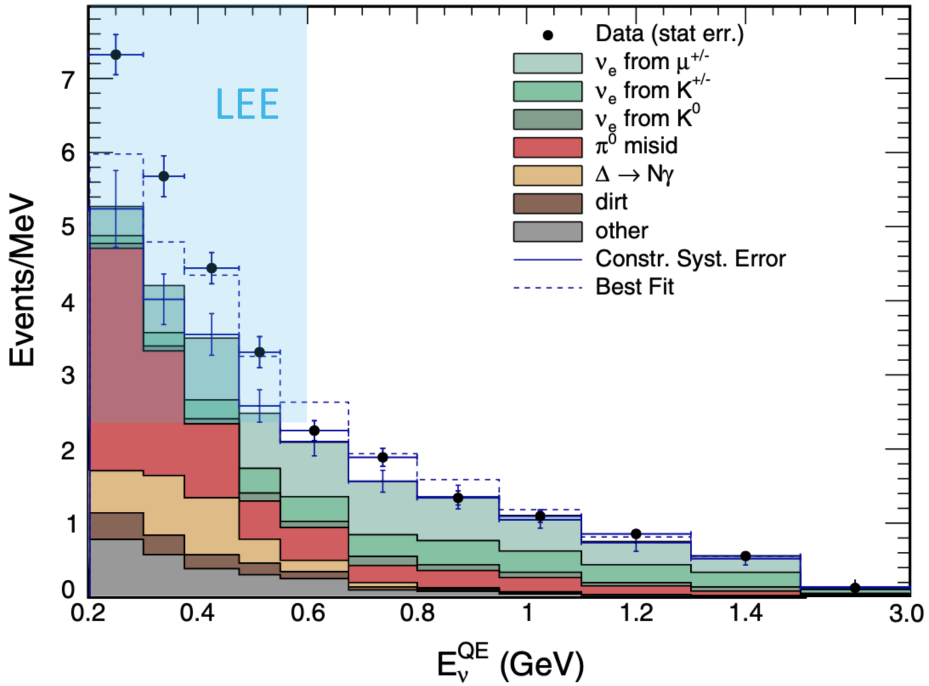
- One of MicroBooNE's investigation goals
- The **Mini Boo**ster **N**eutrino **E**xperiment saw a **4.8σ excess** of electron neutrino-like events at low energies compared to prediction
- 3.8σ excess of $\overline{\nu_e}$ seen earlier by Liquid Scintillator Neutrino Detector (LSND)
  - photon or electron events?
  - something else- *new physics*?

sterile neutrinos?
hypothetical neutrino flavour, only interact via gravity

dark sector?
hypothetical particles, possible DM candidates



Phys. Rev. D 103, 052002



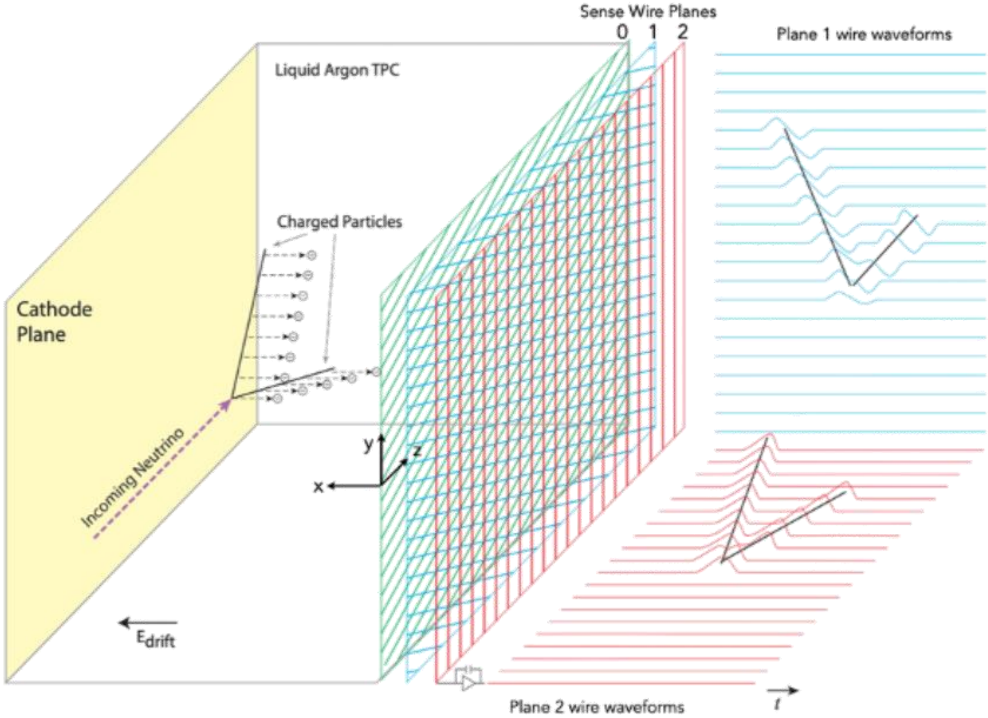
MiniBooNE and LSND could not distinguish between electrons and photons, **but a LArTPC can!**

LArTPCs

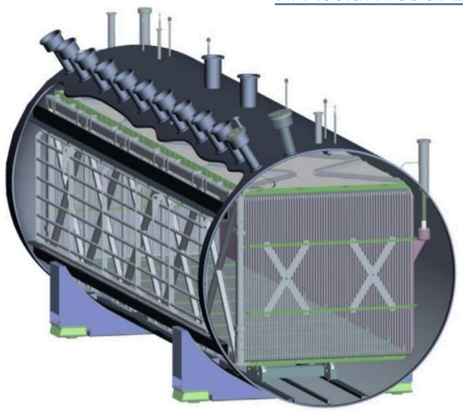
DUNE will use this technology!

- 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° , -60°), 3 mm spacing, for charge collection
  - 32 PMTs to detect scintillation photons

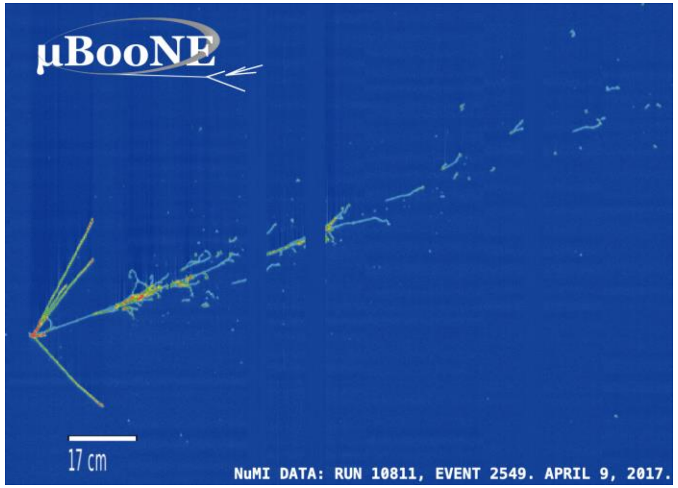


Operational principle of the MicroBooNE LArTPC
R. Acciarri *et al* 2017 *JINST* **12** P02017

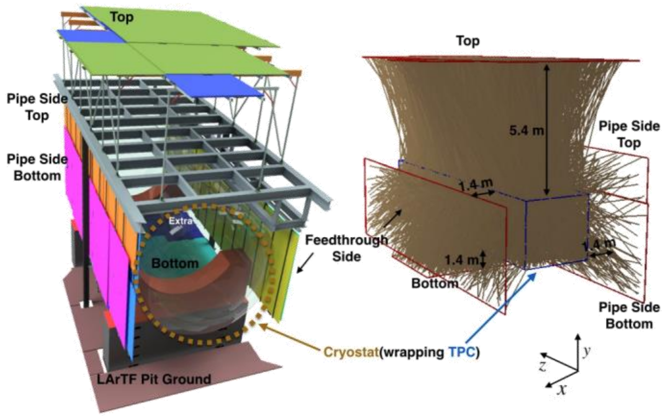


A schematic drawing of the MicroBooNE LArTPC as installed inside the cryostat
P. Abratenko *et al* 2020 Physical Review D 102

MicroBooNE’s LArTPC Capabilities

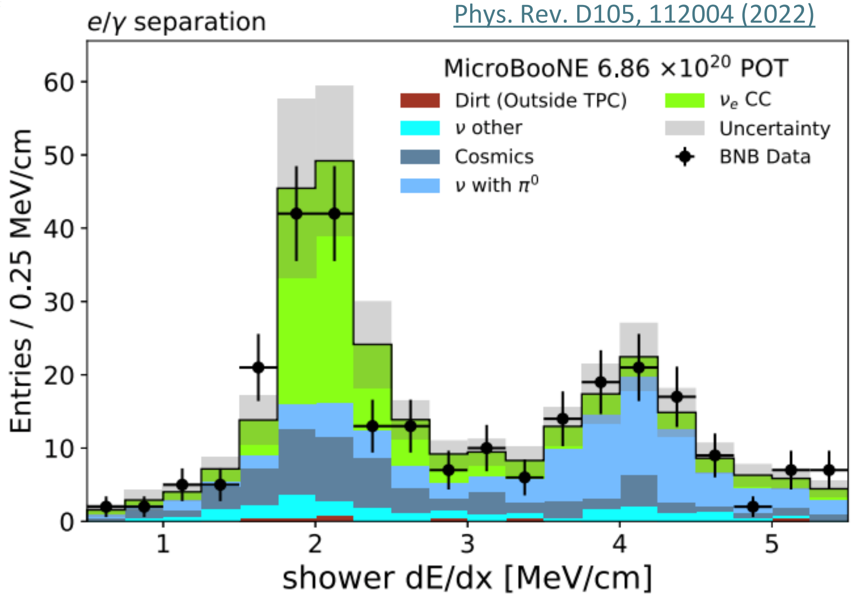


- mm-level spatial resolution
  - 3D interaction images
- Fully active tracking calorimeter: precise energy resolution
- Excellent particle identification
  - Including distinguishing electrons from photons
- Cosmic Ray Tagger (CRT) installed around cryostat to improve cosmic background rejection



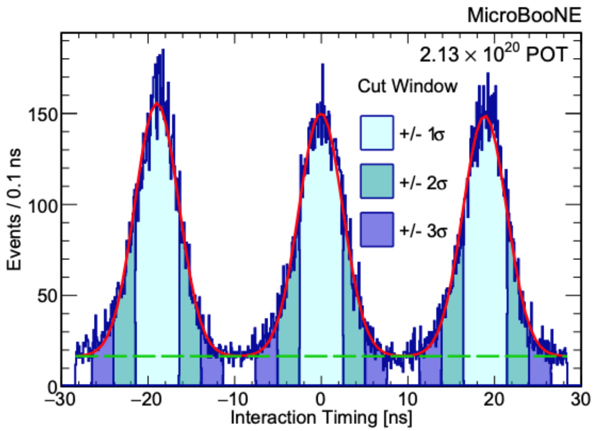
C. Adams *et al* 2019 *JINST* **14** P04004

Phys. Rev. D105, 112004 (2022)



Analysis techniques

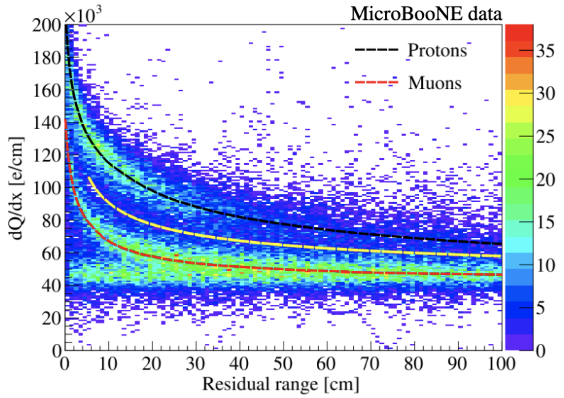
Our latest developments in LArTPC physics:

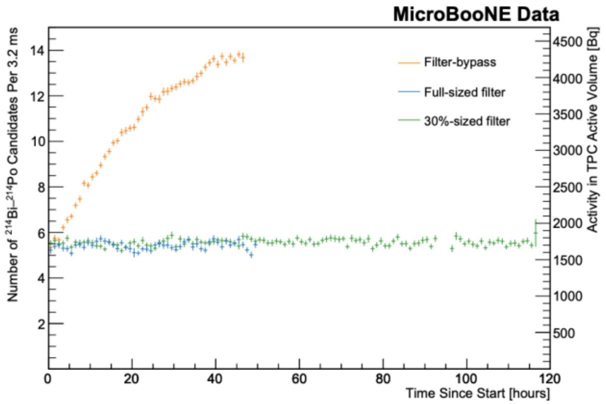


ns timing resolution

helpful for BSM searches

Phys.Rev.D108,052010 (2023)

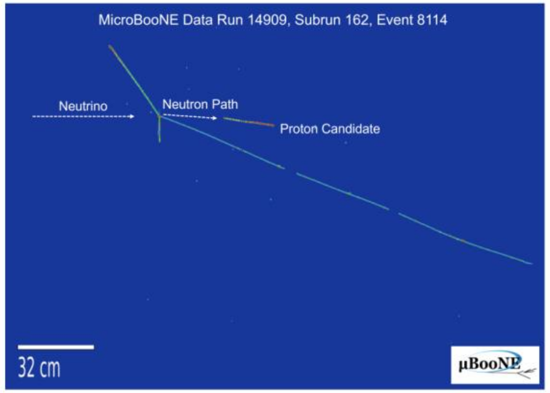




reconstruction advancement

MeV-scale reconstruction: aids low-energy calorimetry

arXiv:2203.10147, *JINST* **17** P01037 (2022)



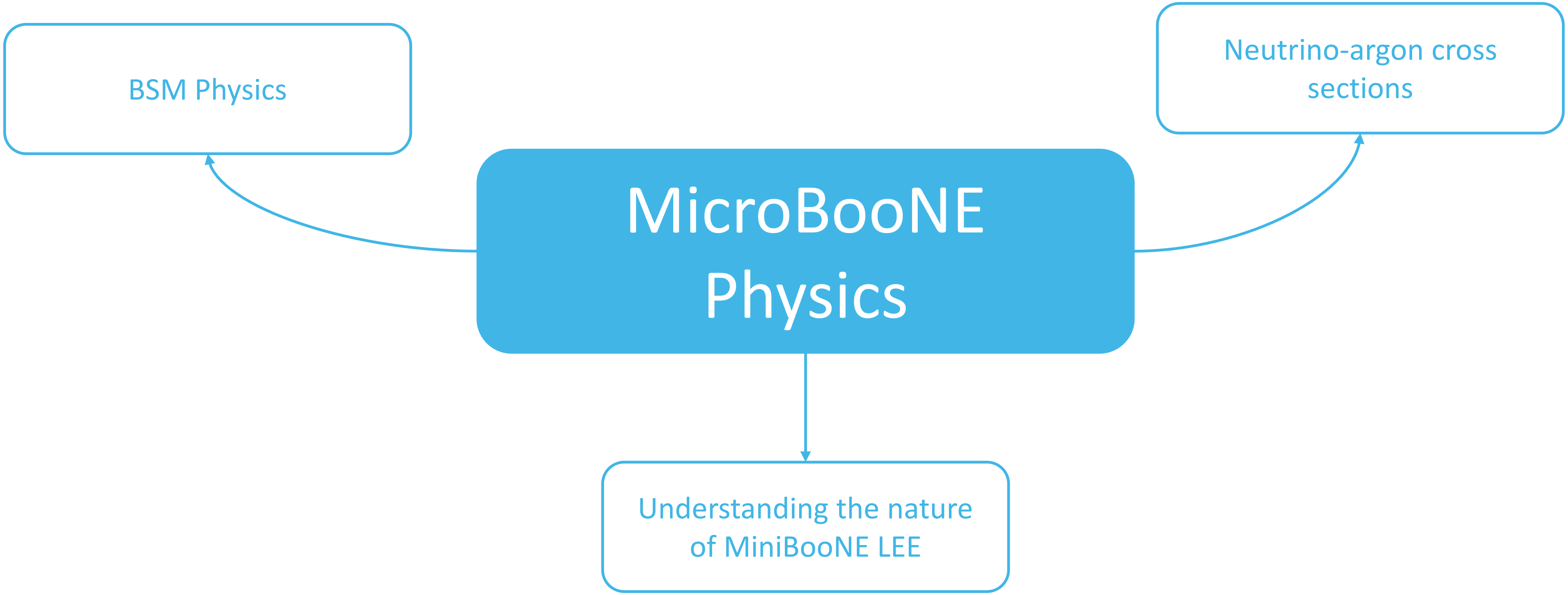
neutron identification

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

BSM Physics

Neutrino-argon cross sections

MicroBooNE Physics

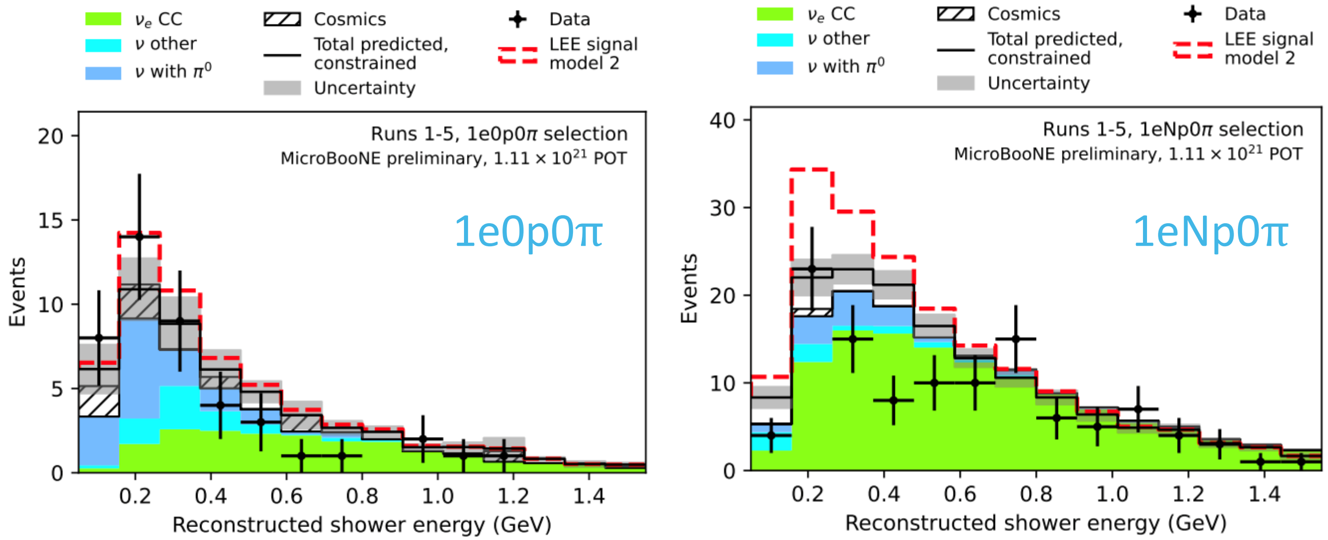
Understanding the nature of MiniBooNE LEE

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 ≥ 99% CL in all investigated variables (inc. electron angle and energy variables)

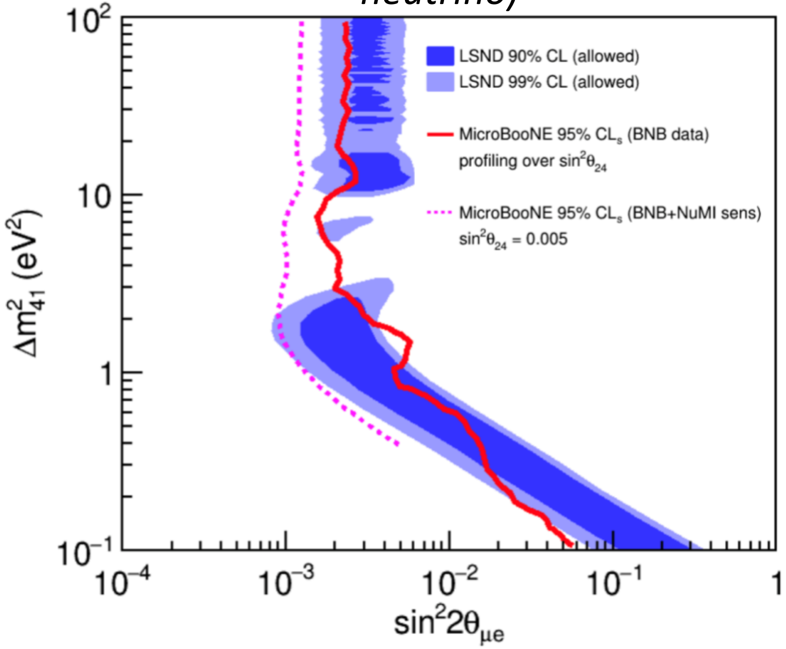


MICROBOONE-NOTE-1127-PUB

BSM as LEE exploration

3+1 Sterile Neutrinos

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

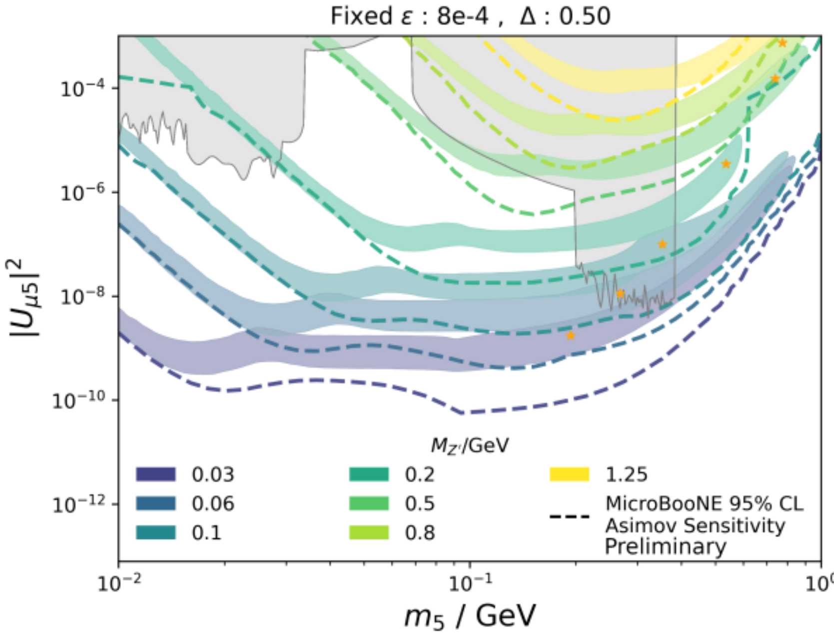


significantly improved sensitivity by combining BNB and NuMI data: new analysis will be sensitive to more LSND parameter space

MICROBOONE-NOTE-1116-PUB, MICROBOONE-NOTE-1132-PUB

Dark Sector e^+e^- Final States

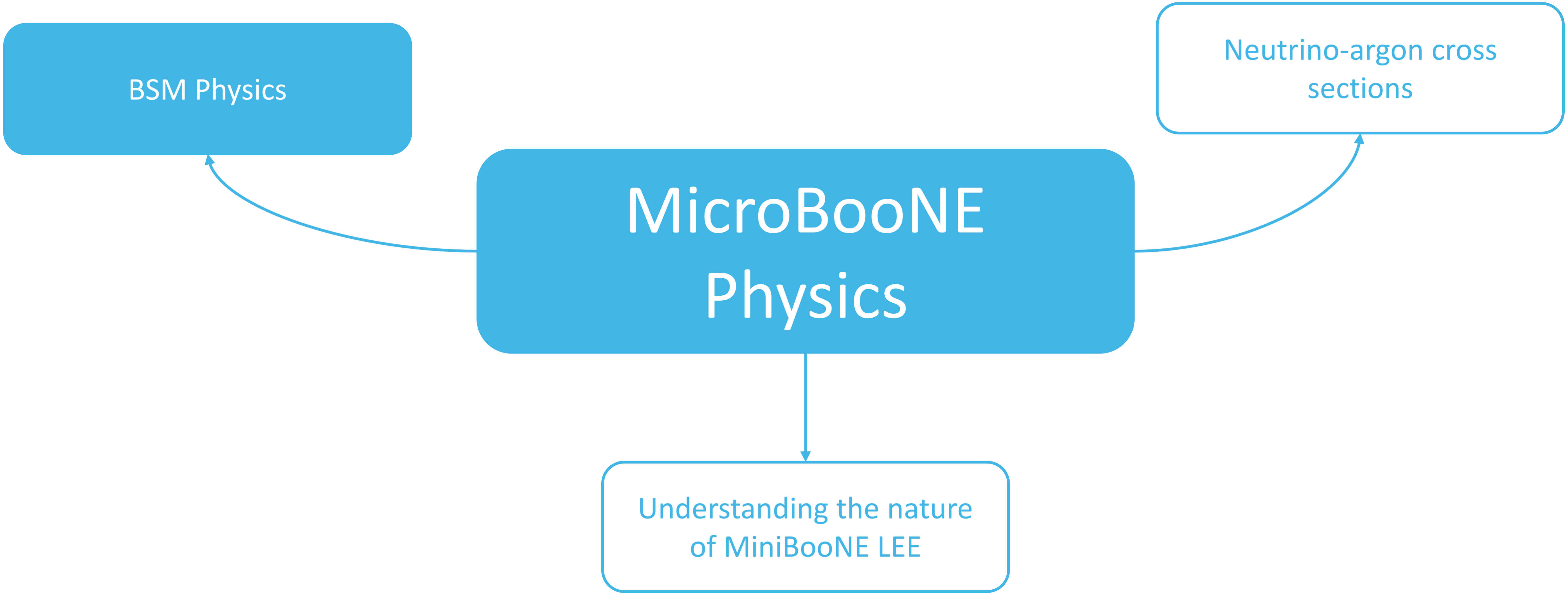
Dark sector neutrinos decaying into overlapping/asymmetric e^+e^- could lead to excess



substantial improvements in efficiency, exploring new dark sector parameter space

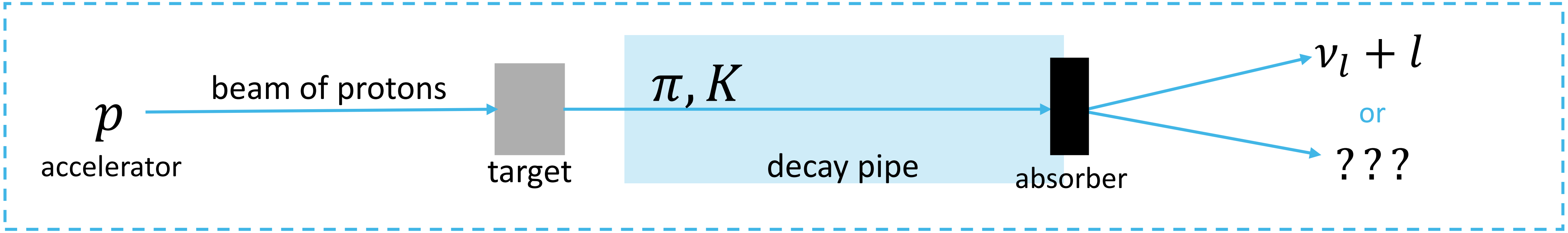
MICROBOONE-NOTE-1124-PUB

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...

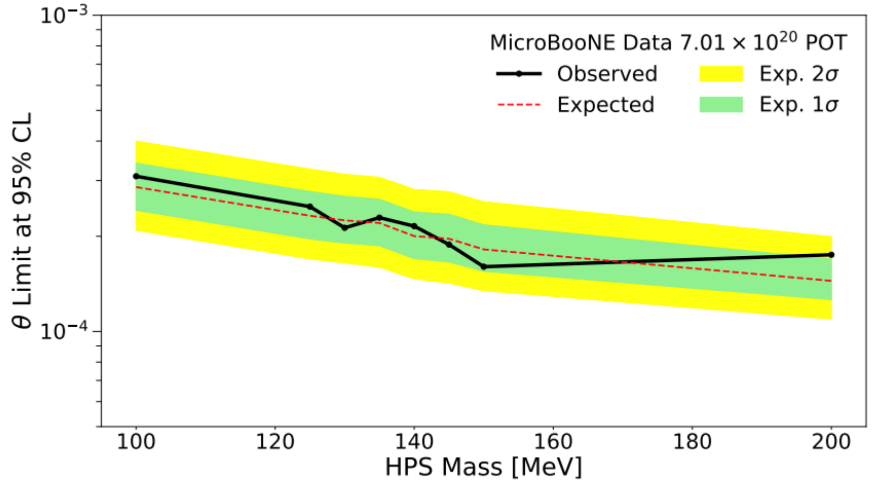


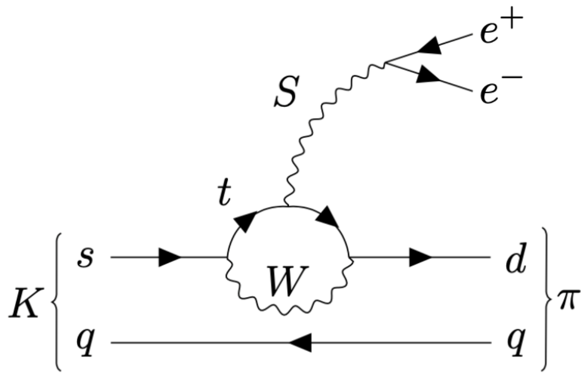
- MicroBooNE has world leading limits in searches for new particles in $\mathcal{O}$(10 MeV) – 300 MeV range under several phenomenological models

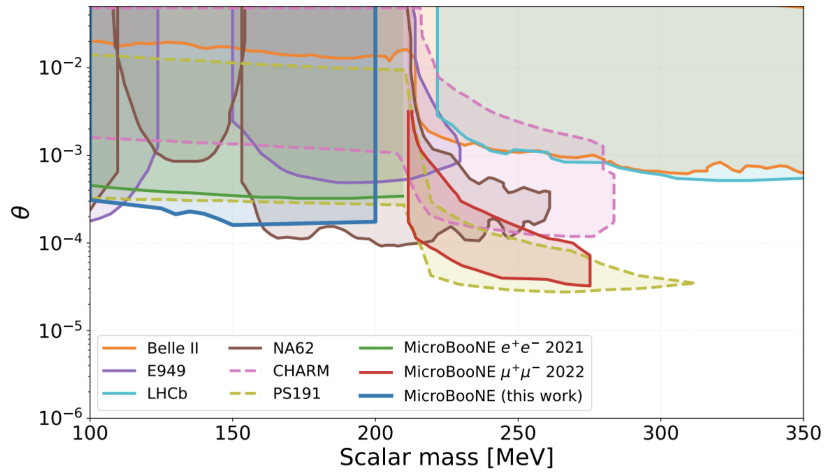
BSM: searches for new physics

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)

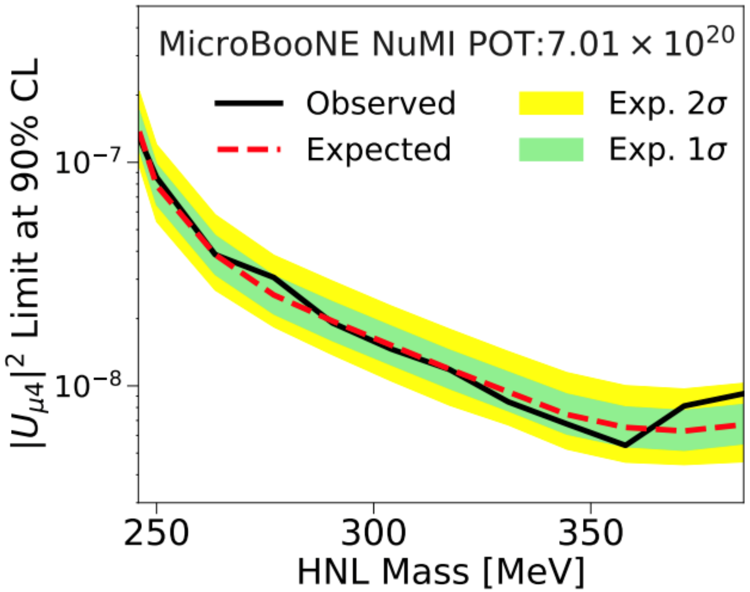






MicroBooNE Public Note

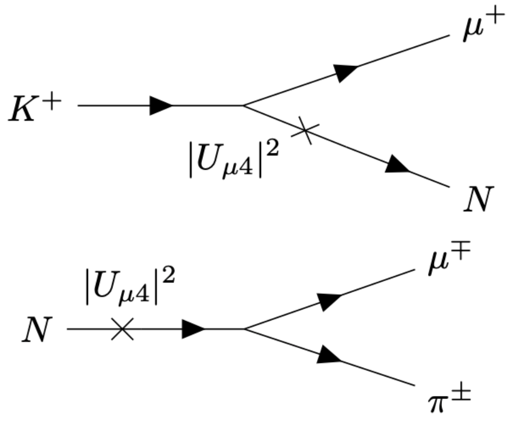
BSM: searches for new physics



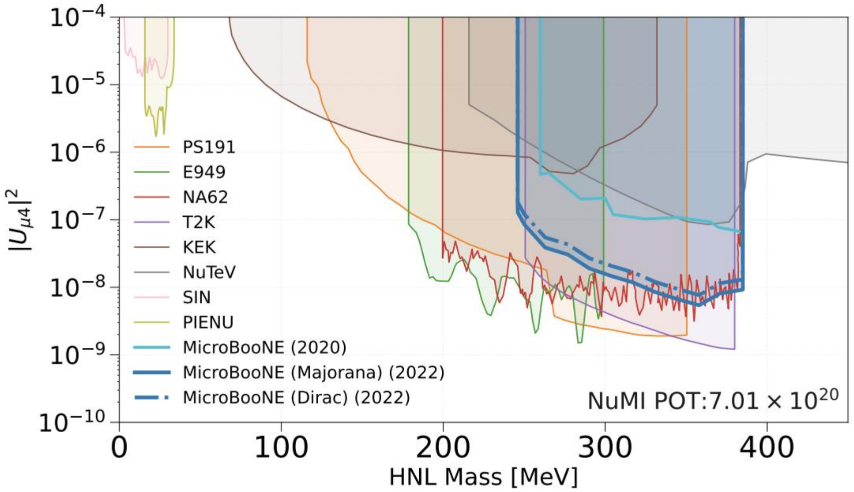
Heavy neutral leptons (HNLs)

- 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 $\|U_{\mu4}\|^2$
246	12.9×10^{-8}
385	0.92×10^{-8}



Phys. Rev. D **106**, 092006



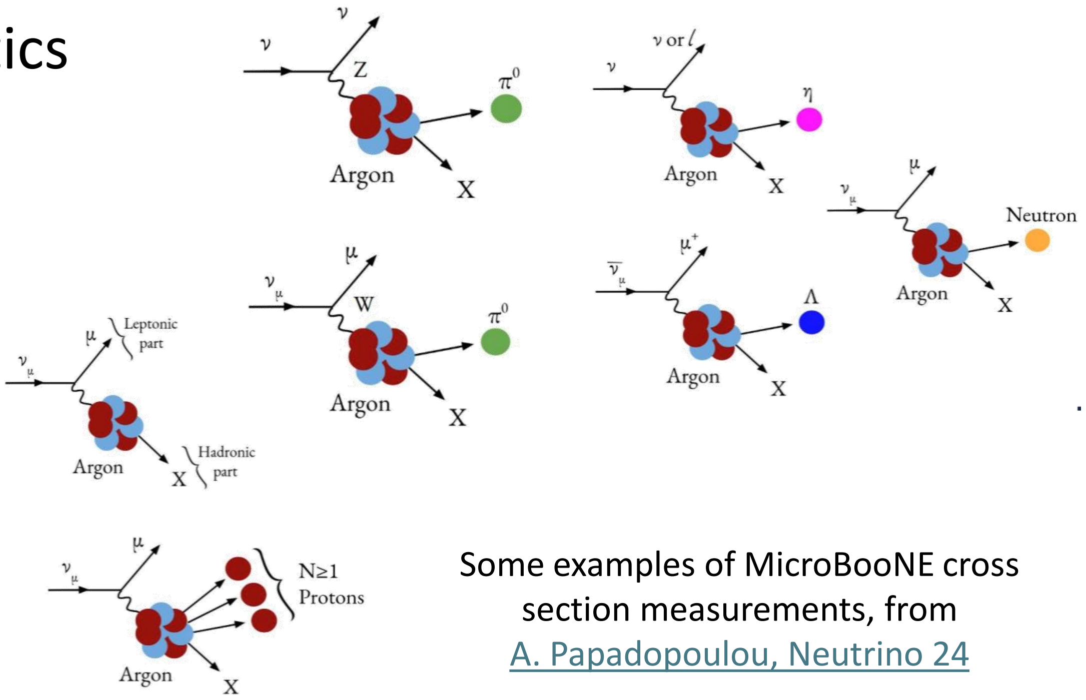
Physics with MicroBooNE

MicroBooNE Physics

- BSM Physics
- Neutrino-argon cross sections
- Understanding the nature of MiniBooNE LEE

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**



Some examples of MicroBooNE cross section measurements, from [A. Papadopoulou, Neutrino 24]

First CCπ^0/NCπ^0 differential cross sections

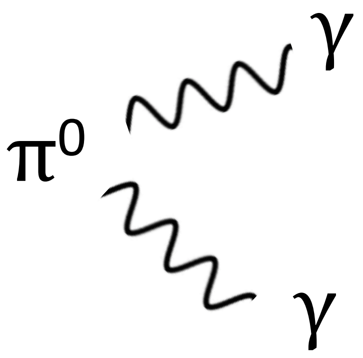
- π^0 are an important background in ν_e searches
  - A π^0 interaction produces 2 showers, but if 1 is missed, it can look like a ν_e interaction

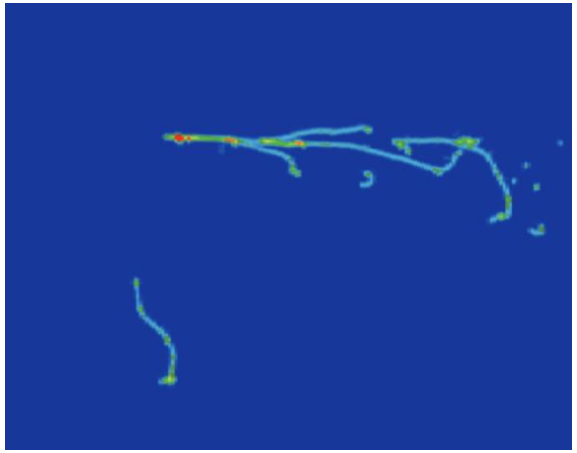
    This could be because…

    → energy is too low (less common in MicroBooNE: low thresholds)

    → one shower has left the detector

    → showers may be on top of each other

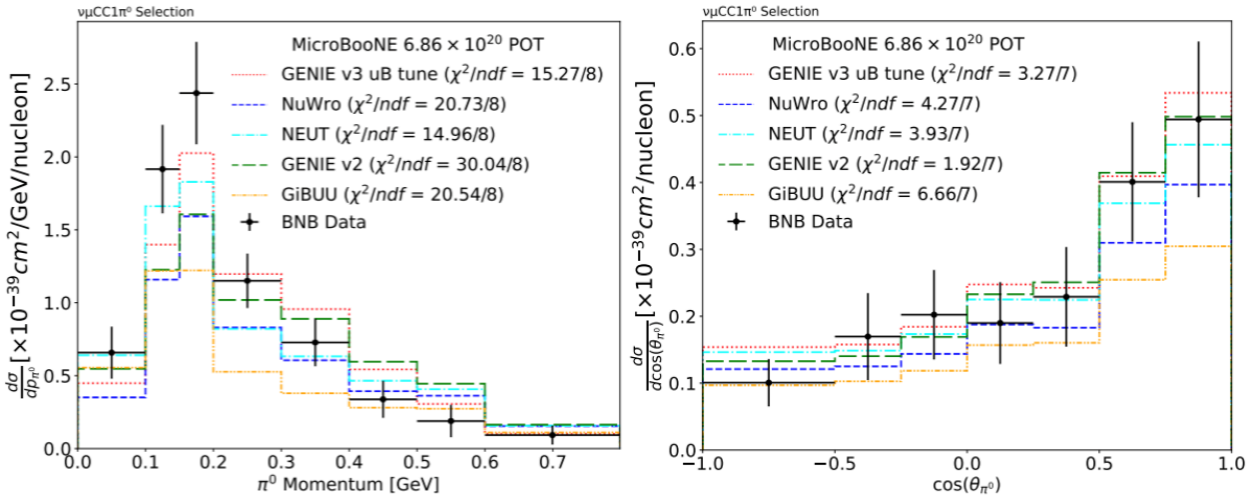




First $CC\pi^0$/$NC\pi^0$ differential cross sections

$CC\pi^0$

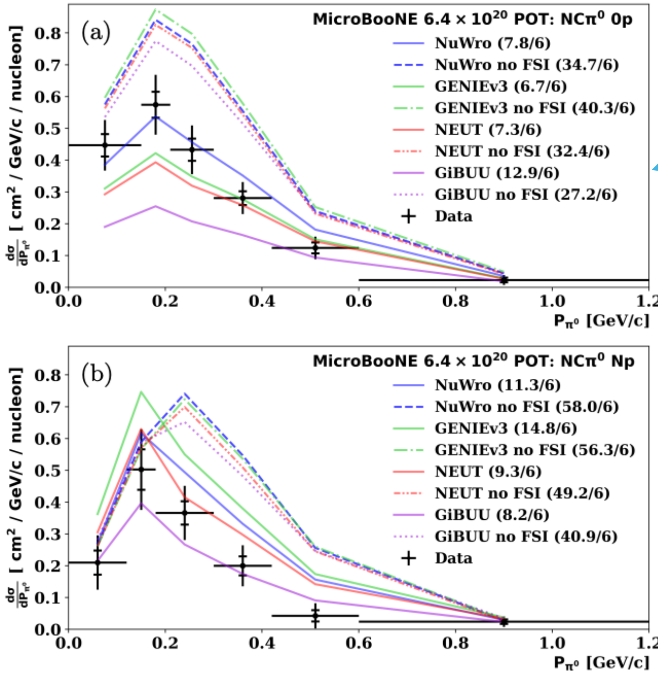
$$\nu_\mu + \mathrm{Ar} \rightarrow \mu^- + \pi^0 + 0\pi^\pm + X,$$



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

arXiv:2404.09949

$NC\pi^0$



0 protons

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

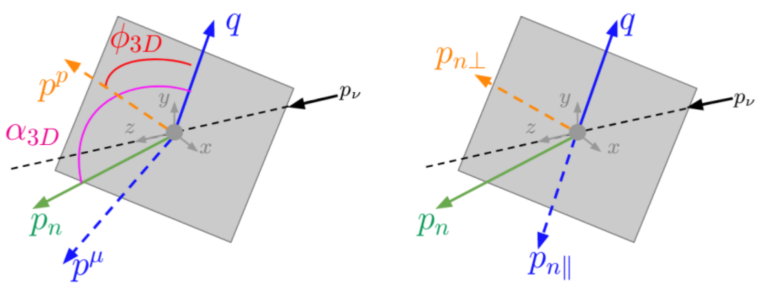
1 proton

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

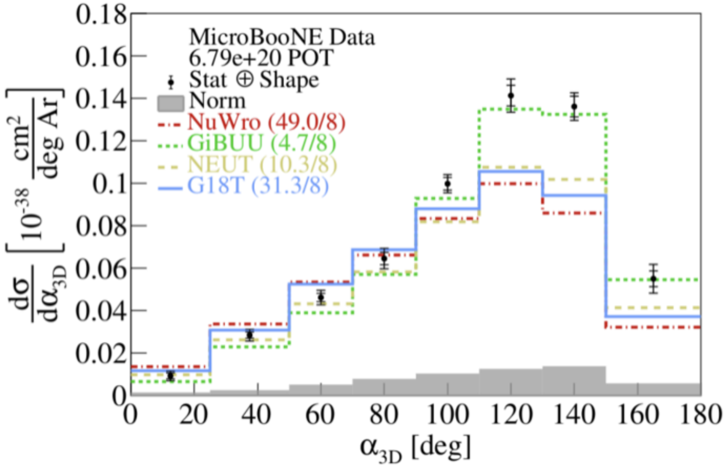
arXiv:2404.10948

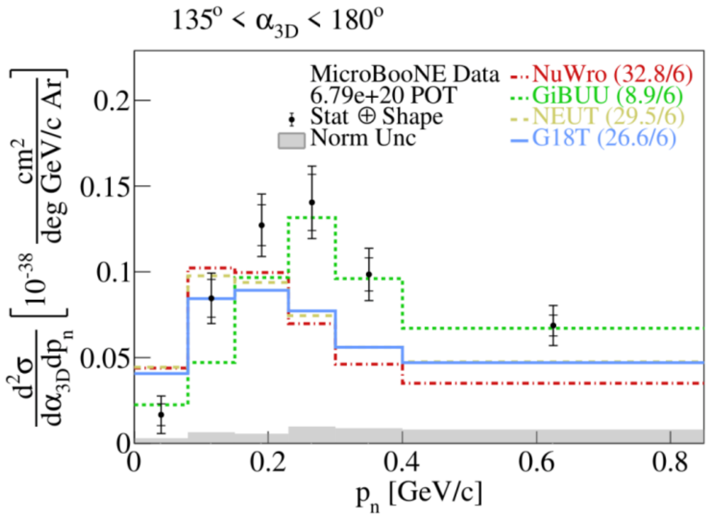
CC1p cross sections using kinematic imbalance

- first flux-integrated single and double-differential cross section measurements in these variables using ν_μ-Ar CC1p0π interactions



generalised kinematic imbalance variables (GKI)





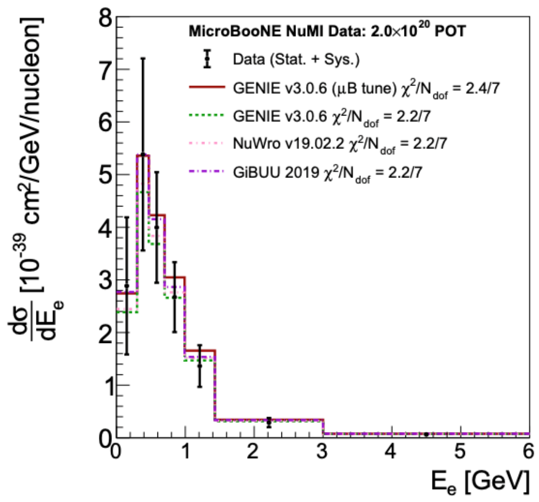
flux-integrated single-differential cross section, clear model discrimination; double-differential also presented

Phys. Rev. D **109**, 092007

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

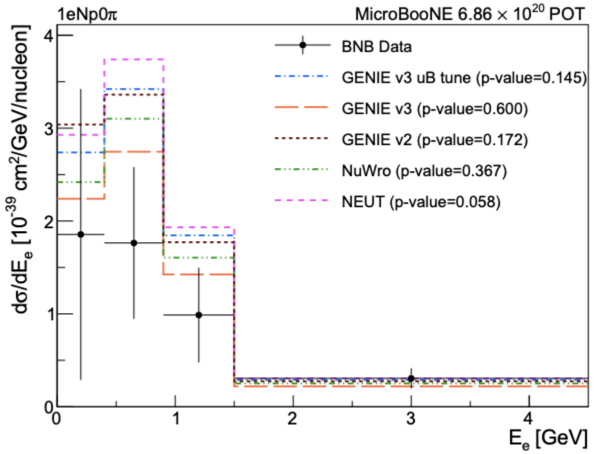
- Due to being off-axis, NuMI provides MicroBooNE a higher flux of ν_e and $\overline{\nu}_e$
  - Neutrino cross sections probe nuclear effects, needed for DUNE oscillation experiments
- Inclusive measurements of $\nu_e + \overline{\nu}_e$, performed; exclusive ν_e and $\overline{\nu}_e$ measurements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

- Currently measurements of $\nu_e/\overline{\nu}_e$ cross sections using the full MicroBooNE dataset are in progress



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

Phys. Rev. D 105, L051102 (2022)



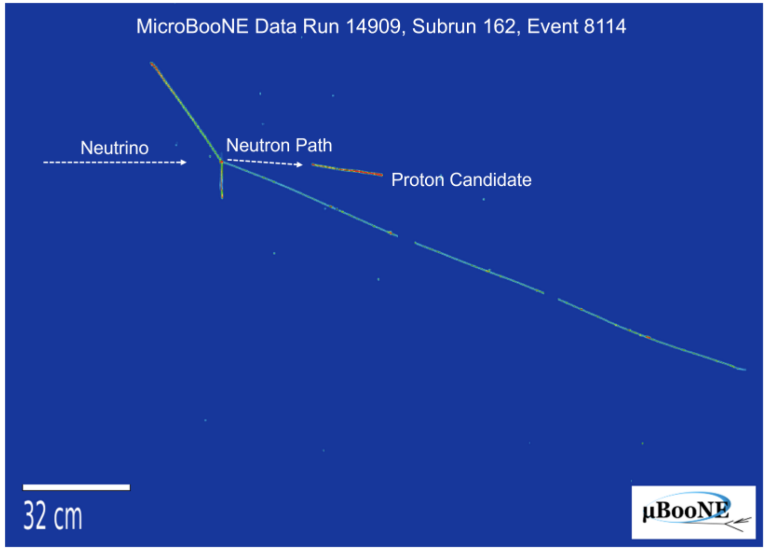
Unfolded differential exclusive ν_e cross section (1eNp0π)

Phys. Rev. D 106, L051102 (2022)

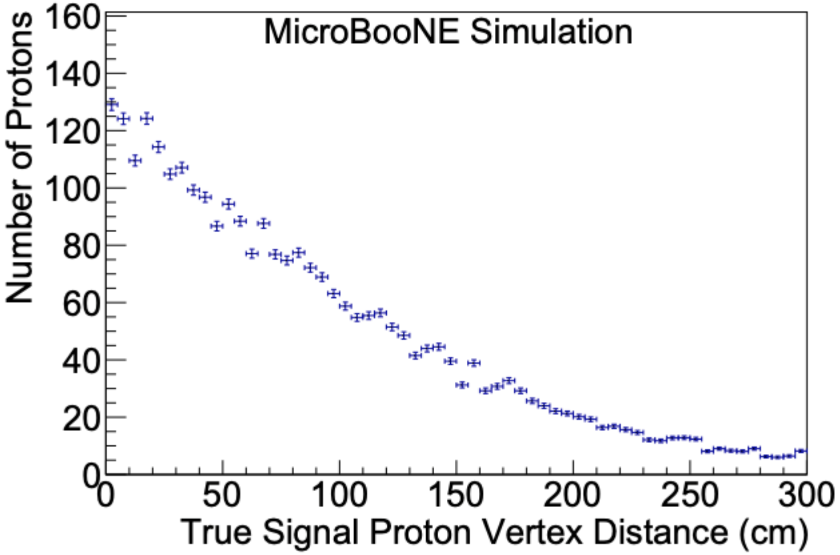
Neutron identification

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

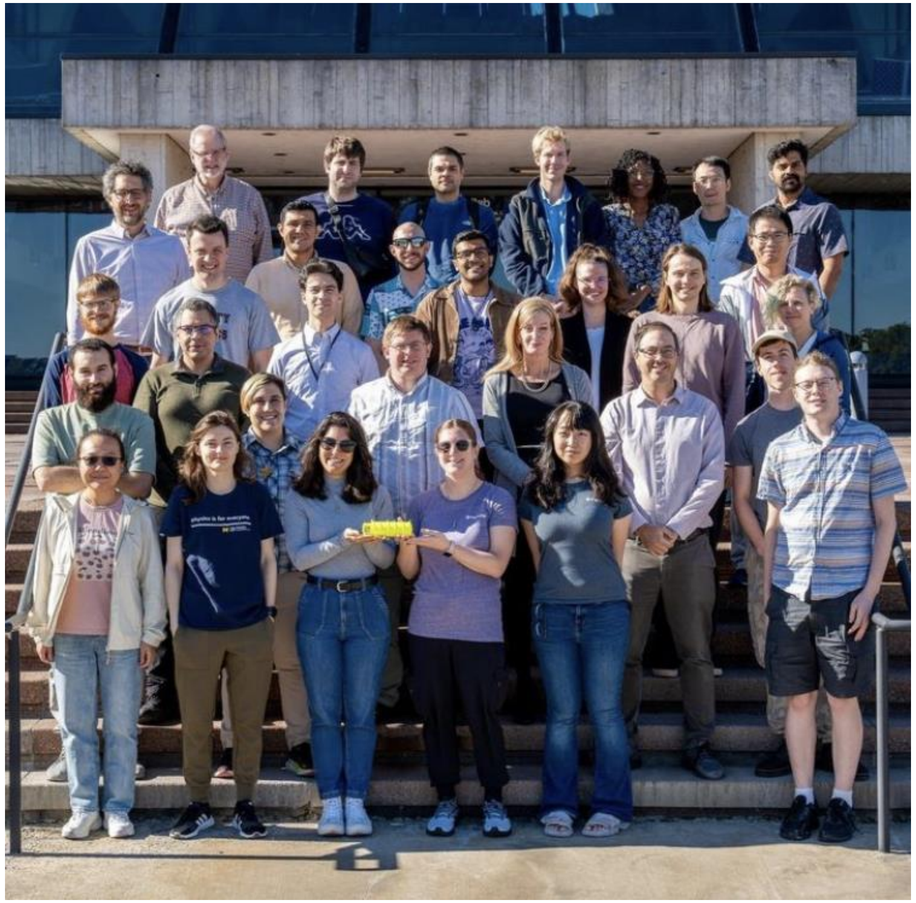
✨70 papers✨

(and counting!)

Summary

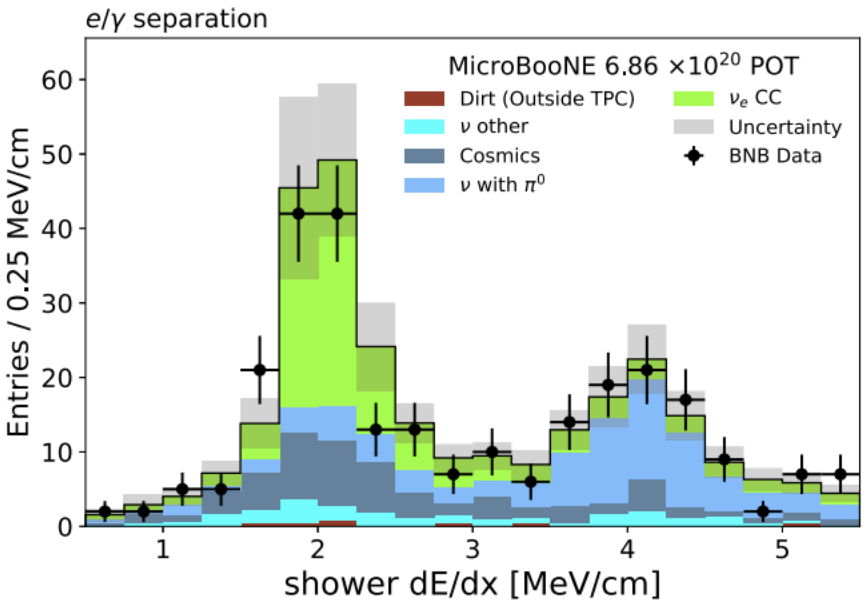
- MicroBooNE is a LArTPC neutrino detector based at Fermilab
  - Large, well-understood neutrino-argon interaction dataset
- We are a very active collaboration with recent results in several areas of physics!
- Further analyses aim to utilise the full dataset, incorporate NuMI and BNB data together, 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 $\mathrm{d}E/\mathrm{d}x$ 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

µBooNE

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 NCπ^0 @ BNB, Phys. Rev. D 107, 012004
- 2D ν_μ NCπ^0 @ BNB, arXiv:2404.10948
- ν_μ CCπ^0 @ BNB, arXiv:2404.09949

CC0π

- 1D ν_e CCNp0π @ BNB, Phys. Rev. D 106, L051102
- 1D & 2D ν_μ CC1p0π transverse imbalance @ BNB, Phys. Rev. Lett. 131, 101802 Phys. Rev. D 108, 053002
- 1D & 2D ν_μ CC1p0π generalized imbalance @ BNB, Phys. Rev. D 109, 092007
- 1D ν_μ CC1p0π @ BNB, Phys. Rev. Lett. 125, 201803
- 1D ν_μ CC2p @ BNB, arXiv:2211.03734
- 1D ν_μ CCNp0π @ BNB, Phys. Rev. D102, 112013
- 2D ν_μ CCNp0π @ 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

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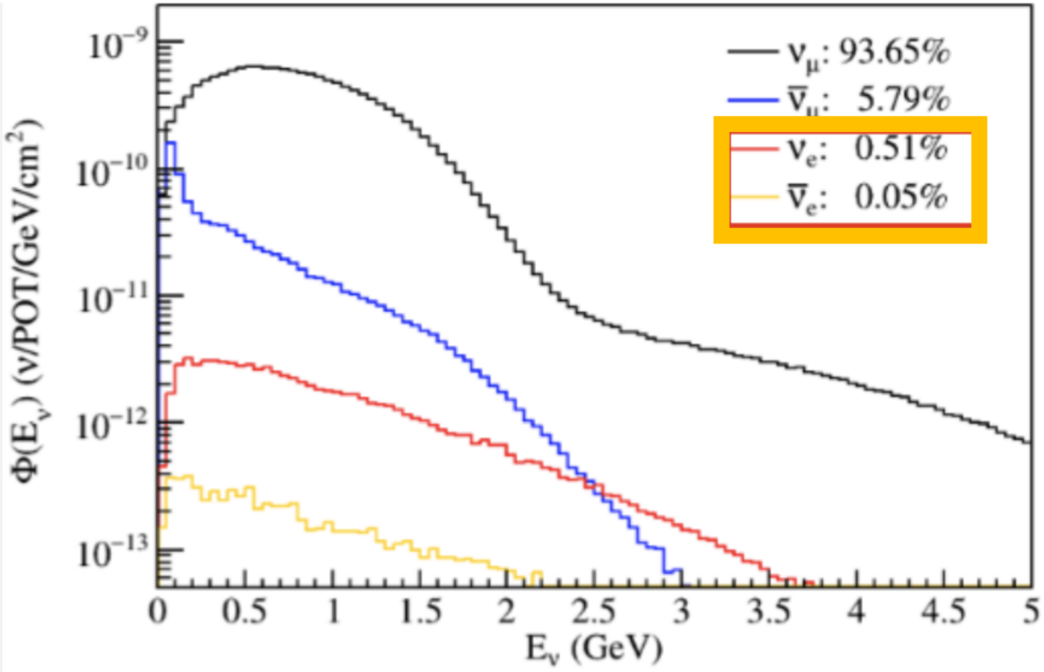
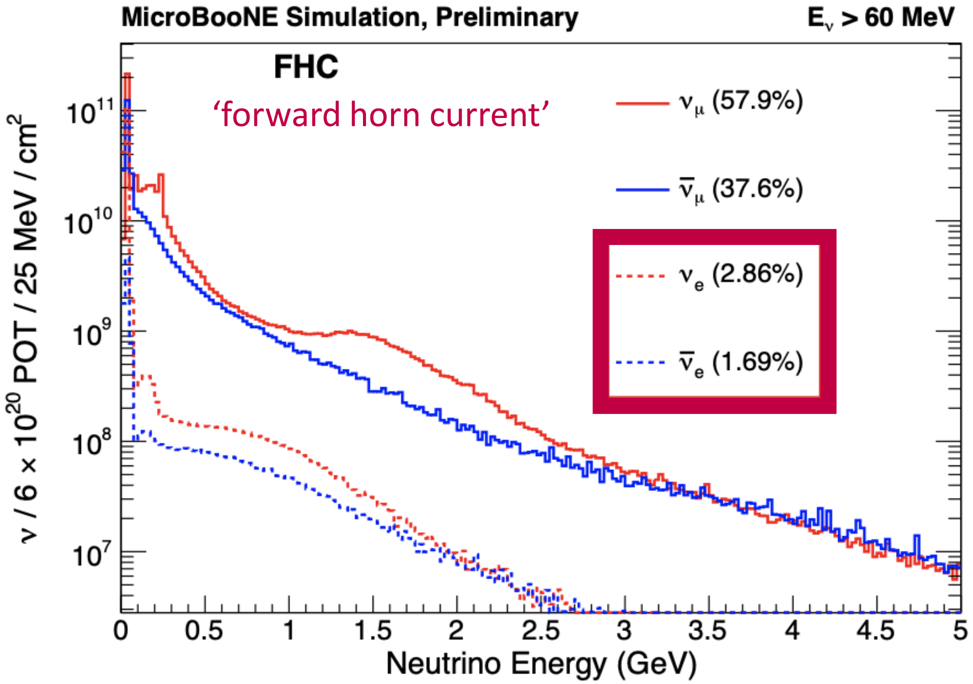
A. Papadopoulou, Neutrino 24

Beam fluxes

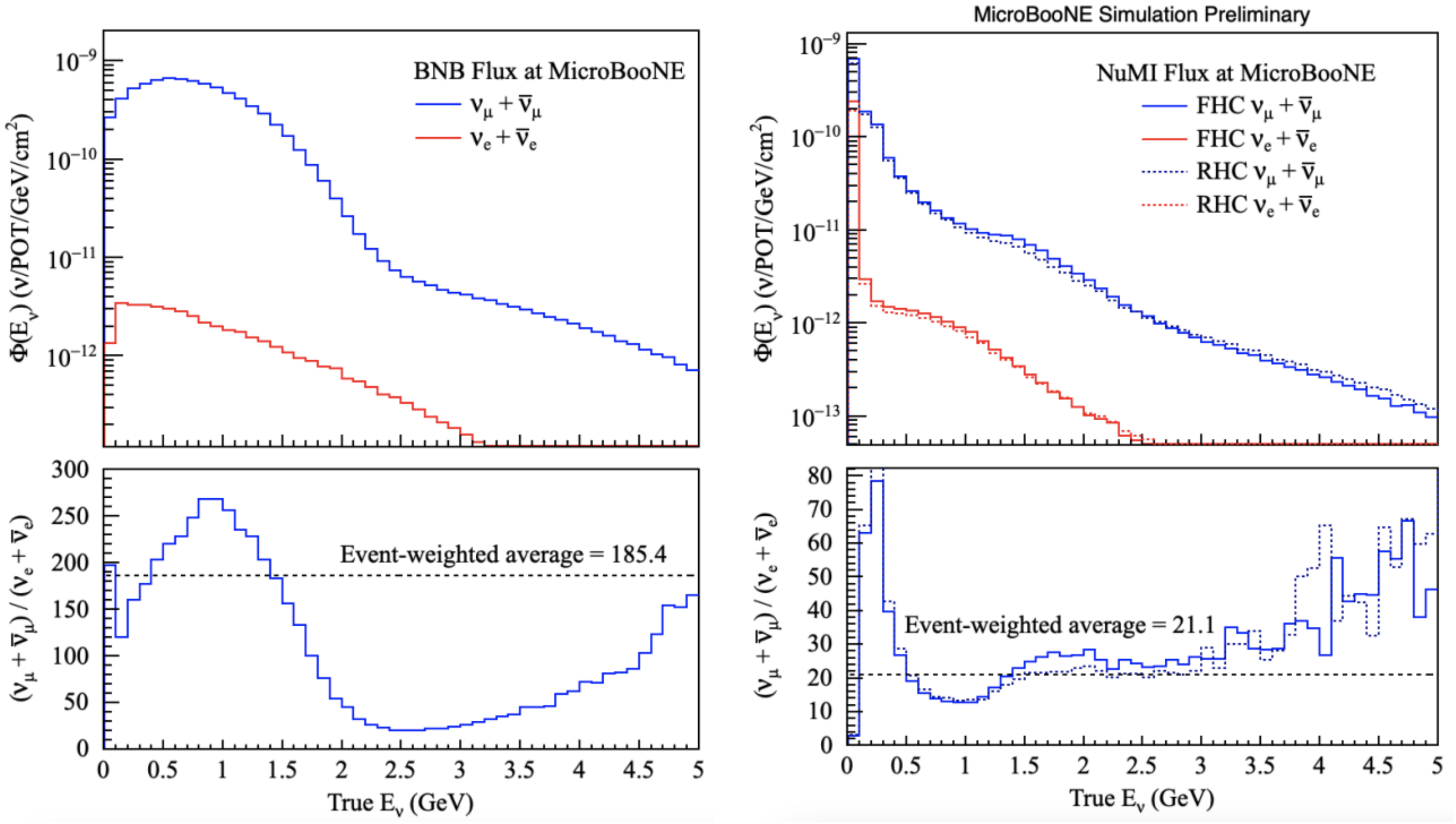


BNB



NuMI

Beam fluxes



(a) BNB flux **(b)** NuMI flux

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