EPS-HEP CONFERENCE
07-11 JULY, 2025
PALAIS DU PHARO
MARSEILLE, FRANCE

Neutrino-argon cross-section measurements from the MicroBooNE experiment

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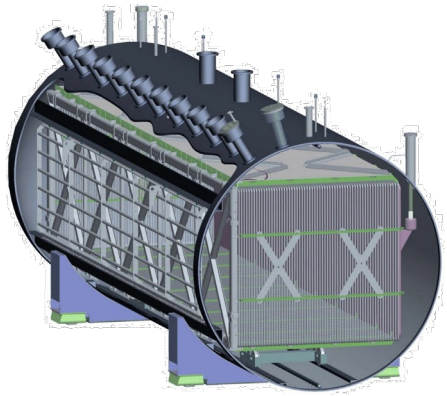
(on behalf of the MicroBooNE Collaboration)
University of Edinburgh
9th July 2025

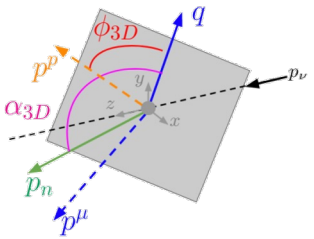
μBooNE

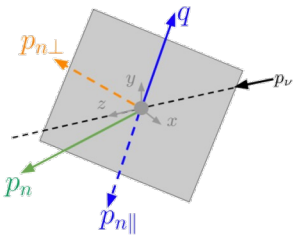
THE UNIVERSITY *of* EDINBURGH

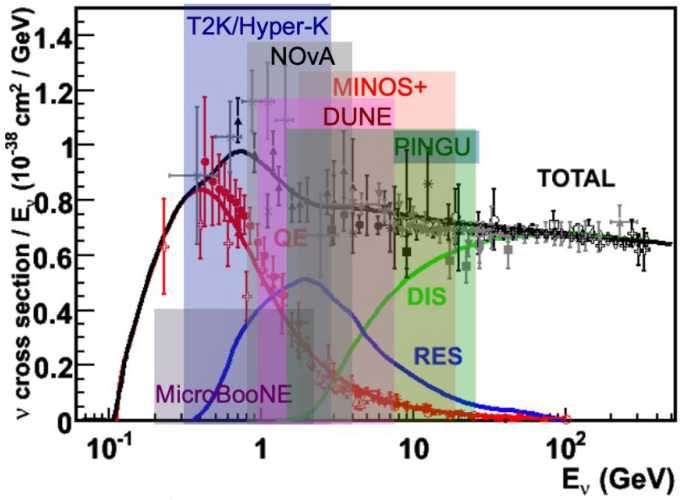
Outline

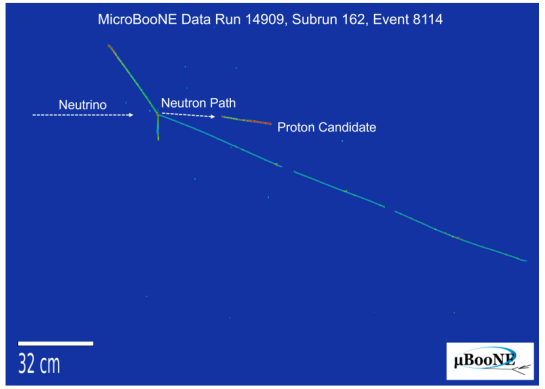
- The MicroBooNE detector
- Analysis techniques
- Cross sections at MicroBooNE
  - In-depth kinematic studies
  - Pion production
  - Neutrinos and antineutrinos
  - Rare production channels
  - Low-energy regime
- Future analyses





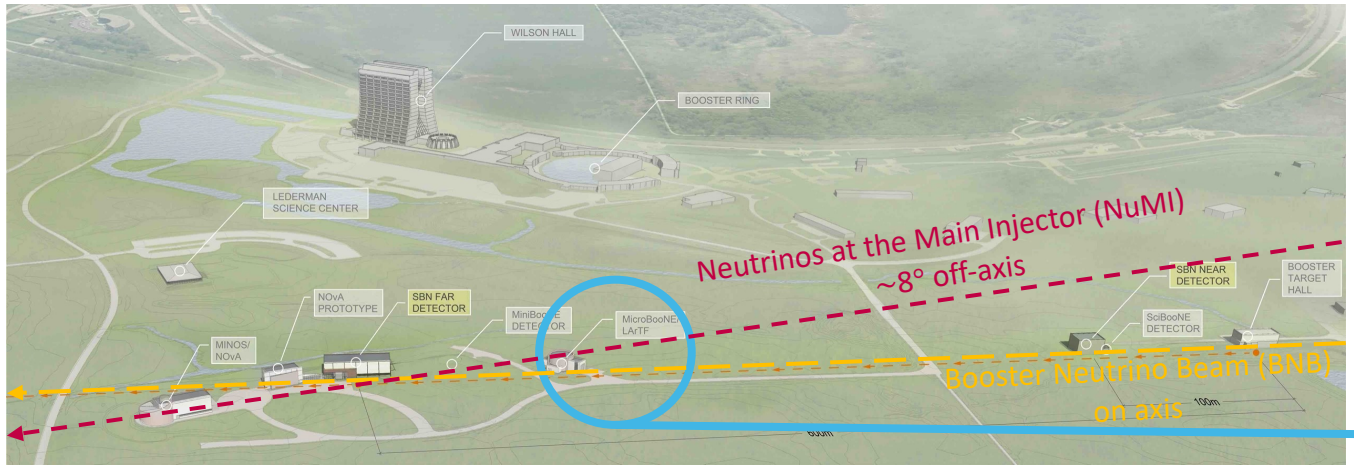






The MicroBooNE Detector

- The **Micro Boo**ster **N**eutrino **E**xperiment is a short baseline neutrino experiment at Fermilab (IL, USA)

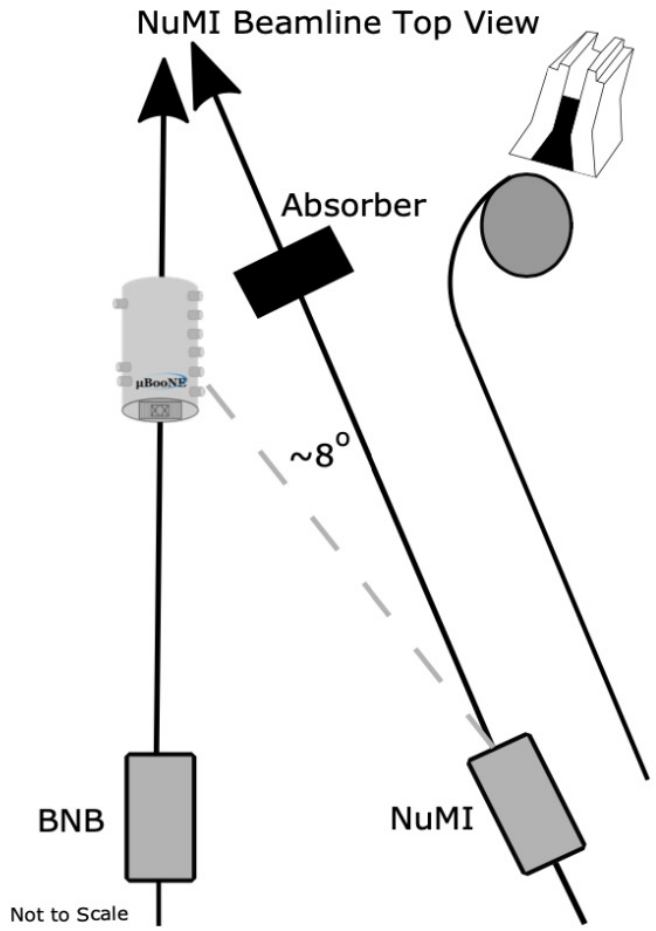


MicroBooNE
470 m from BNB target
~680 m from NuMI target

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

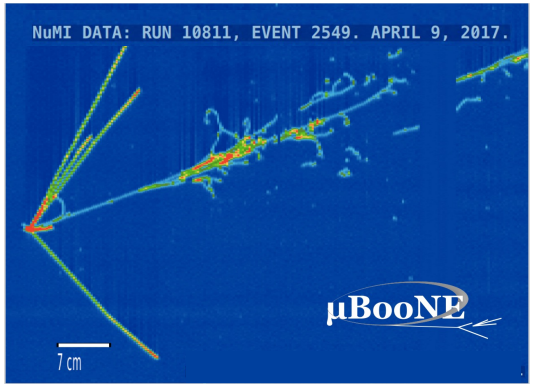
One detector, two beams

- MicroBooNE receives neutrinos from two beams:
  - Booster Neutrino Beam (**BNB**)
    - target 470 m from MicroBooNE, **on axis**
    - 8 GeV protons, Be target
    - $< E_{\nu_\mu} > \approx$ 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 ~ 680 m from MicroBooNE, **off axis** (8°)
    - 120 GeV protons, C target
    - $< E_{\nu_\mu} > \approx$ 500 MeV
    - 2.5% ν_e and $\overline{\nu_e}$, 97.5% ν_μ and $\overline{\nu_\mu}$

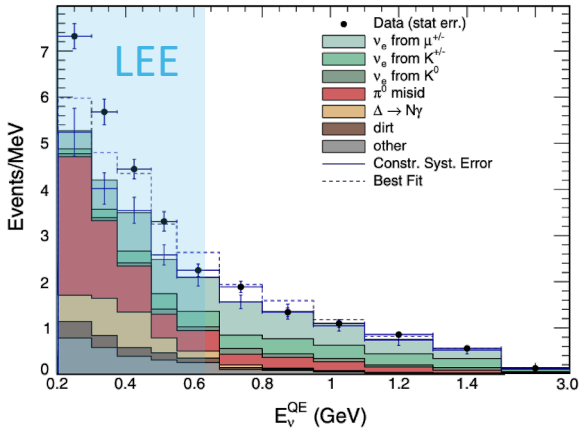


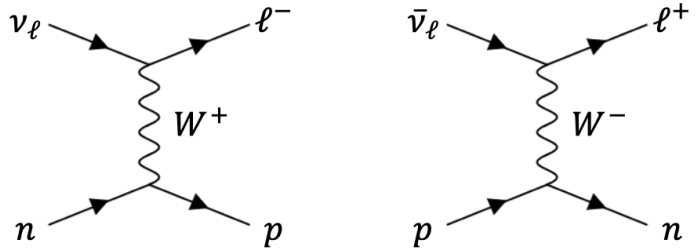
MicroBooNE's physics goals

- Advancing LArTPC technology
- Investigating MiniBooNE's 'low energy excess'
  - LArTPC has capability to address anomaly
- Beyond Standard Model searches
- **Neutrino-argon cross-section measurements**



Phys. Rev. D 103, 052002



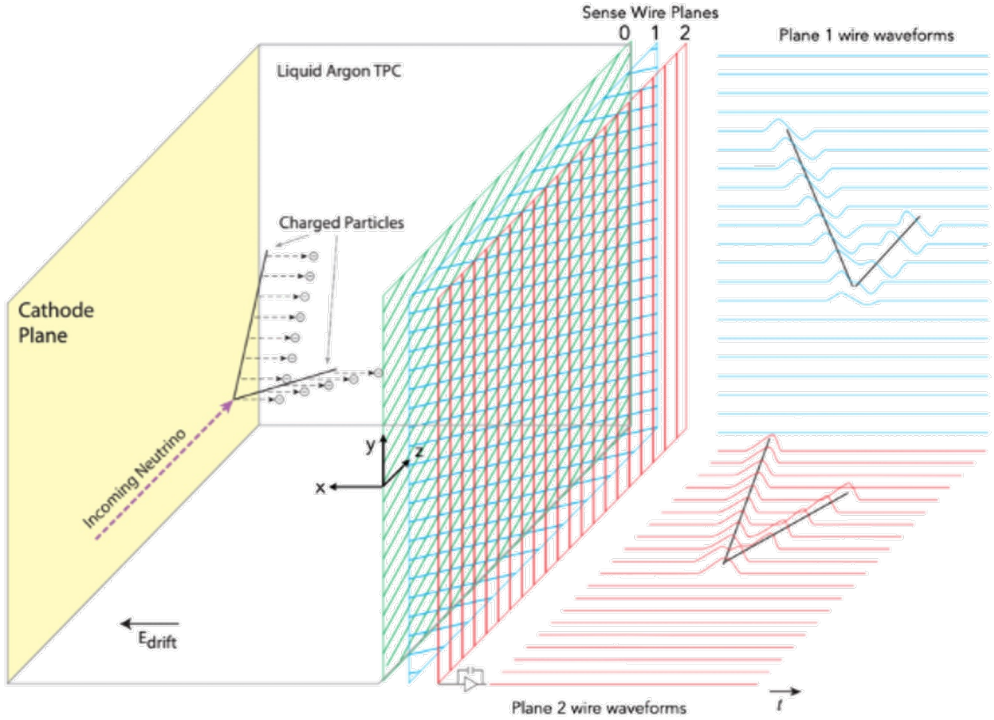


LArTPCs

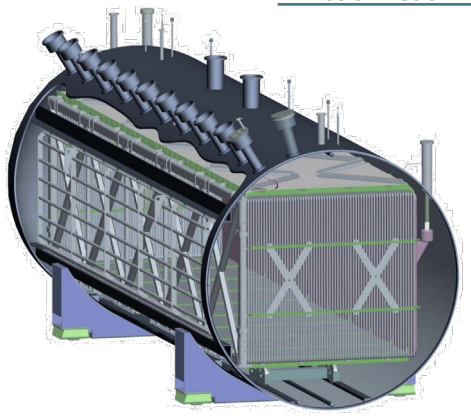
DUNE will use this technology!

- 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

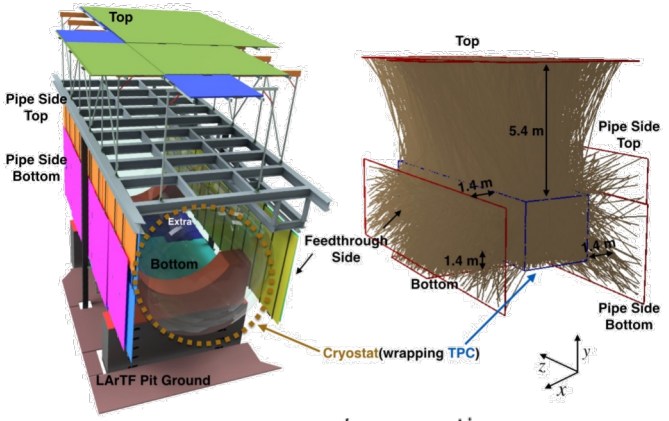


A schematic drawing of the MicroBooNE LArTPC as installed inside the cryostat
P. Abratenko *et al* 2020 Physical Review D 102

MicroBooNE's LArTPC Capabilities

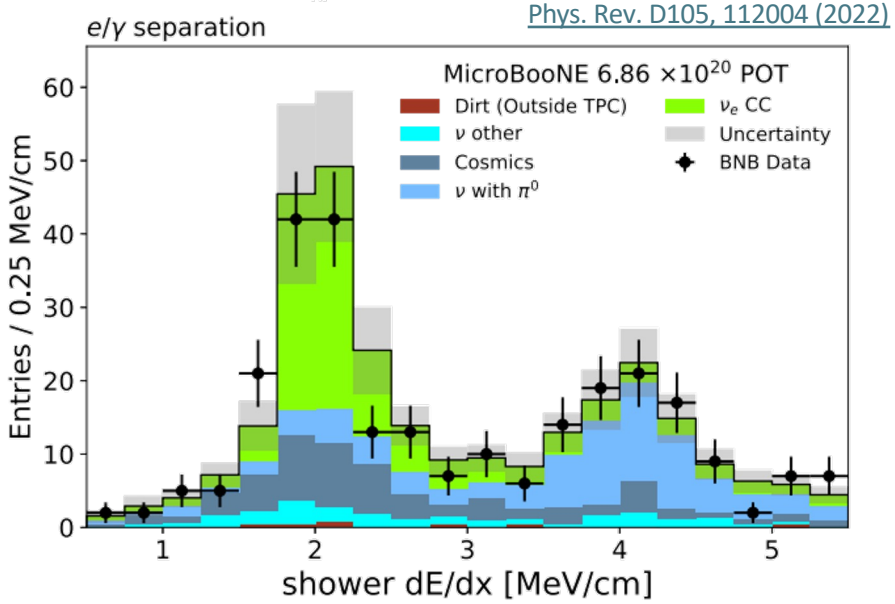
- mm-level spatial resolution (3 mm)
  - 3D interaction images
- Fully active tracking calorimeter: precise energy resolution
- Excellent particle identification
  - Including distinguishing electrons from photons

- Cosmic Ray Tagger (CRT) installed around cryostat to improve cosmic background rejection
- Automated reconstruction



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

Phys. Rev. D105, 112004 (2022)



Cross-sections at MicroBooNE

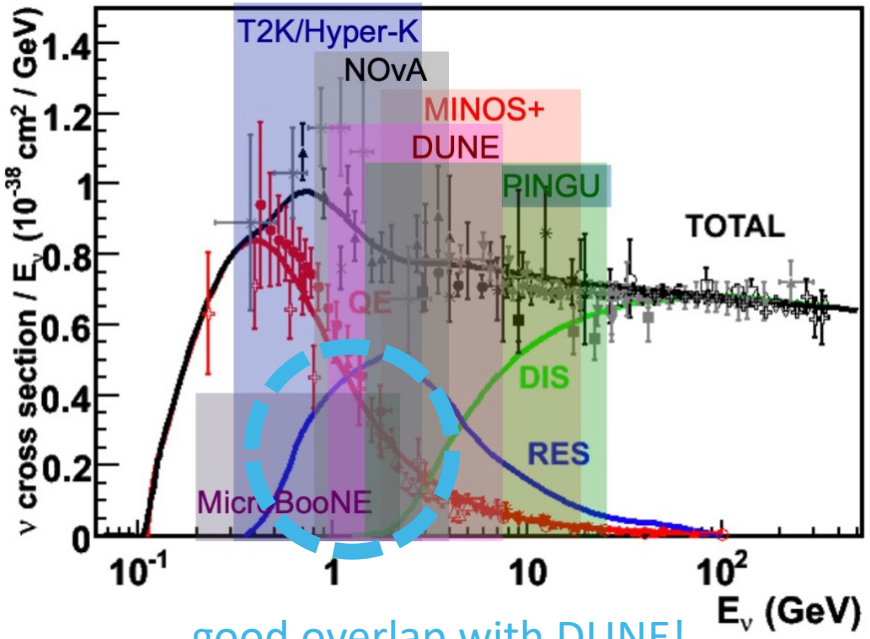
Why ν-Ar cross sections ?

- Furthers understanding of **how neutrinos interact with matter**

$$N = \Phi T \sigma$$

- Crucial for next generation experiments, such as **DUNE**
  - Cross sections probe of nuclear effects
  - Reducing uncertainty on neutrino-nucleus interactions is crucial
  - Allows testing and improvement of nuclear and FSI modelling

- Important for **oscillation analyses**
  - Measuring expected number of events

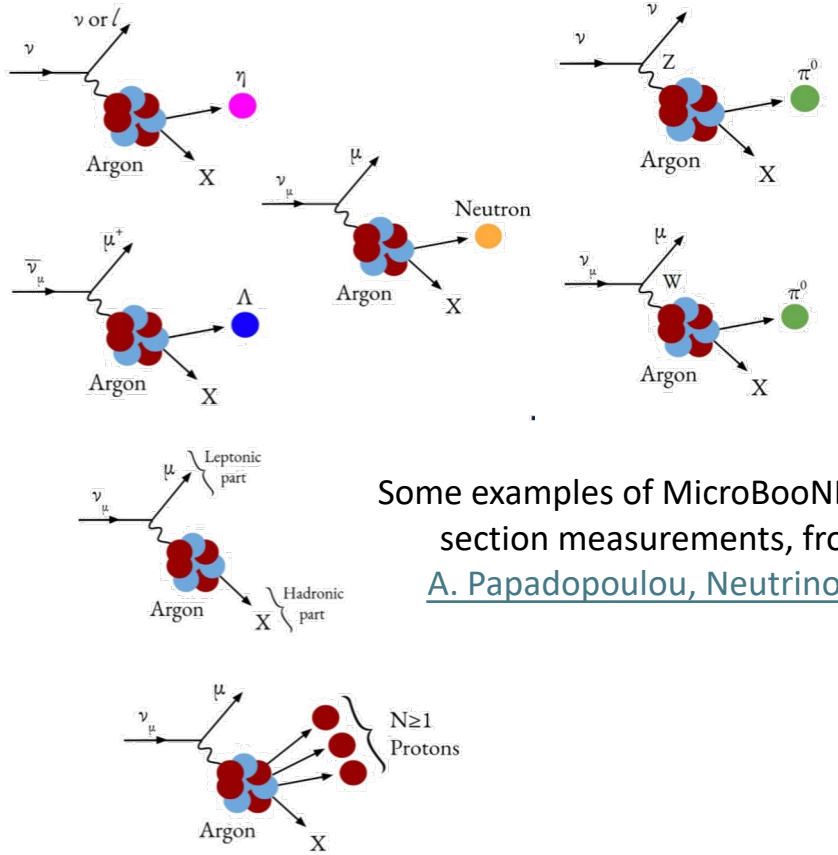


good overlap with DUNE!

Cross sections at MicroBooNE

- MicroBooNE possesses a large, well-understood neutrino-argon interaction dataset after 5 years of data taking
  - Accurate energy reconstruction for kinematics
  - State-of-the-art modelling

- over 20 ν-Ar cross sections published
  - **First measurements of many ν-Ar interactions**



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

Our published cross section papers…

CC inclusive

- 1D ν_μ CC inclusive @ BNB, PRL **123**, 131801
- 1D ν_μ CC E_ν @ BNB, PRL **128**, 151801
- 3D CC E_ν @ BNB, arXiv:2307.06413
- 1D ν_e CC Inclusive @ NuMI, PRD **104** 052002, PRD **105** L051102
- 2D ν_μ CC0pNp inclusive @ BNB, arXiv:2402.19216, arXiv:2402.19281

Rare channels & novel techniques

- η production @ BNB, PRL **132**, 151801
- Λ production @ NuMI, PRL **130**, 231802
- K^+ production @ BNB, arXiv:2503.00291
- Neutron identification, arXiv:2406.10583

CC0π

- 1D ν_e CCNp0π @ BNB, PRD **106**, L051102
- 1D & 2D ν_μ CC1p0π TKI @ BNB, PRL **131**, 101802, PRD **108**, 053002
- 1D & 2D ν_μ CC1p0π GKI @ BNB, PRD **109**, 092007
- 1D ν_μ CC1p0π @ BNB, PRL **125**, 201803
- 1D ν_μ CC2p @ BNB, arXiv:2211.03734
- 1D ν_μ CCNp0π @ BNB, Phys. Rev. D **102**, 112013
- 2D ν_μ CCNp0π @ BNB, arXiv:2403.19574
- 1D & 2D ν_μ CC0π @ BNB, arXiv:2507.00921

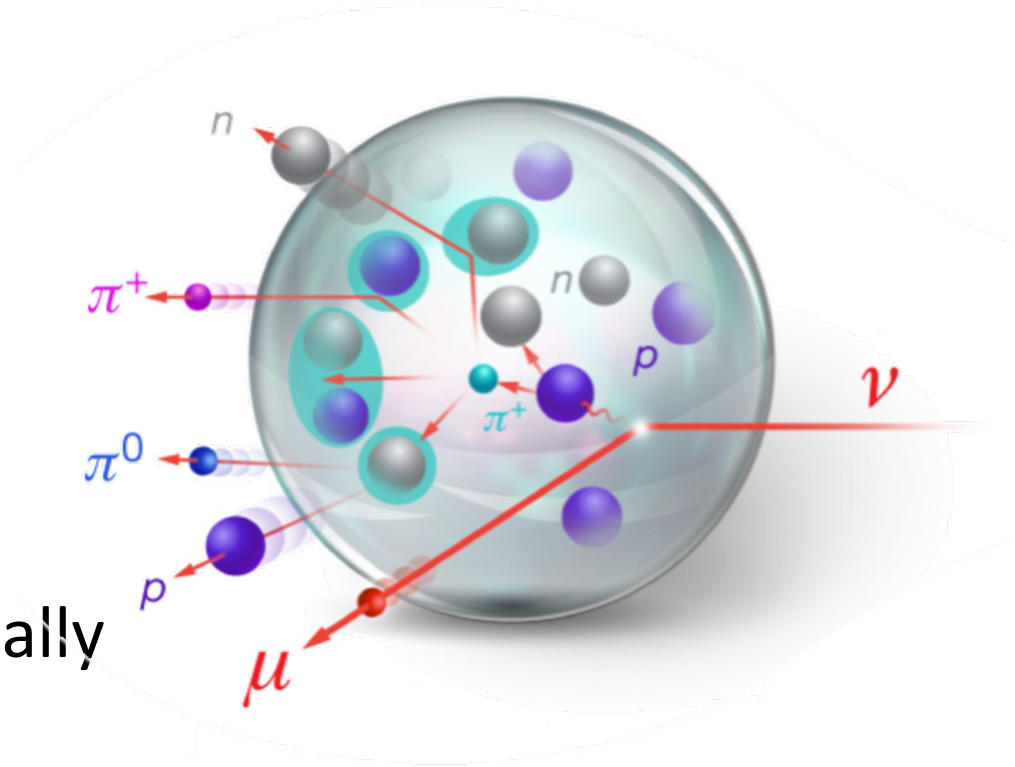
Pion production

- ν_μ NCπ^0 @ BNB, PRD **107**, 012004
- 2D ν_μ NCπ^0 @ BNB, arXiv:2404.10948
- ν_μ CCπ^0 @ BNB, arXiv:2404.09949

…with several more in progress, plus many technical papers!

Motivation

- Understanding **nuclear interactions** is a big challenge
- **Pions** and **kinematic imbalances** are of interest to the community as they are typically poorly described by models



- Modelling **backgrounds** is essential as they may obscure new physics

→ MicroBooNE's recent results provide insights into these issues

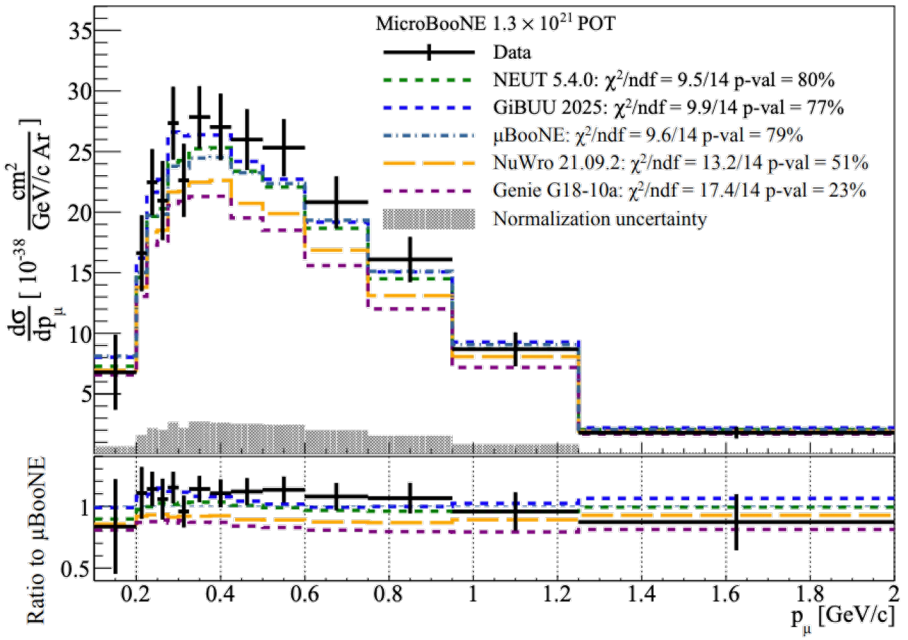
In-depth kinematic studies

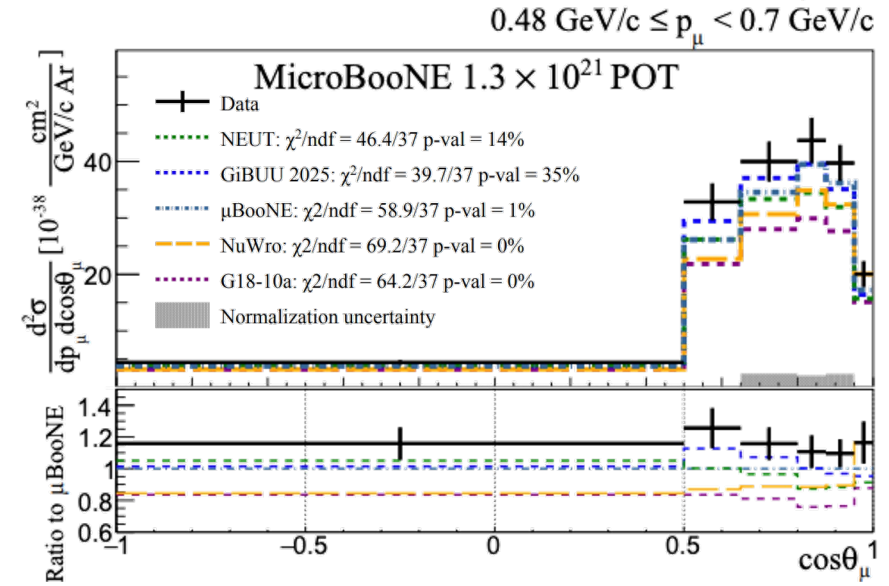
- Important for model discrimination
- Atmospheric neutrinos

ν_μCC0π ✨ **Brand new**: July 1st 2025! ✨

https://arxiv.org/pdf/2507.00921

- Signal dominated by QE-like interactions
- Good data-generator agreement for single-differential measurements
- Few generators are able to adequately describe the data in double-differential distributions
  - GiBUU 2025 performed best
- Allows comparison with Cherenkov detector experiments

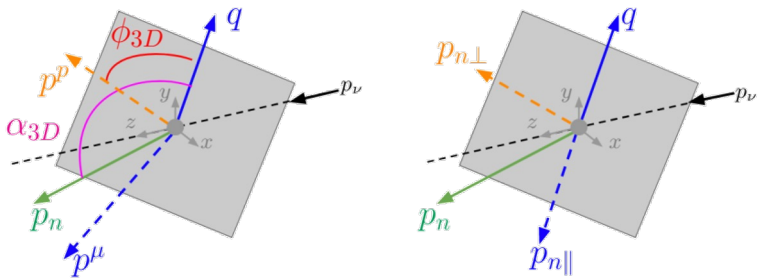




CC1p cross sections using kinematic imbalance

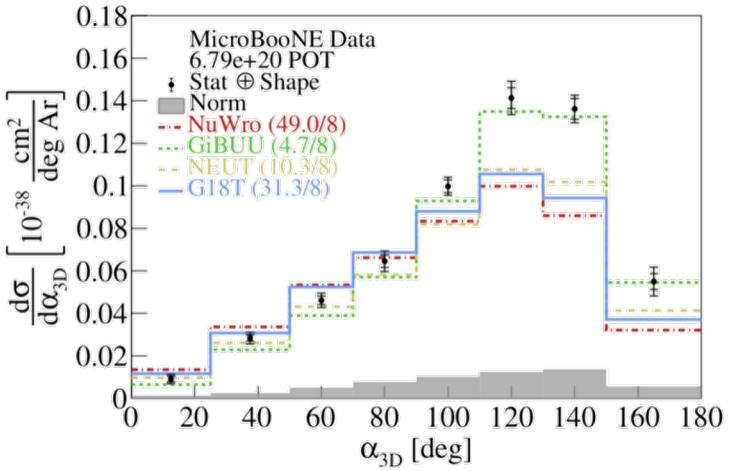
- first flux-integrated single and double-differential cross section measurements in these variables using ν_μ-Ar CC1p0π interactions

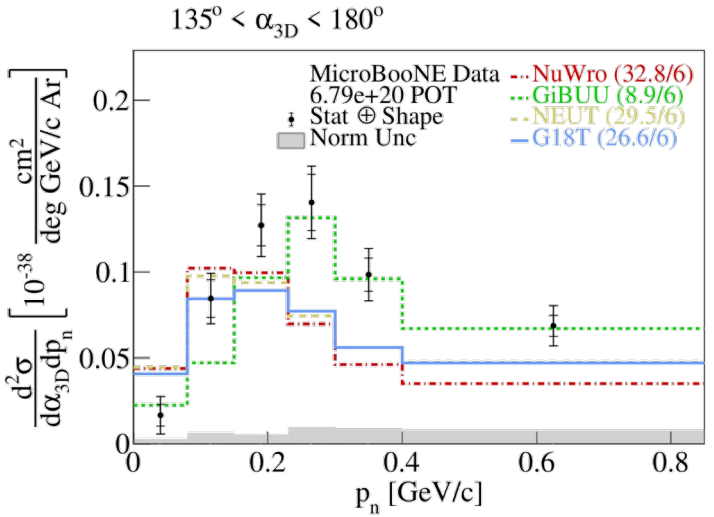
generalised kinematic imbalance variables (GKI)



- powerful, sensitive tool for separating nuclear effects (Fermi motion, FSI, nucleon-nucleon correlation), while minimizing the correlation to the neutrino energy

Single-Transverse Variables (STV) and Transverse Kinematic Imbalance (TKI) also investigated



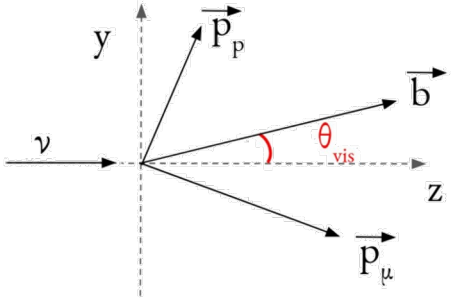


flux-integrated single-differential cross section, clear model discrimination; double-differential also presented

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

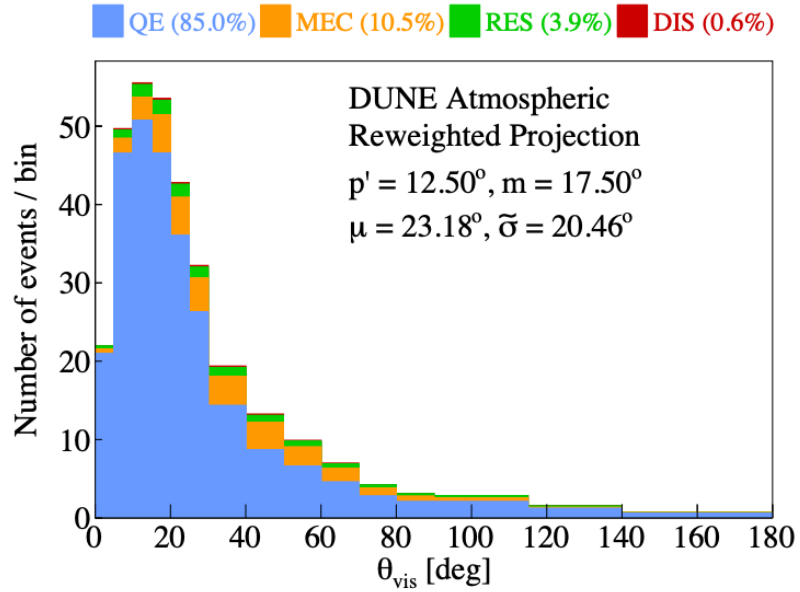
AKI for atmospheric neutrinos

- **A**ngular **K**inematic **I**mbalance

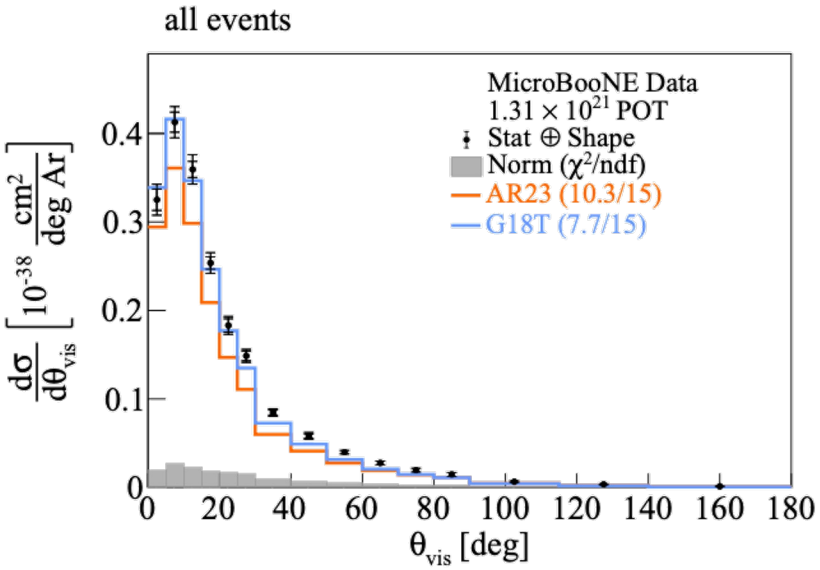


- Validation for a method to infer the neutrino direction, for 1μ1p atmospheric detection
  - Used to inform sub-GeV atmospheric oscillation studies for DUNE

- Differential cross sections sensitive to FSI and hadron reinteractions



arXiv:2504.17758 (2025)

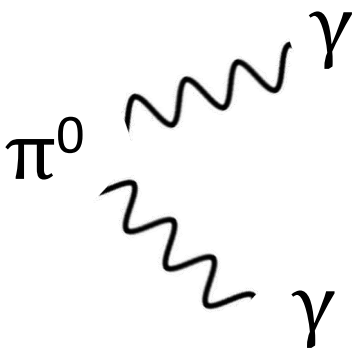


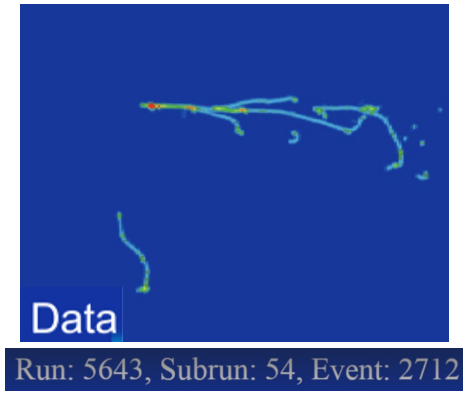
Pion production

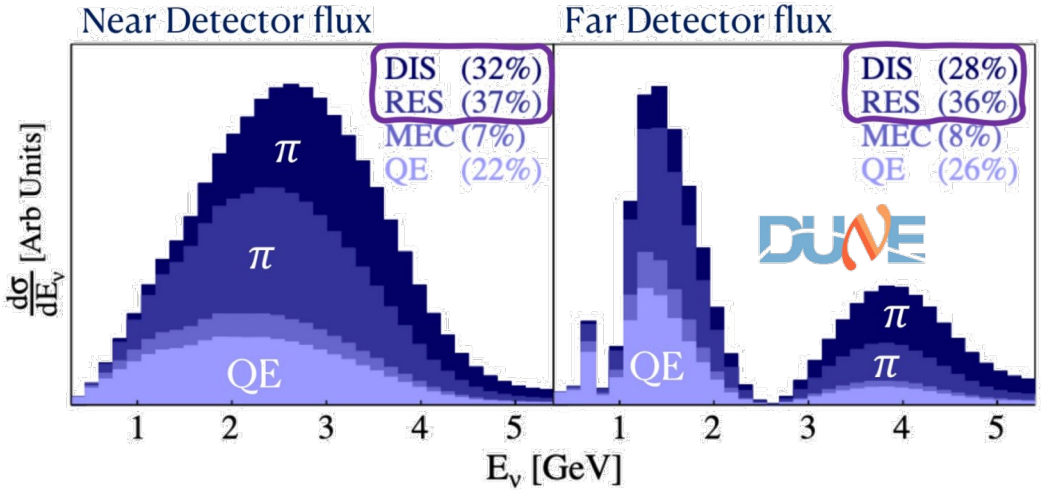
- Poorly modelled
- Relevant for DUNE energy reconstruction
- Background source

Pions at MicroBooNE

- 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
- Resonant pion production historically underconstrained
  - Model improvement needed in QE-SIS-DIS region



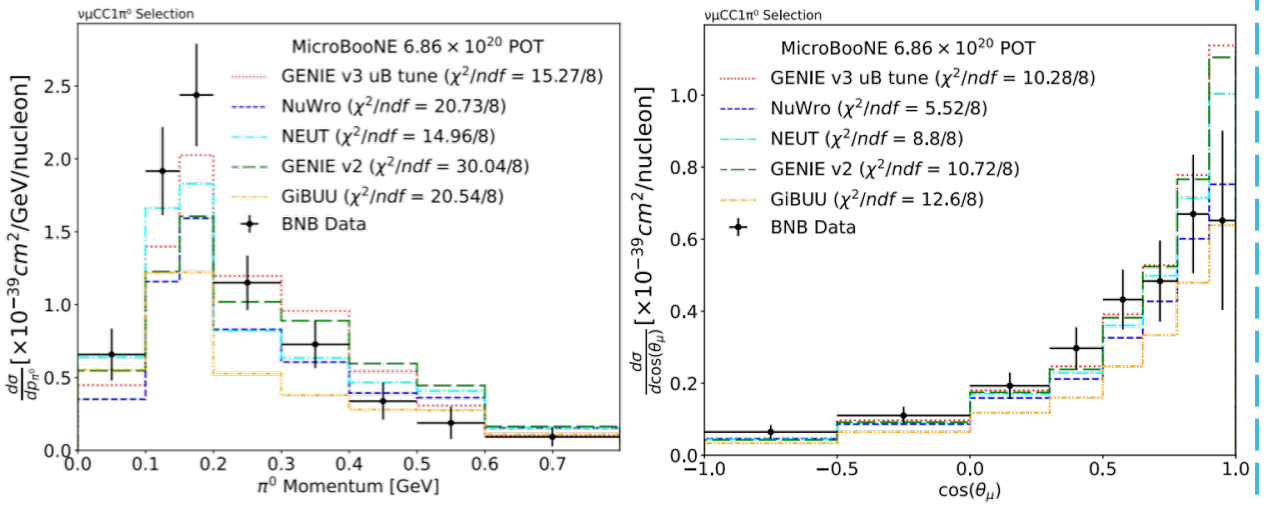




First CCπ^0/NCπ^0 differential cross sections on Ar

CCπ^0

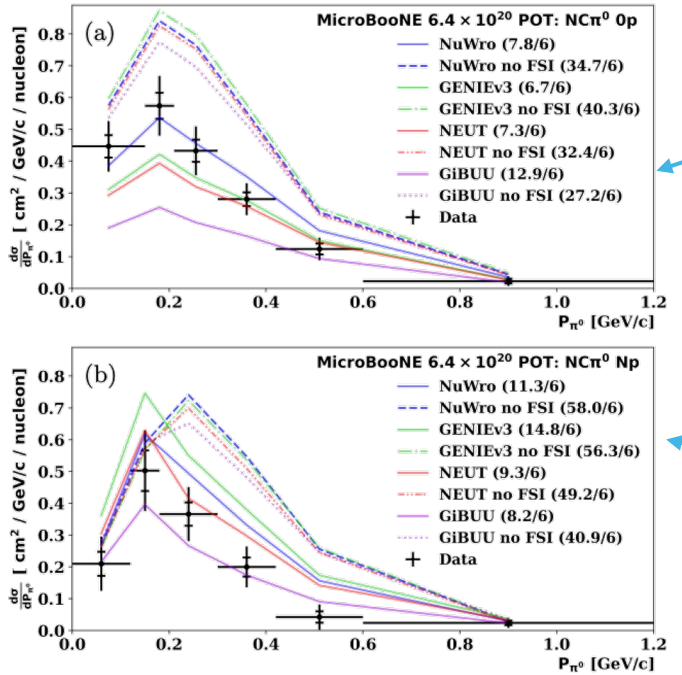
$$\nu_\mu + \mathrm{Ar} \rightarrow \mu^- + \pi^0 + 0\pi^\pm + \mathrm{X}$$



- Differential cross sections presented in muon momentum, neutrino-muon scattering angle, and muon-pion opening angle
- Good data-generator agreement except for forward muon angles and medium momentum ranges

Phys. Rev. D110, 092014 (2024)

NCπ^0



0 protons

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

1 proton

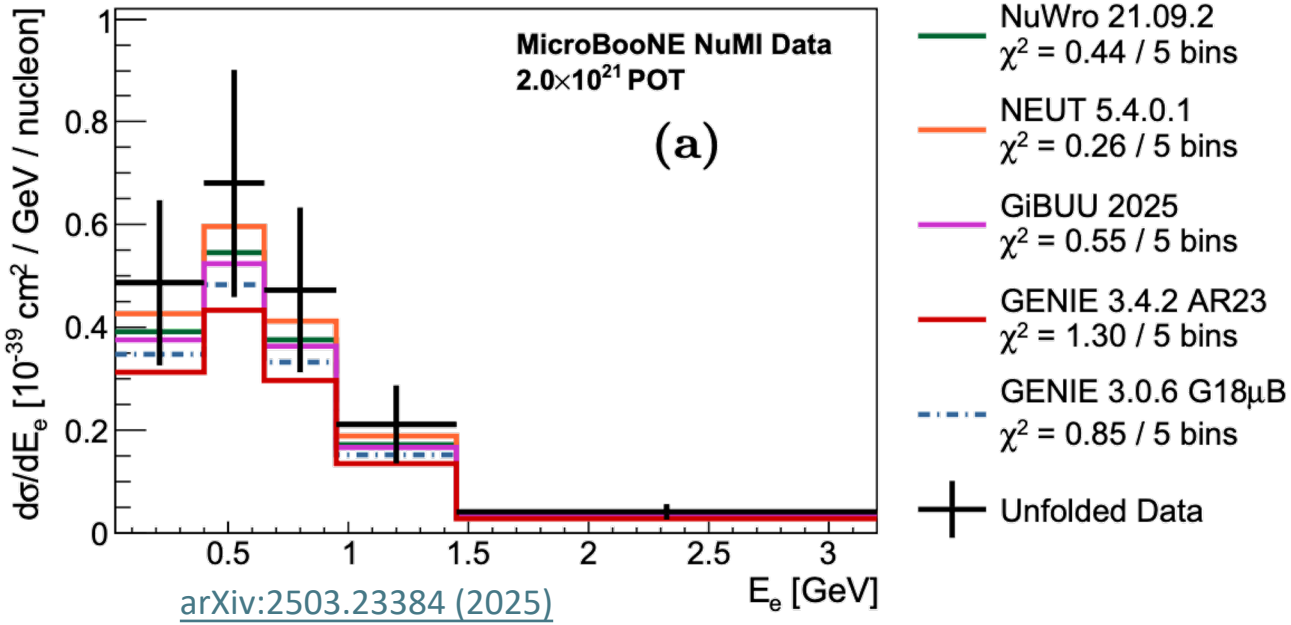
- Double-differential cross section in $\cos(\theta_{\pi^0})$, P_{π^0} also published
- FSI models favoured by data; useful study as NCπ^0 often underestimated by generators

Phys. Rev. Letters 134, 161802 (2025)

First ν_e and $\overline{\nu_e}$ CC$\pi^{\pm}$ flux-averaged cross section on Ar

- First ever differential $\boldsymbol{\nu_e + \overline{\nu_e}}$ $\mathbf{1\pi^{\pm}}$ cross section on argon
  - electron energy, electron and pion angles
- Total cross section **(0.93 ± 0.13 (stat.) ± 0.27 (syst.)) × 10^{-39} cm^2/nucleon**
  - Mean ν_e and $\overline{\nu_e}$ = 730 MeV
- Good model agreement seen
  - Full dataset ν_e CC $1\pi^+$ coming soon

$$\overset{(-)}{\nu}_e + \mathrm{Ar} \rightarrow e^{\pm} + 1\pi^{\pm} + 0\pi^0 + X$$



arXiv:2503.23384 (2025)

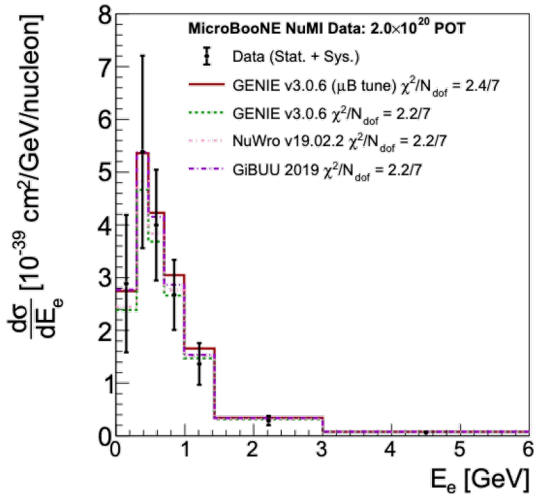
Neutrinos and antineutrinos

- Nuclear effects
- Important for future oscillation experiments

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

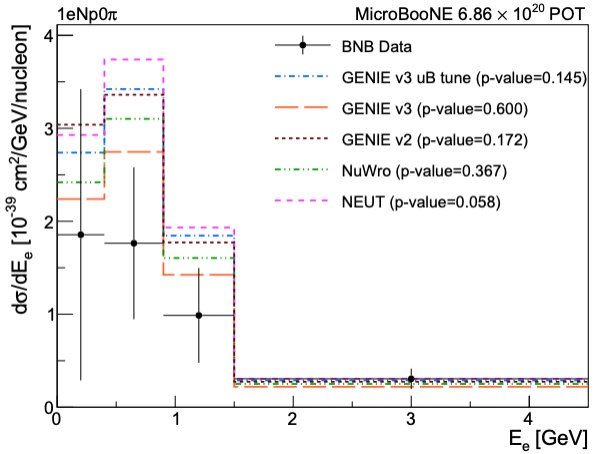
- Due to being off-axis, NuMI provides MicroBooNE a higher flux of ν_e and $\bar{\nu}_e$
  - Neutrino cross sections probe nuclear effects, needed for DUNE oscillation experiments
  - Antineutrinos historically less studied
  - BNB has smaller ν_e content, but exclusive measurements are possible!

- Inclusive measurements of $\nu_e + \bar{\nu}_e$, performed; exclusive ν_e and $\bar{\nu}_e$ measurements in progress
  - Machine learning techniques



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 (1eNp0π)

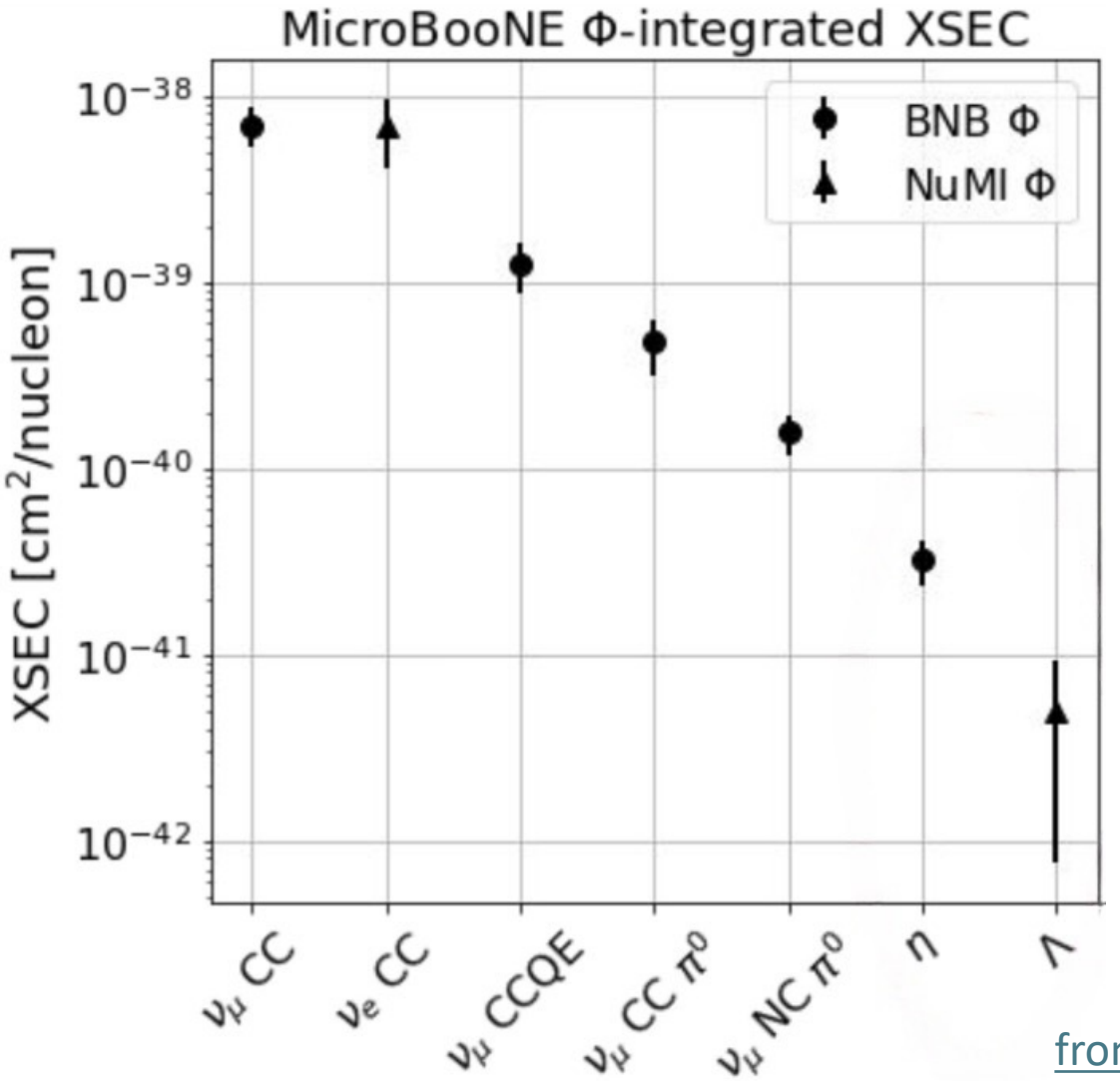
Phys. Rev. D 106, L051102 (2022)

Rare production channels

- First measurements on argon
- Backgrounds for DUNE nucleon decay searches

Rare channels

Plot of MicroBooNE's total cross sections across orders of magnitude



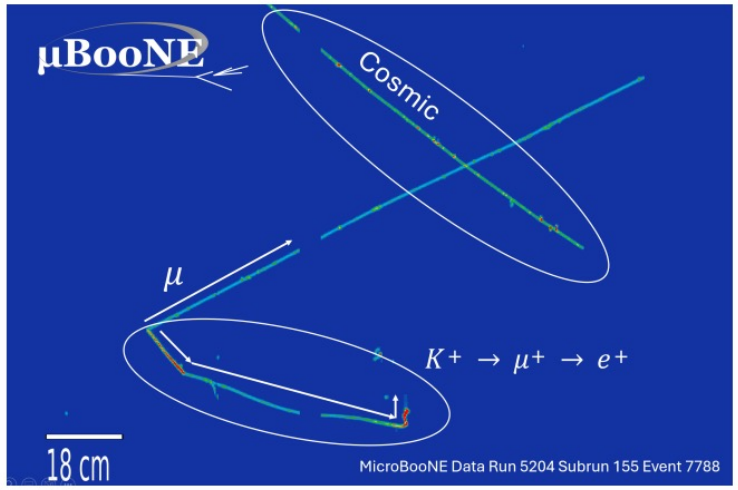
from D. Caratelli

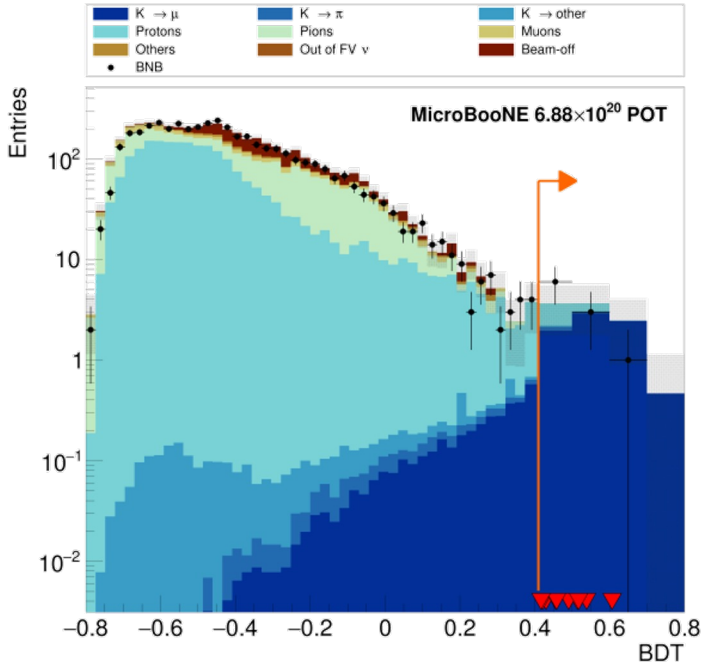
Kaon production

$$\nu_\mu + \mathrm{Ar} \rightarrow \mu^- + K^+ + X$$

- First measurement of ν_μ-induced K^+ production on Ar
- 10 candidate events selected using BDT
- Crucial for background mitigation for DUNE nucleon decay searches

Generator	cross section (10^{-42}cm^2/nucleon)
GENIE v2.12.10	8.67
GENIE v3.00.06	8.42
NEUT 5.4.0.1	9.71
NuWro 19.02.1	10.87
MicroBooNE Data	**7.93 ± 3.27 (stat.) ± 2.92 (syst.)**



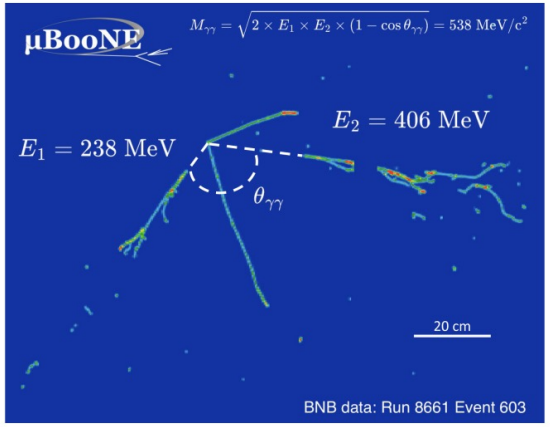


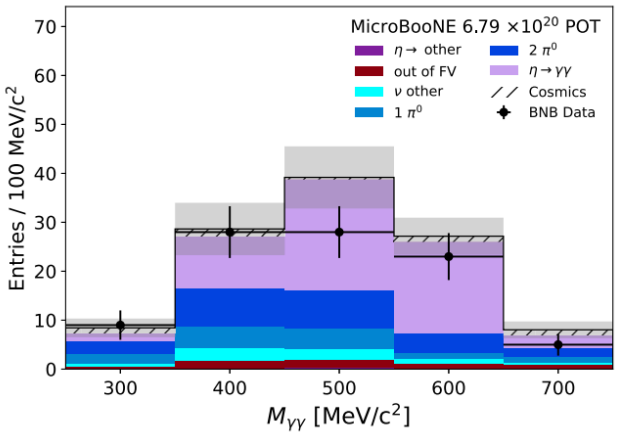
arXiv:2503.00291 (2025)

Rare channels

Important for constraining backgrounds for nucleon decay searches and investigating high order resonances

η meson production





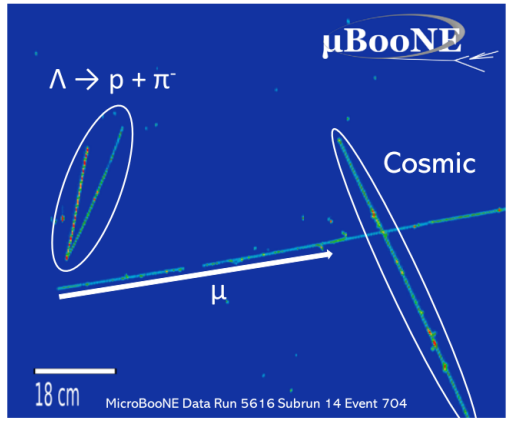
$3.22 \pm 0.84(\text{stat}) \pm 0.86(\text{syst}) \times 10^{-41}\ \text{cm}^2/\text{nucleon}$

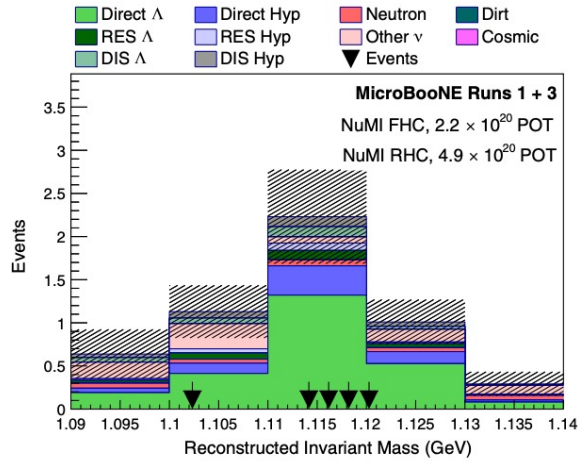
- powerful probe of higher order resonances
- novel calibration technique for EM showers in accelerator experiments

PhysRevLett.132.151801

Λ baryon production

$$\bar{\nu}_\mu + \text{Ar} \rightarrow \mu^+ + \Lambda + X$$





$2.0^{+2.2}_{-1.7} \times 10^{-40}\ \text{cm}^2/\text{Ar}$

- first measurement of this Cabibbo-suppressed process on Ar

PhysRevLett.130.231802

Low-energy regime

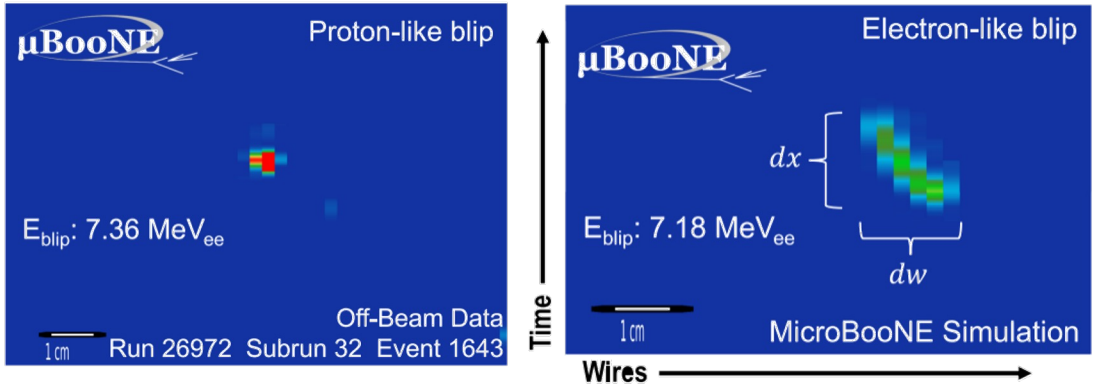
- High reconstruction resolution
- Pushing the limits of LArTPC technology

Low-energy regime

Improving future physics sensitivity (e.g. DUNE supernova neutrinos)

MeV-scale reconstruction

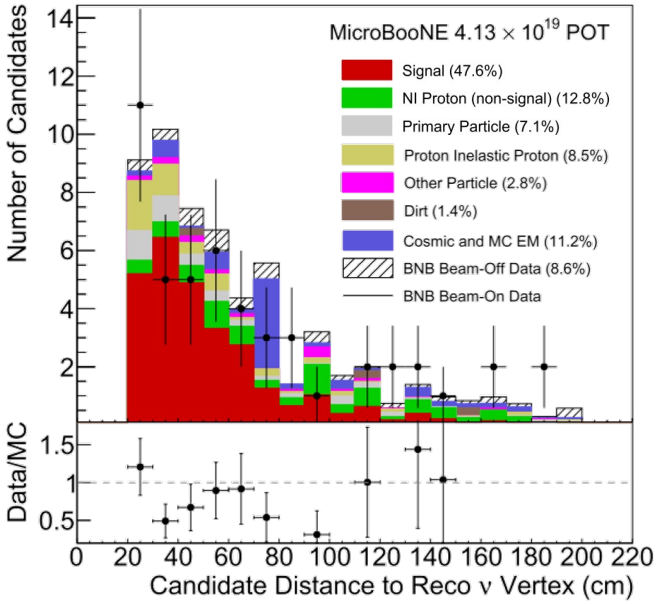
PhysRevD.111.032005

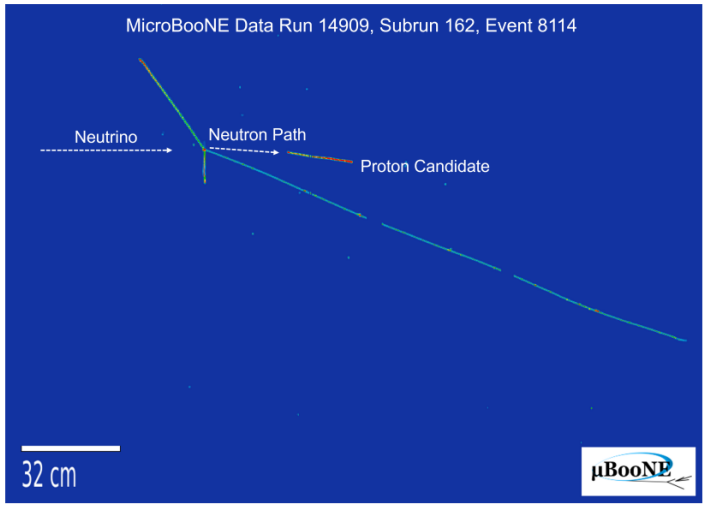


- Using ‘blips’: MeV-scale energy depositions
- Verifies electron energy calibration to few percent

Neutron identification

Eur. Phys. J. C **84**, 1052 (2024)





- Neutrons found using secondary protons separated from neutrino vertex
  - Applicable to other LArTPCs
  - Measures neutron production from neutrinos; could provide statistical separation between neutrinos and antineutrinos
- Prospects for efficiency improvements

Future analyses

- Several cross section measurements in progress…
- New/extended results expected using whole dataset, or NuMI + BNB
- Implementing updated NuMI flux
  - More accurate with better geometric and physics models

CC inclusive

- ν_μ CC inclusive @ NuMI
- ν_e/ν_μ ratios @ BNB, NuMI
- 3D E_ν, E_μ, E_{had} @ NuMI & BNB
- anti-ν_e @ NuMI

Pion production

- ν_μ CC1π^+ @ BNB & NuMI
- ν_μ CCNπ @ NuMI
- 1D ν_μ CCπ^0 @BNB
- 2D ν_μ CC/NC π^0 @ BNB
- 2D $\nu_{e,\mu}$ NCπ^0 @ BNB

CC/NC 0π

- 2D ν_μ CC1p0π GKI @ BNB
- 2D ν_μ CCNp0π @ BNB
- 1D ν_e CC0πNp @ NuMI
- 1D ν_μ NC1p0π @ BNB

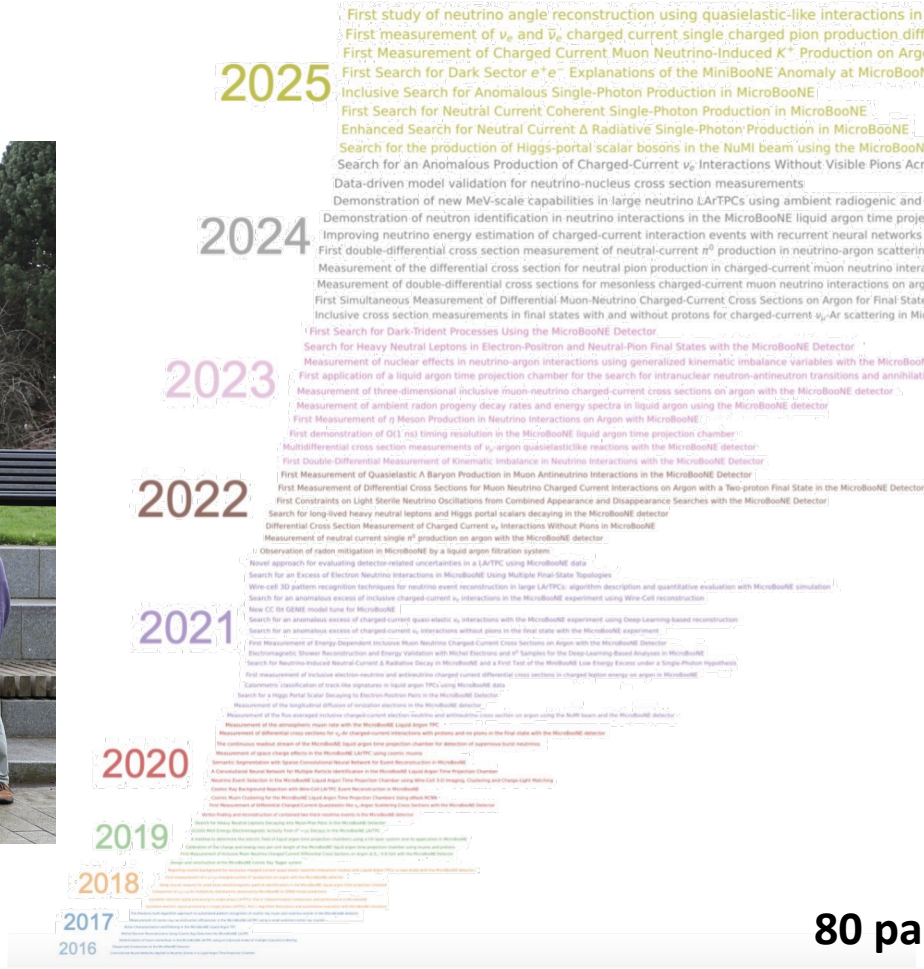
Rare channels & novel techniques

- MeV-scale physics
- Low-energy neutrons @ BNB

Summary

- MicroBooNE is a LArTPC neutrino detector based at Fermilab
  - Large, well-understood ν-Ar interaction dataset, several **first measurements of ν-Ar** interactions
- Recent results in pion production, detailed kinematics, rare channels, and MeV-scale regime
  - background constraints and model studies critical for the broader LArTPC neutrino physics program
- Still more to come!
  - Further analyses aim to utilise the full dataset, incorporate NuMI and BNB data together, and implement updated NuMI flux

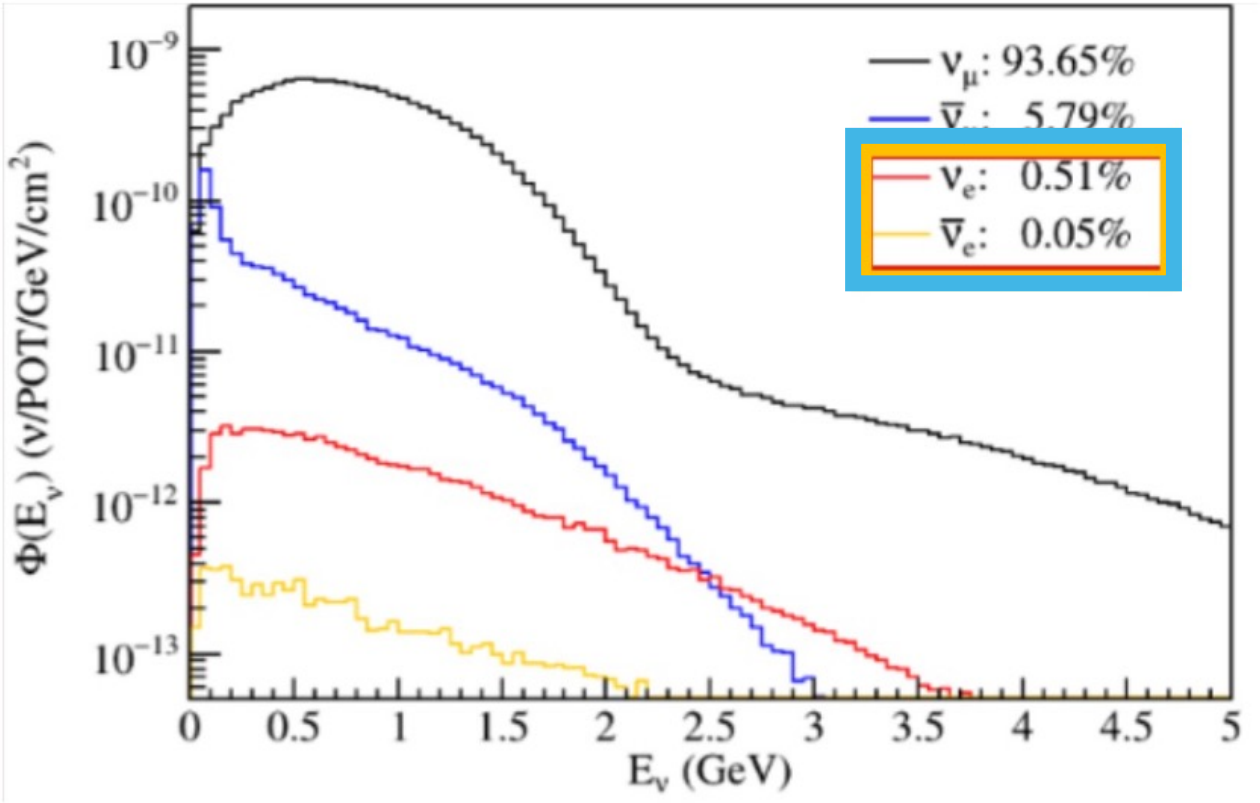
Thank you!



80 papers and counting!

Backup

BNB flux at MicroBooNE



NuMI flux at MicroBooNE