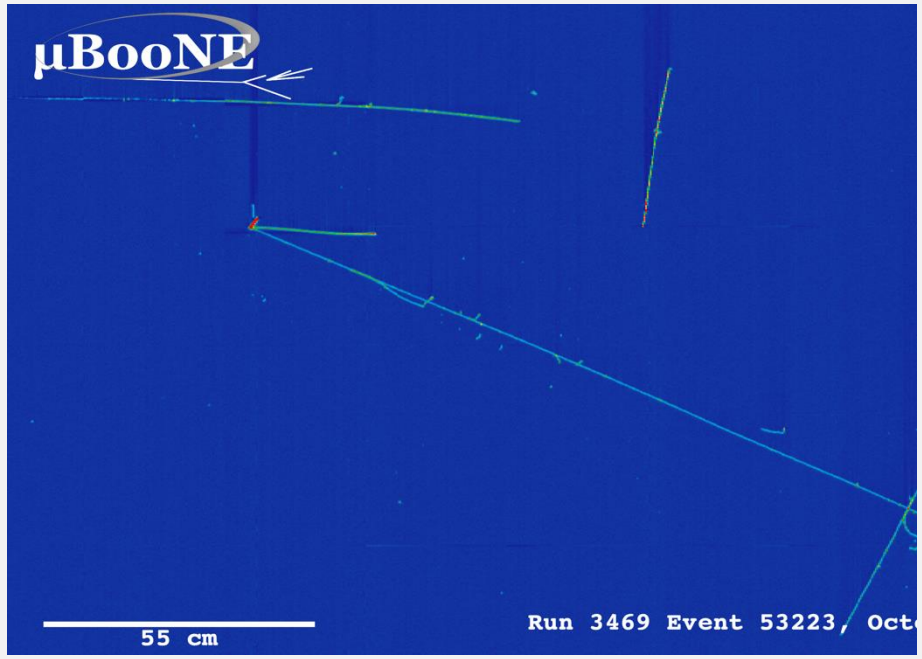
NOW 2024

Neutrino Oscillation Workshop

# Recent MicroBooNE neutrino cross section results

Jaroslaw Nowak

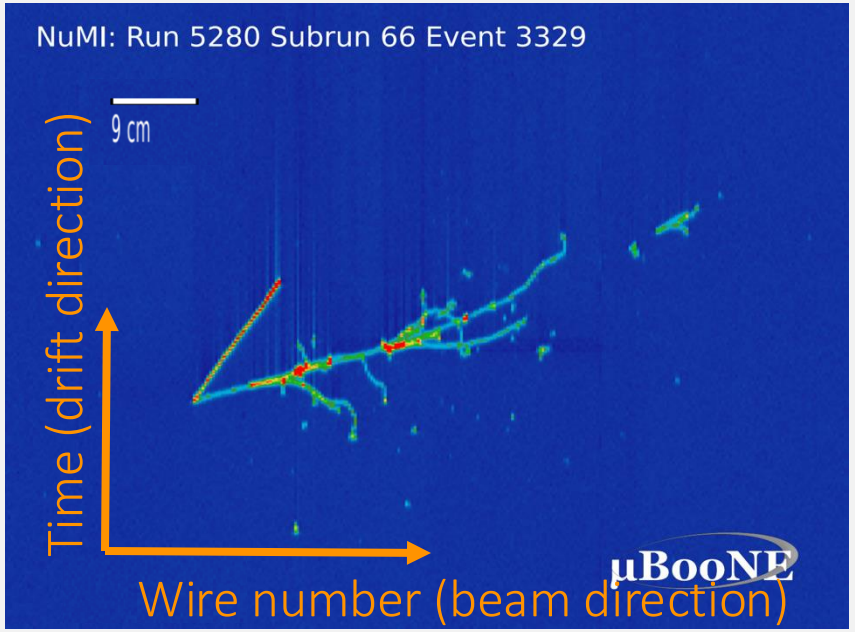
for the MicroBooNE Collaboration

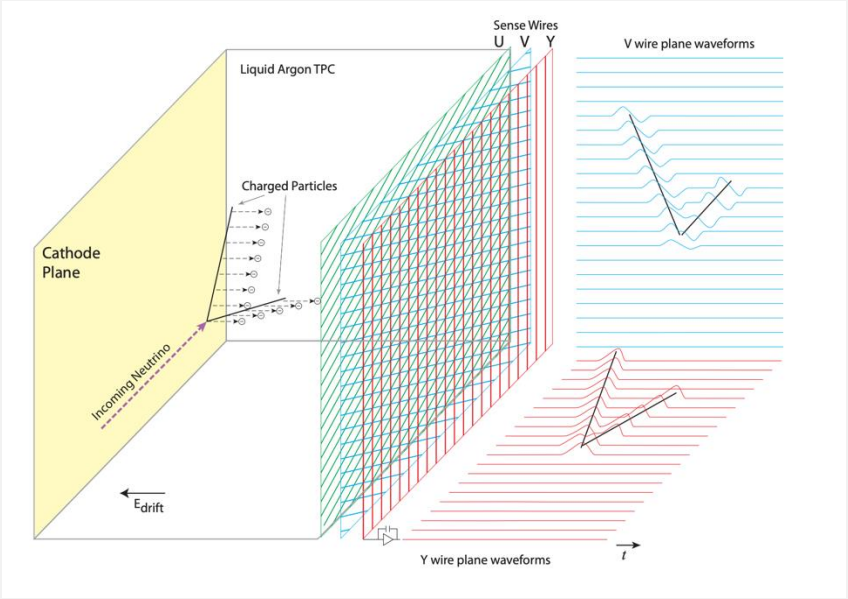


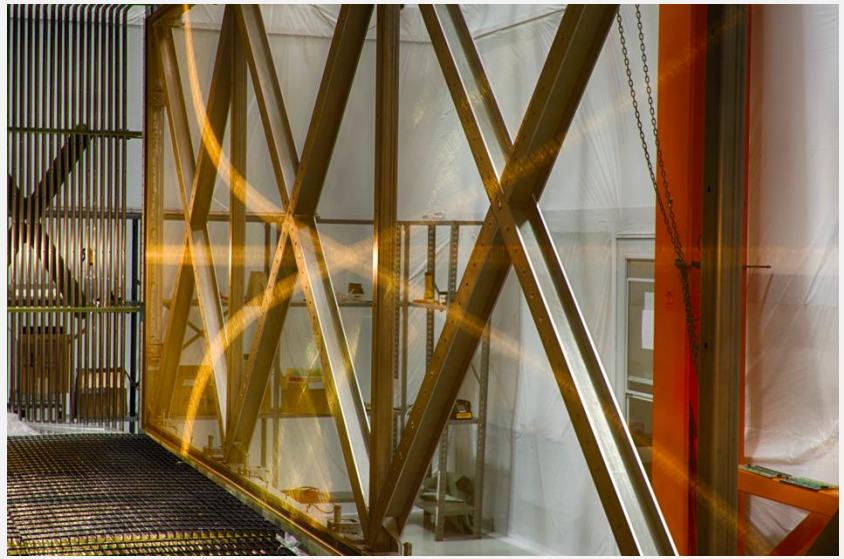

Lancaster University

# Liquid argon time projection chamber

- Fully-active tracking calorimeter
- **3 planes** of wires (vertical, +60°, -60°) with **3mm spacing**
- **32 PMTs** collect light from flash at time of interaction
- mm-level resolution, low thresholds, excellent particle identification



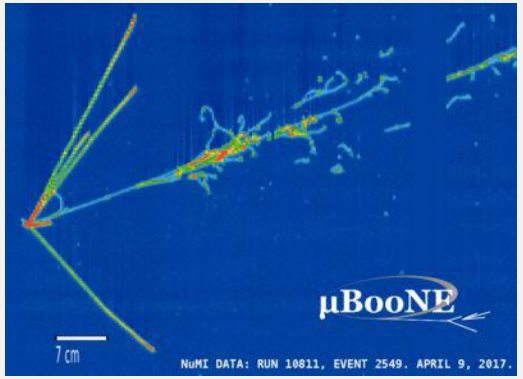
JINST 12 P02017 (2017)

# MicroBooNE: 85-tonne active mass LArTPC

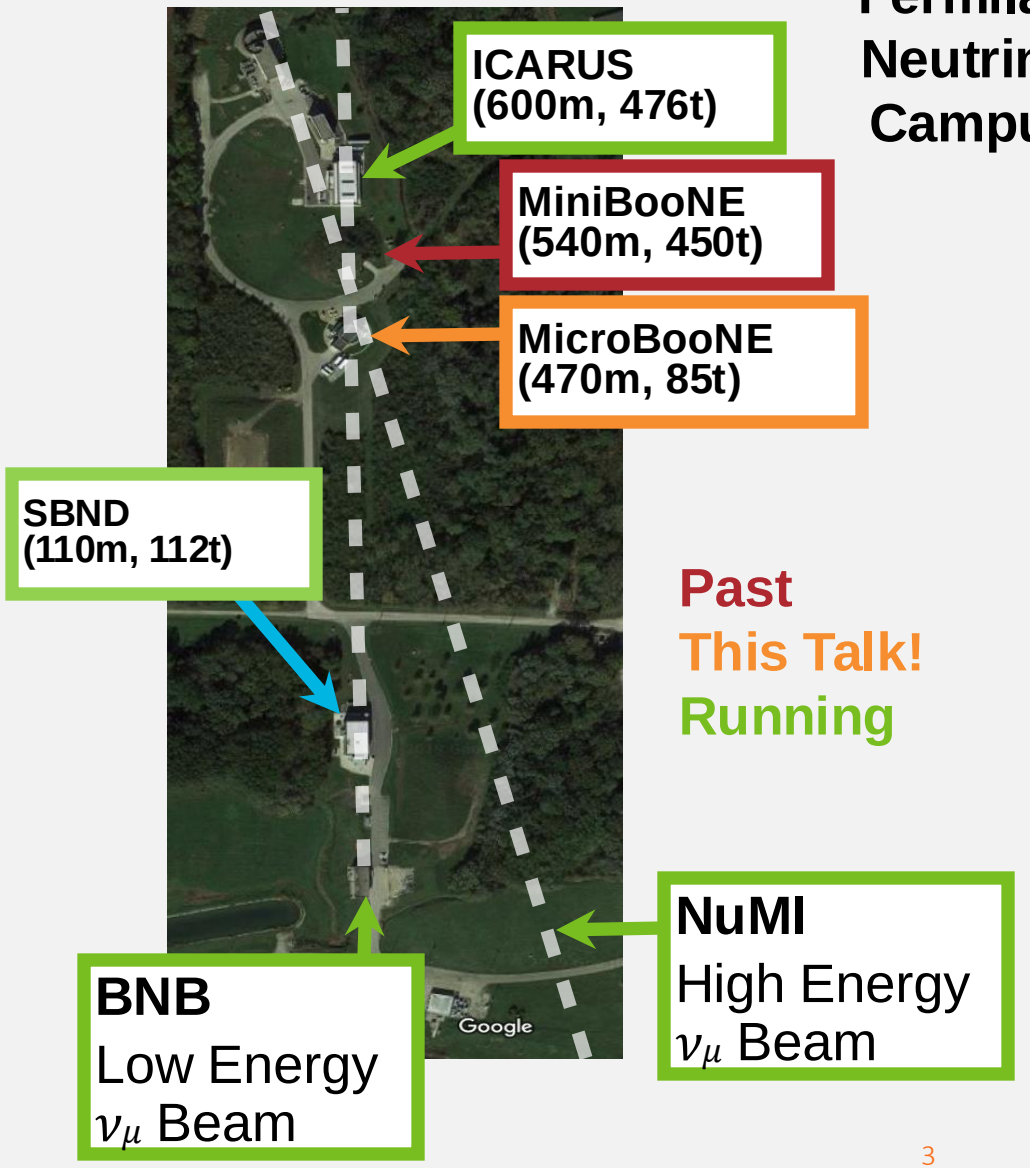
Sits in **two neutrino beams** at Fermilab: BNB and NuMI

Completed 5 years of beam physics data-taking: **world's largest dataset of neutrino interactions on argon (~0.5M)**

MicroBooNE has harnessed the power of LArTPC detector technology to make valuable new precision measurements




JINST 12 P02017 (2017)



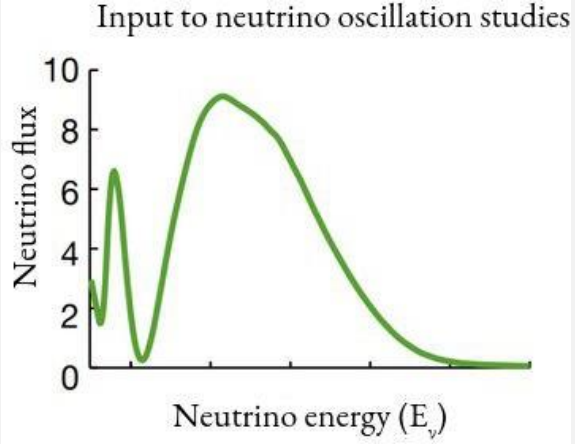
# Leptonic and hadronic system modeling

- Oscillation measurements require accurate energy reconstruction of both lepton and hadron kinematics

Lepton Hadrons

$E_\nu = E_l + \omega$

- Leverage LArTPC reconstruction and particle identification tools to obtain $E_{reco} \simeq E_\nu$



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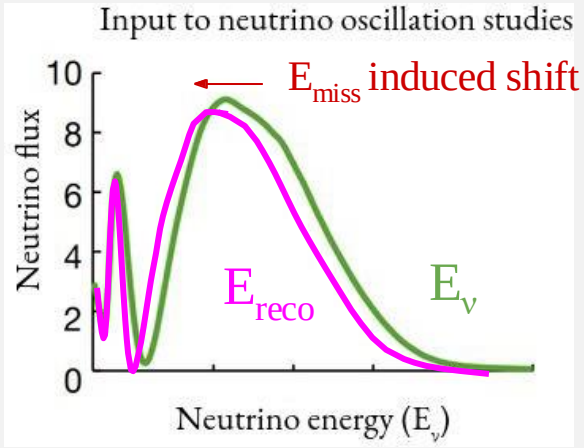
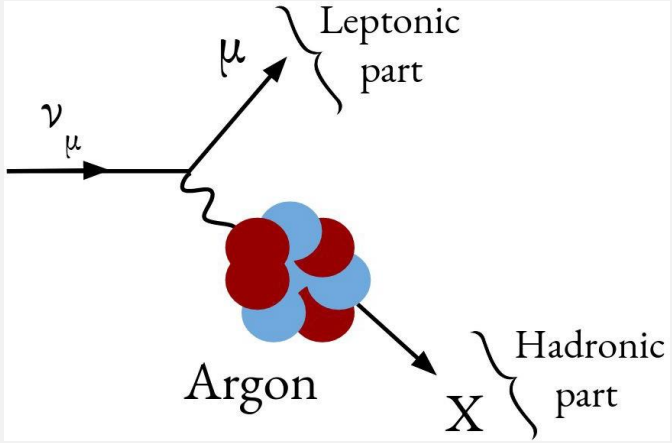



- The TPC cannot reconstruct all particles, and we need to correct for missing energy ($E_{miss}$) which might be large fraction of total energy balance

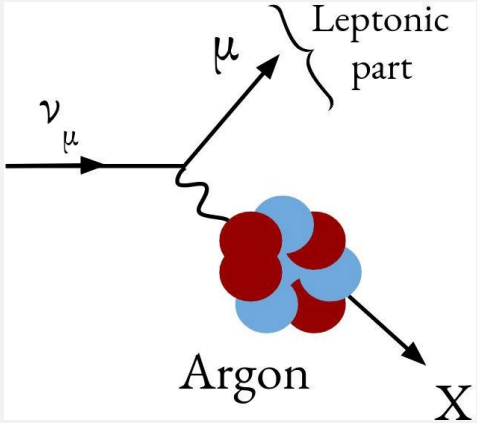
$$\omega = E_{had} + E_{miss}$$

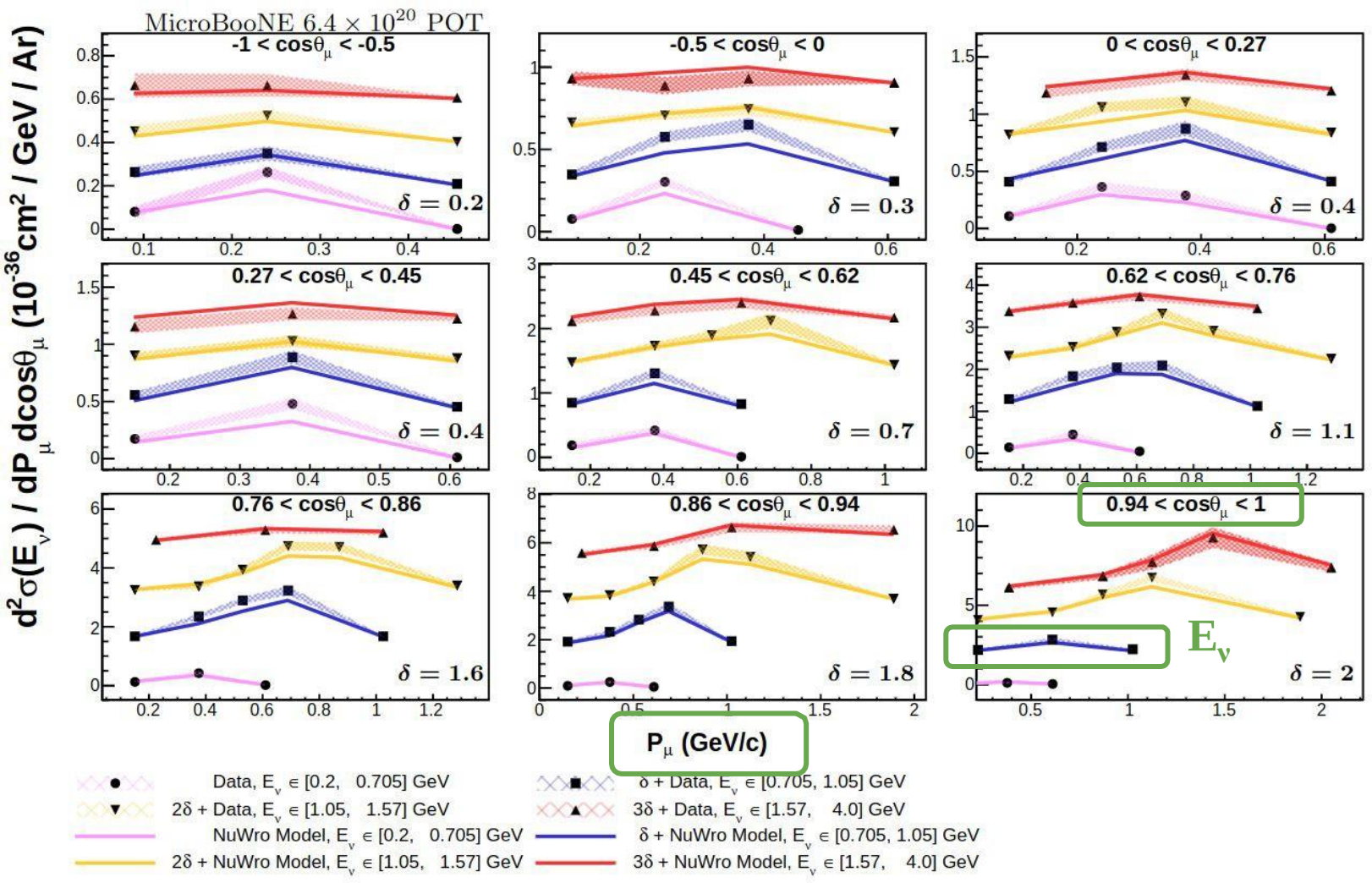
- Dedicated analyses developed to investigate both parts



# Leptonic system modeling

*inclusive muon-neutrino charged-current cross section on argon*



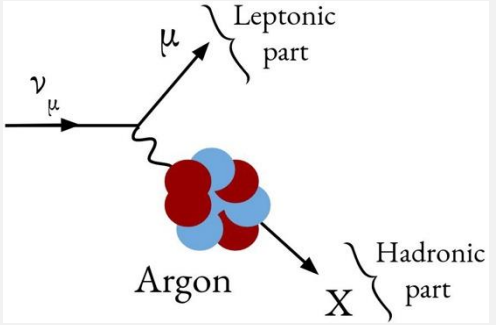




- First three-dimensional cross-section result on argon
- Extensive validation to detect potential missing energy mismodeling
- Enables cross section measurements as a function of the neutrino energy ($E_\nu$)

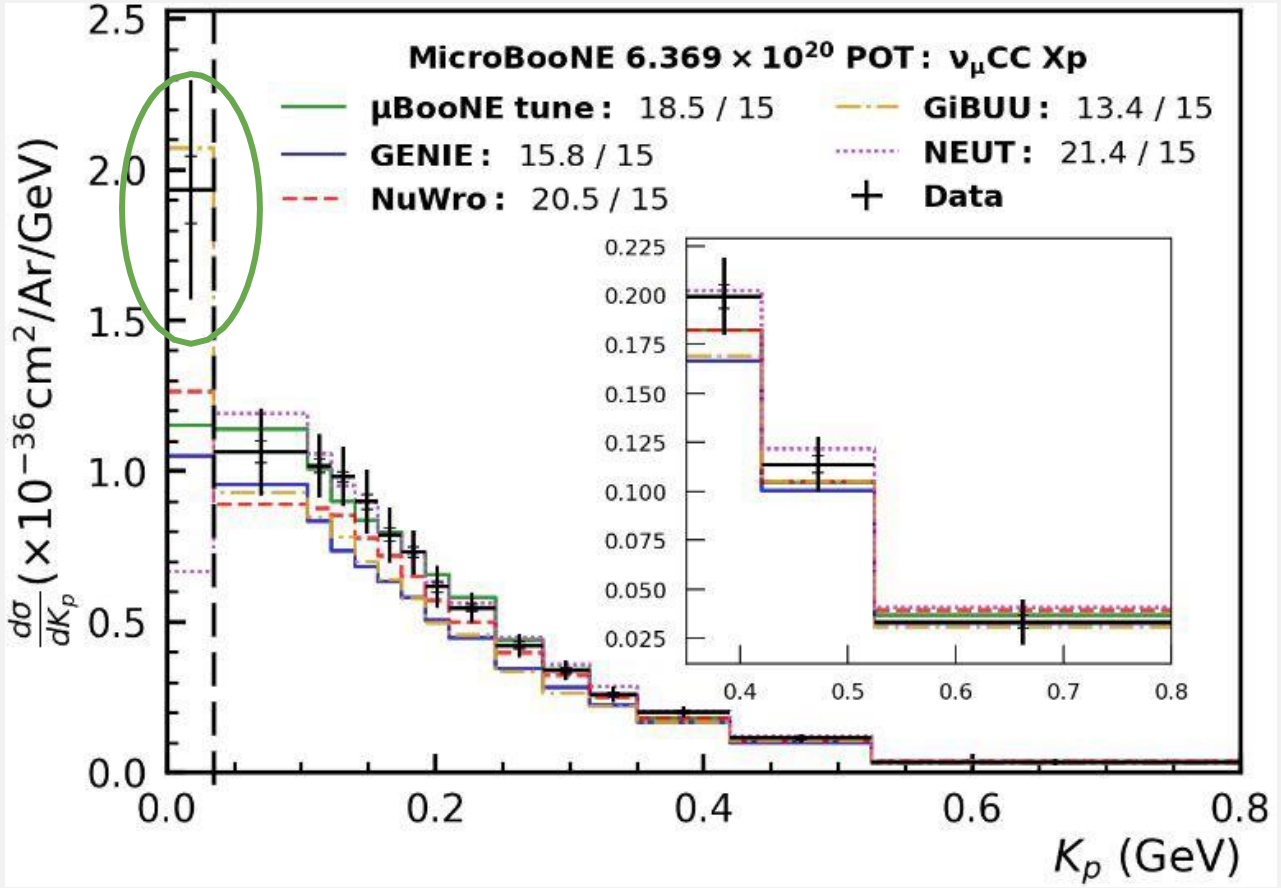
[arXiv:2307.06413](arXiv:2307.06413)

$\chi^2$ /ndf = 212.1/138, p-value = 0.0001

# Hadronic system modeling




0p N≥1p

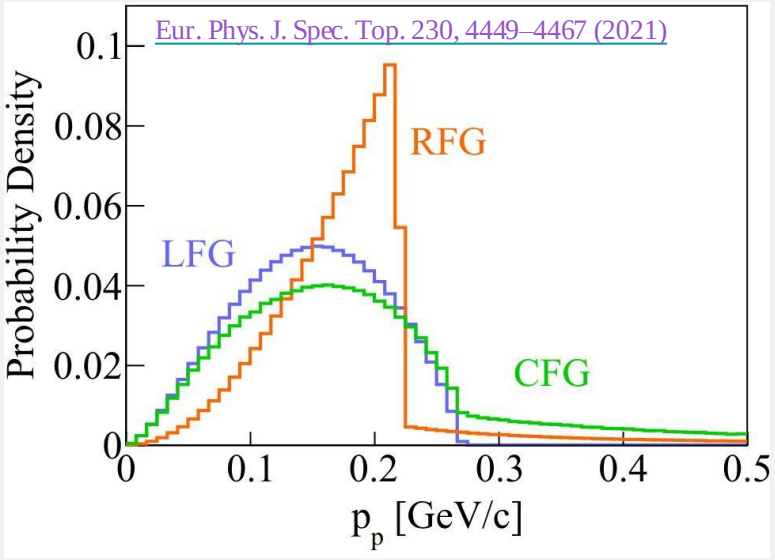



- Leveraging low proton detection threshold to investigate events with and without detected protons
- Extensive model validation to detect potential biases
- Additional evidence for a need for sophisticated treatment of hadron reinteractions

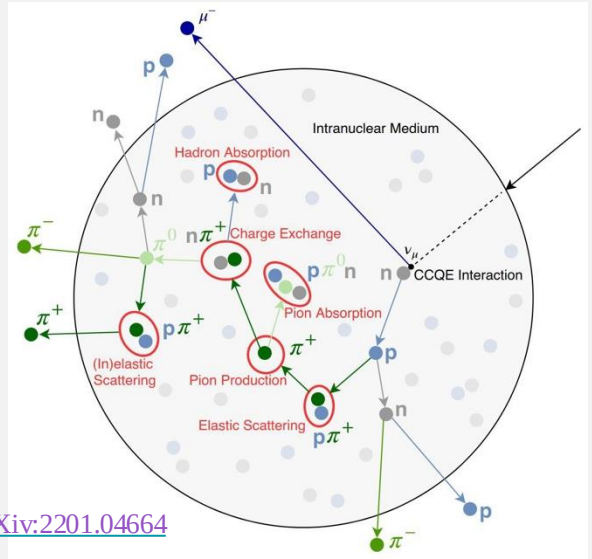
Phys. Rev. D 110, 013006
Phys. Rev. Lett. 133, 041801

# Nuclear effects with pionless analyses

## Nuclear ground-state distributions

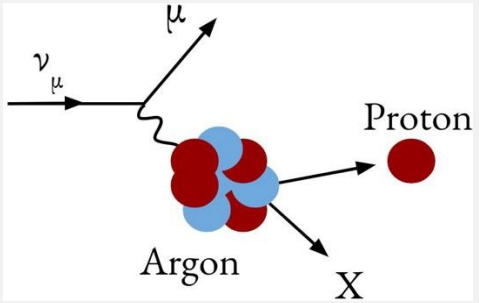


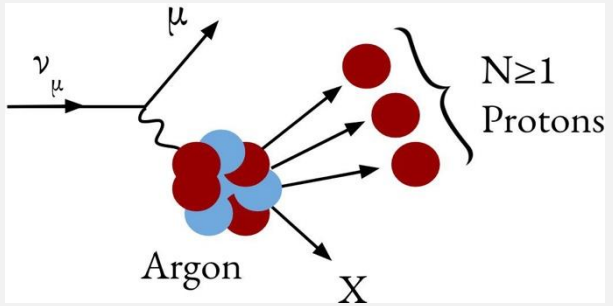

## Hadron reinteractions



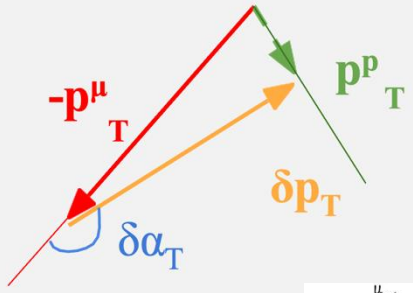

arXiv:2201.04664

- Leverage high-quality LArTPC proton reconstruction and low detection thresholds (250 MeV/c)
- Probing nuclear ground-state distributions and hadron reinteractions on heavy argon nuclei
- Two analyses investigating nuclear effects using transverse and generalized kinematic imbalance

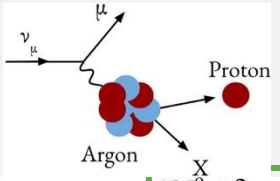


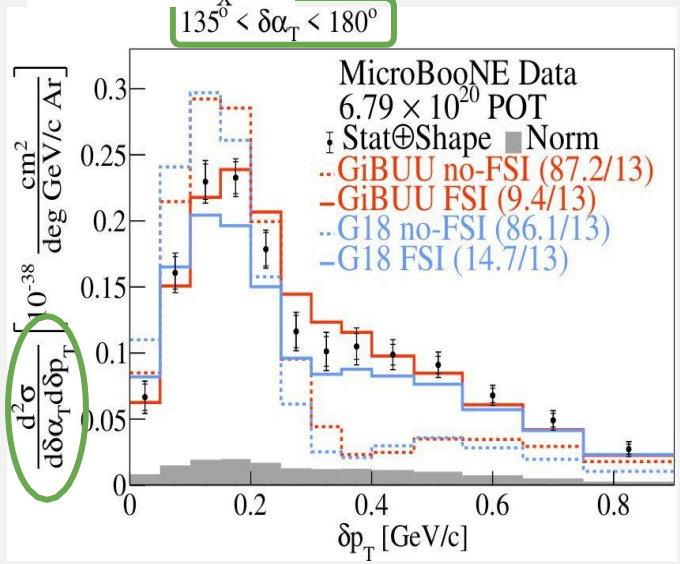



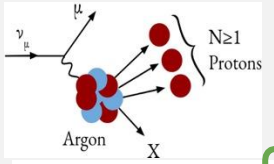
# Transverse kinematic imbalance

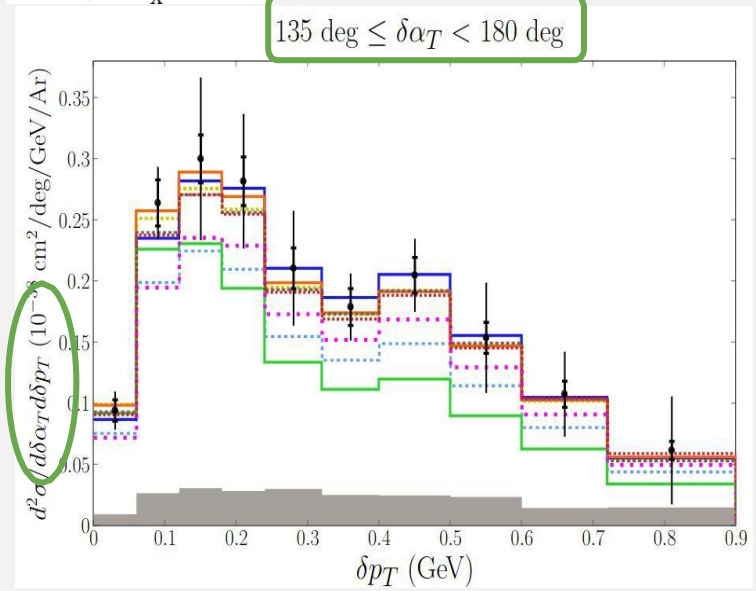


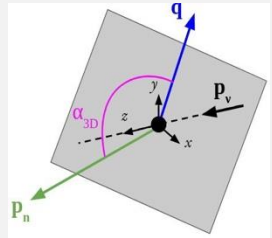

- First investigation of nuclear effects in two transverse kinematic imbalance variables simultaneously on argon
- Enables isolation of nuclear effects more completely than previous measurements in one variable

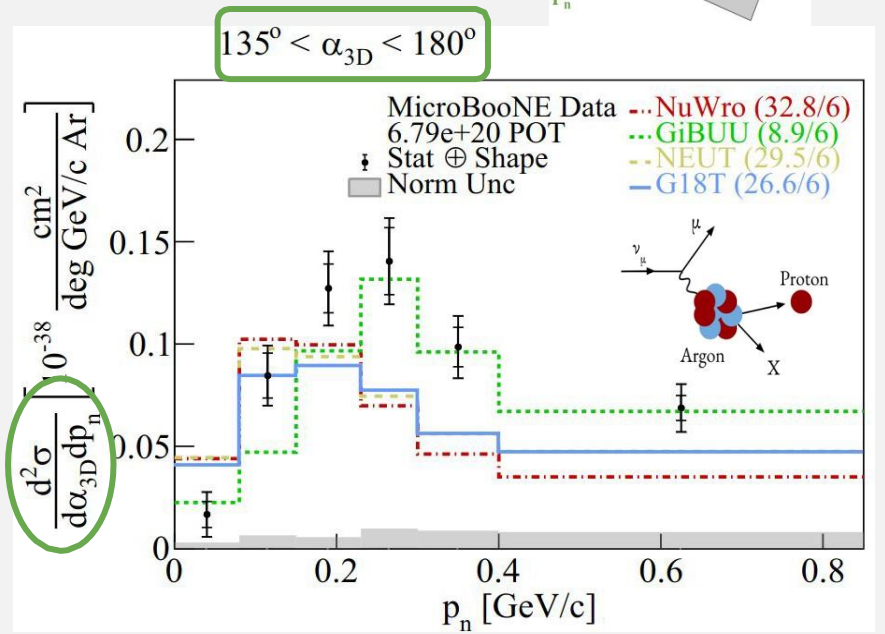


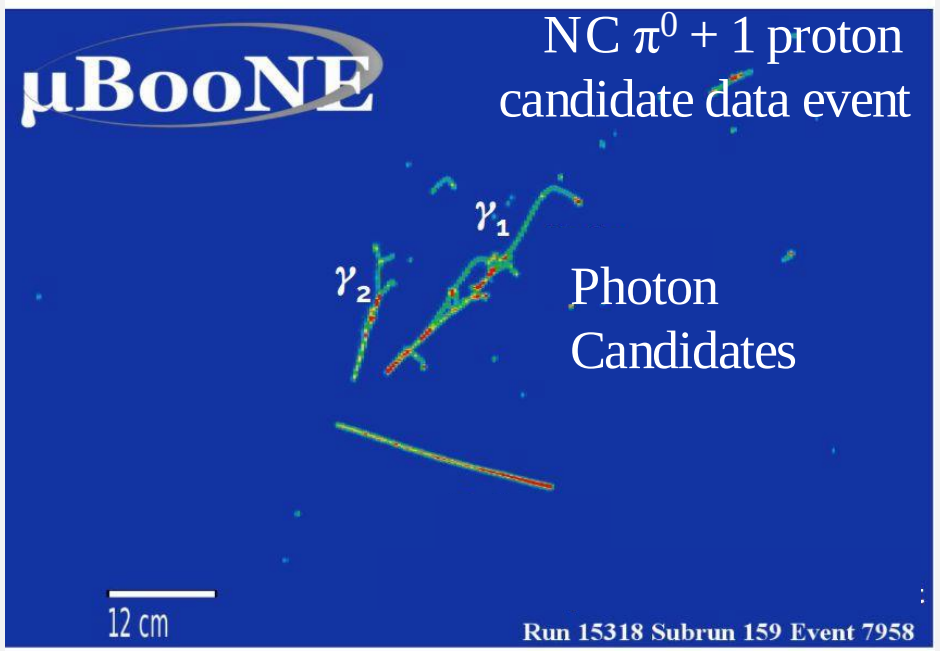



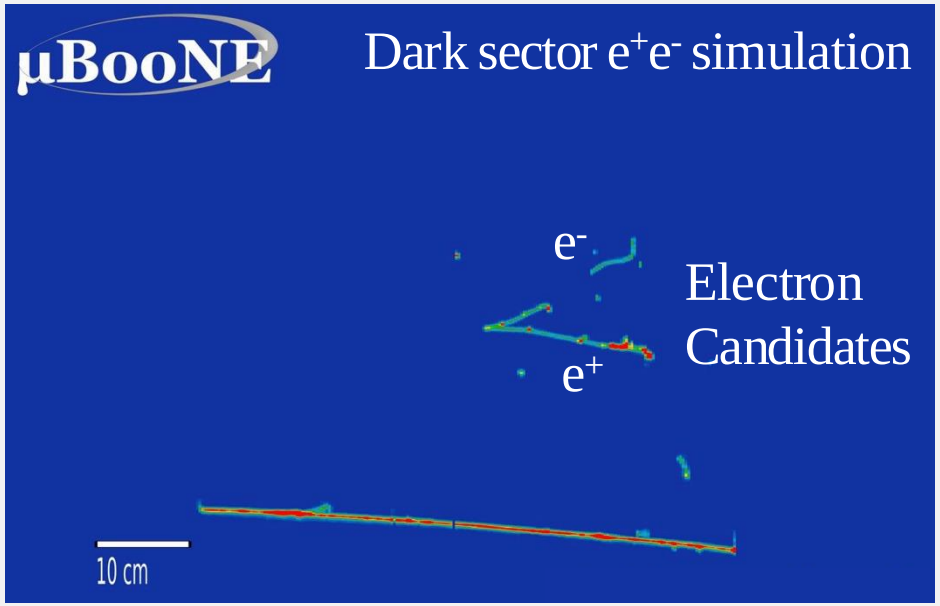

[Phys. Rev. Lett. 131, 101802 (2023)]
[Phys. Rev. D 108, 053002 (2023)]

[arXiv:2403.19574]

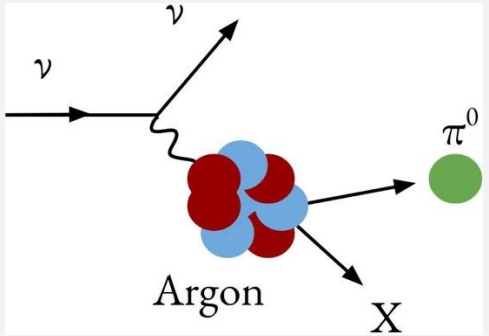
[Phys. Rev. C 95, 065501 (2017)]
[Phys. Rev. D 109, 092007 (2024)]

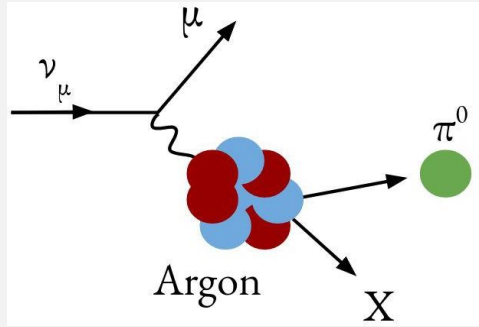
# $\pi^0$ production measurements



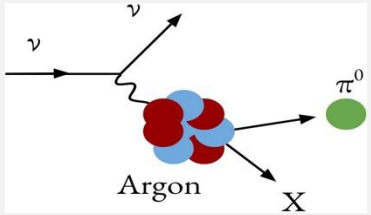



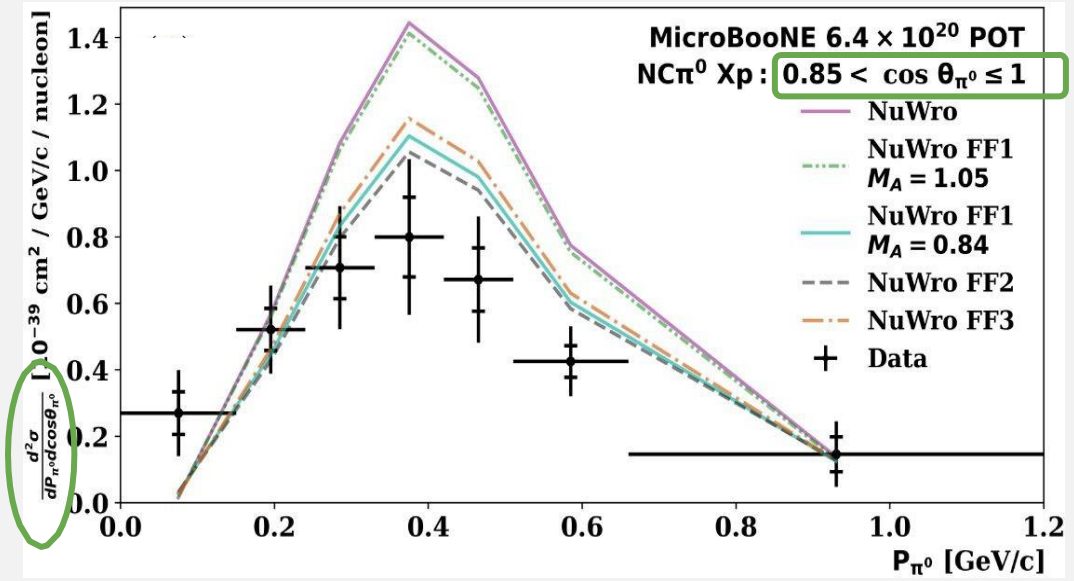

- Significant role in $\nu_e$ appearance studies
- $\pi^0$ events are an irreducible background for single photon and $e^+$ $e^-$ Beyond Standard Model searches
- Probed with neutral and charged current $\pi^0$ measurements



# Neutral current $\pi^0$ production

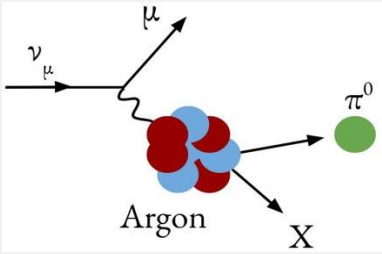


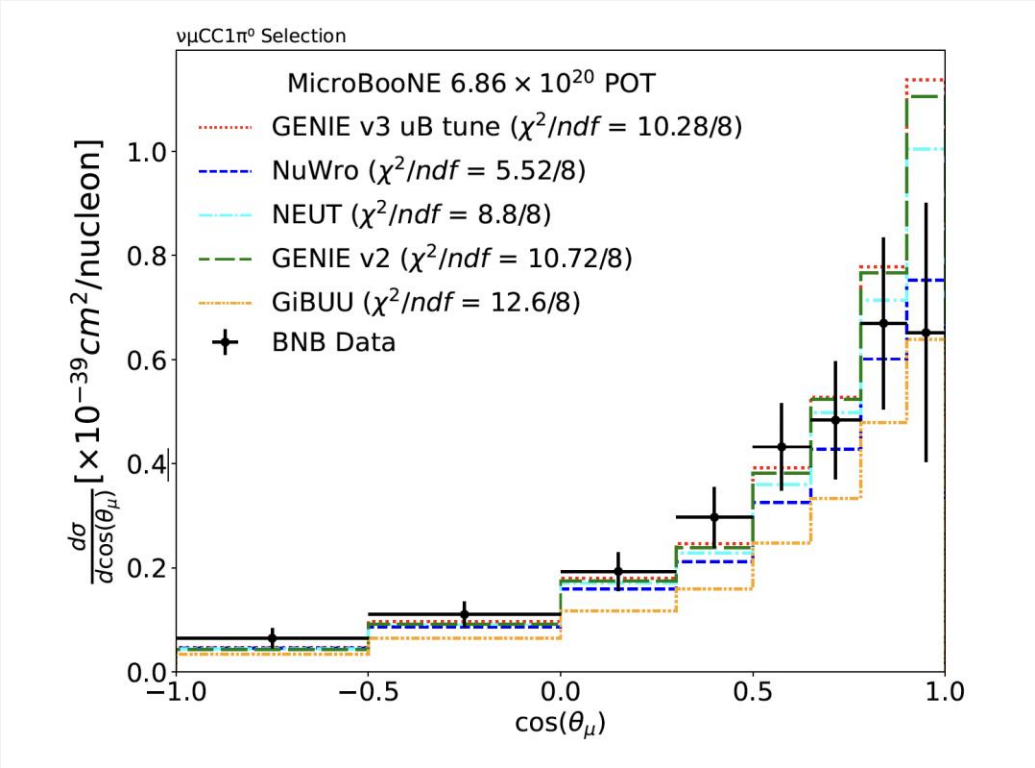

- Dominated by $\Delta(1232)$ resonances
- First measurement in two $\pi^0$ kinematic variables simultaneously
- Systematic overprediction when compared to data
- Demonstrated sensitivity to form factor modeling and hadron reinteractions

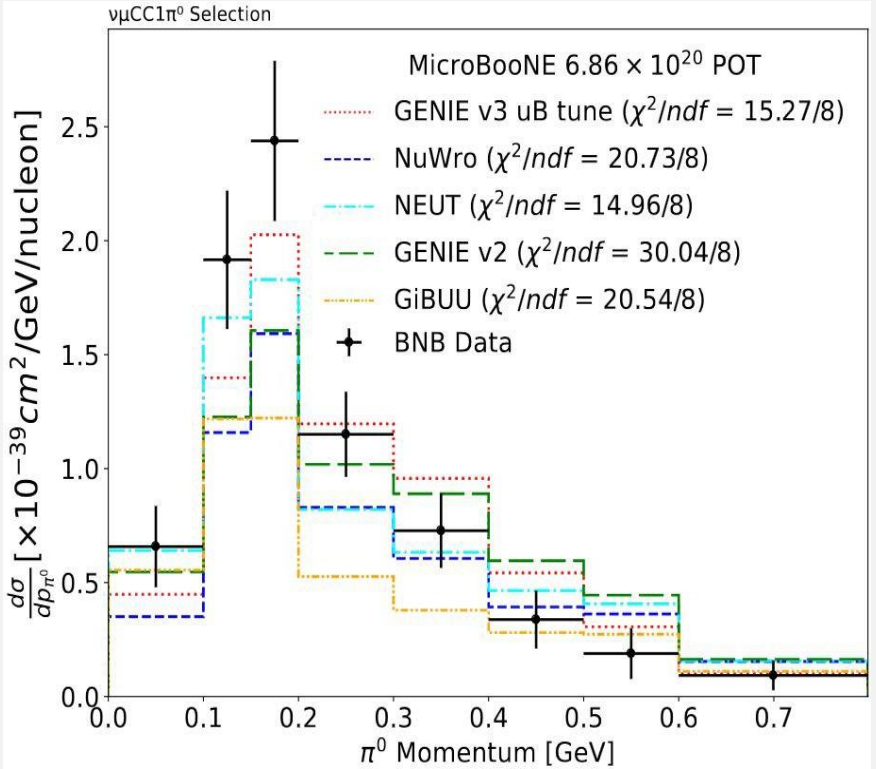
arXiv:2404.10948

# Charged current π⁰ production



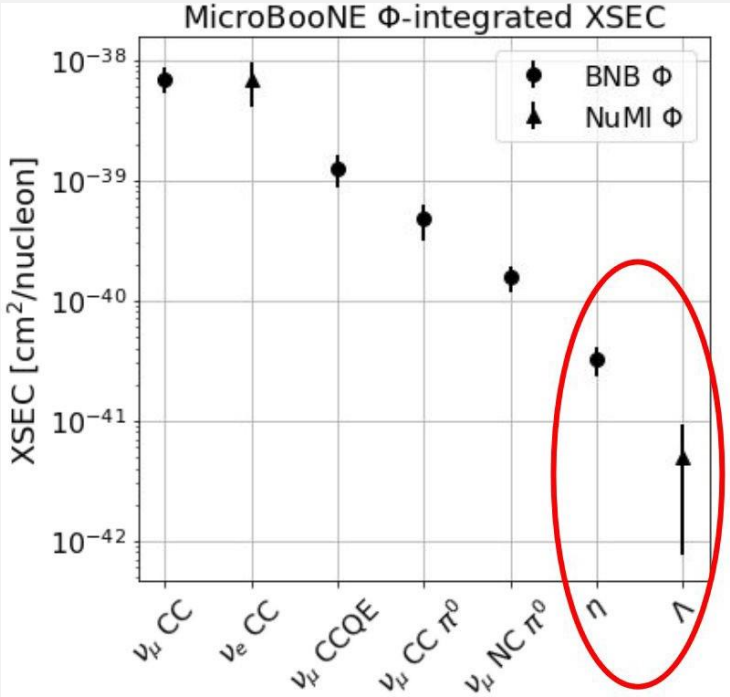

- Dominated by Δ(1232) resonances
- Mismodeling identified in $\pi^0$ momentum and muon forward angles
- Shortcomings associated with the shape of medium $\pi^0$ momentum.




arXiv:2404.09949

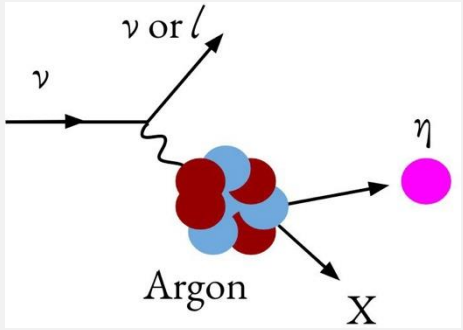
# Novel identification techniques

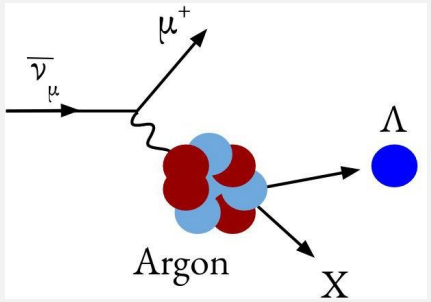


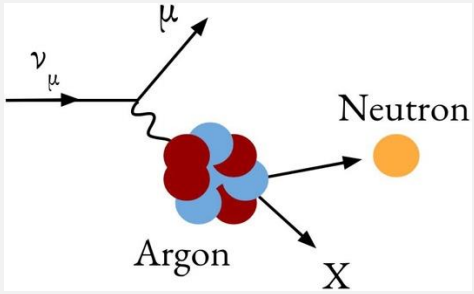

High-precision era requires

- accurate cross sections of even rarest processes
- developing novel identification techniques of challenging topologies

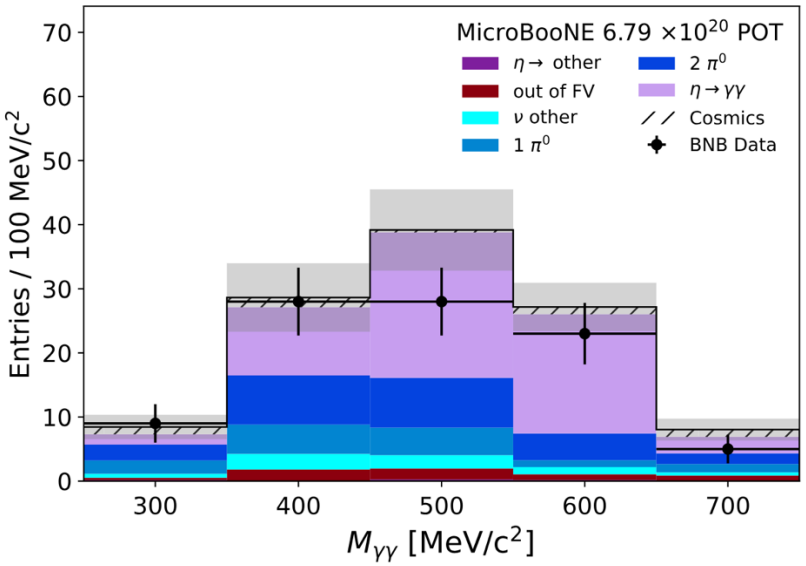
Designed relevant analyses to address these needs

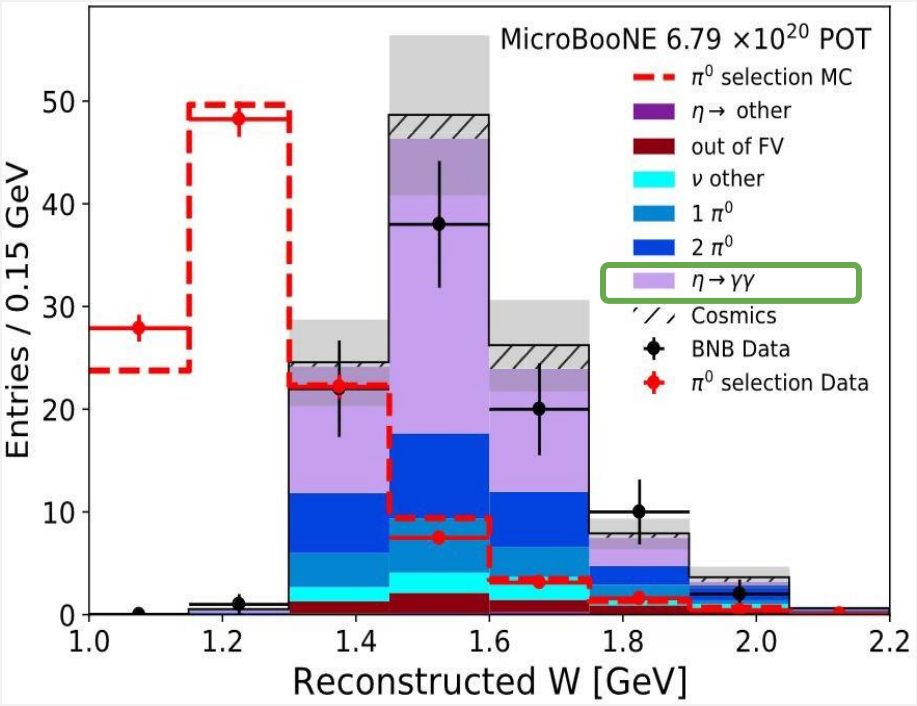


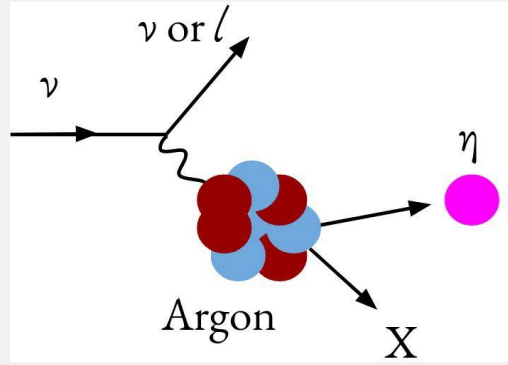



# η meson production



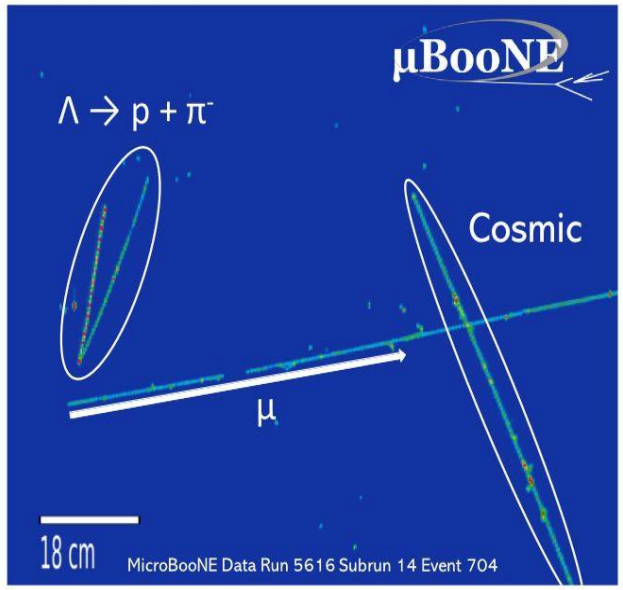

- Powerful new probe of resonances beyond Δ(1232)
- Enabled novel calibration technique for electromagnetic showers in few-GeV region
- Invaluable input for proton decay channels ($p \rightarrow e^{+}\eta$ and $p \rightarrow \mu^{+}\eta$)

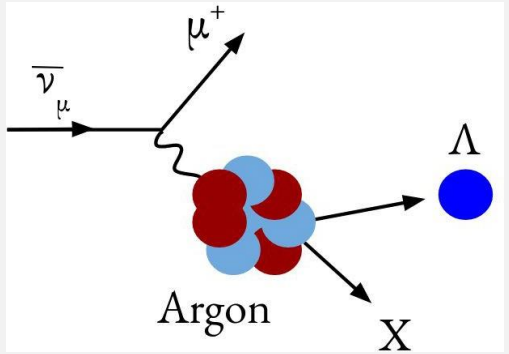
*A flux-integrated cross section for neutrino-induced η production on argon*

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

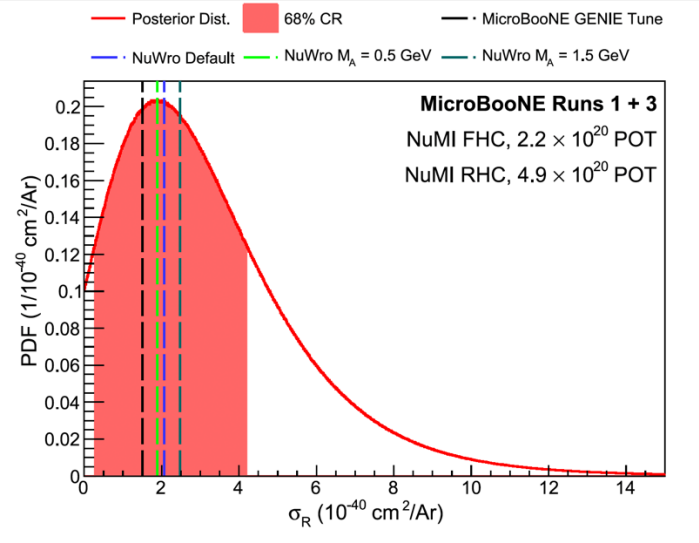
Phys. Rev. Lett. 132, 151801 (2024)

# Λ baryon production




- First measurement with a LArTPC detector
- Very rare process due to Cabibbo suppression with only 5 observed events
- Invaluable input to hyperon interaction modeling and hyperon propagation in dense nuclear matter



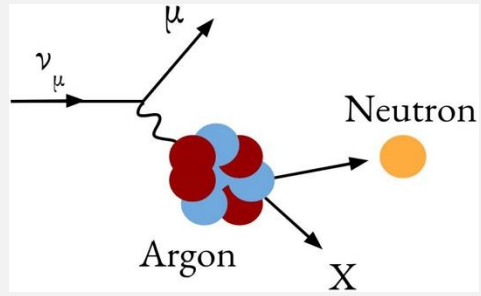

*A flux-integrated cross section for neutrino-induced Λ production on argon*

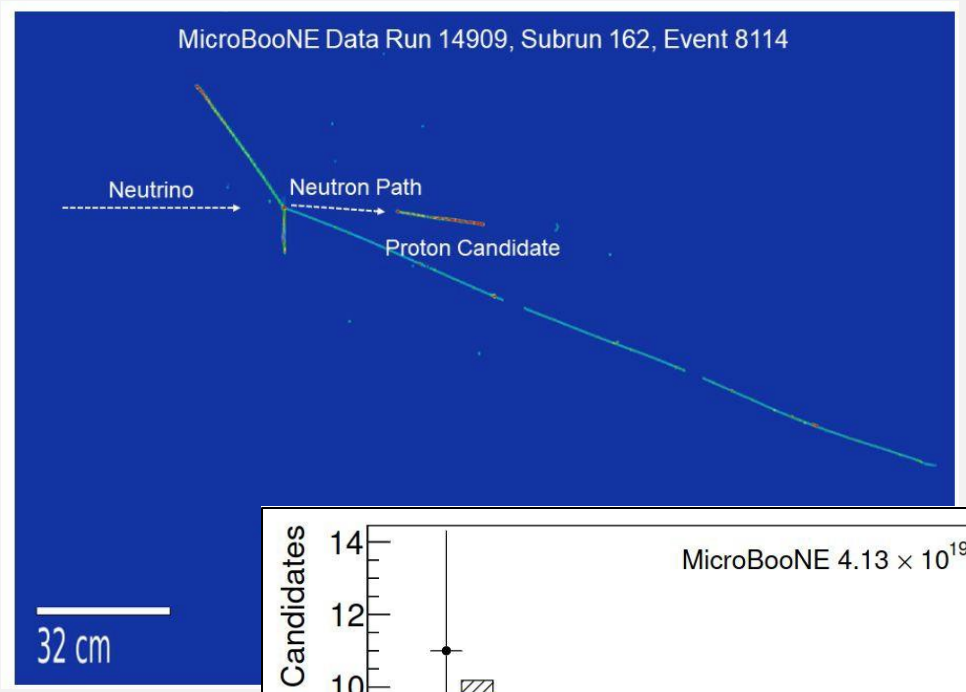
$$\sigma = 2.00^{+2.2}_{-1.7} \times 10^{-40}\ cm^2/Ar$$

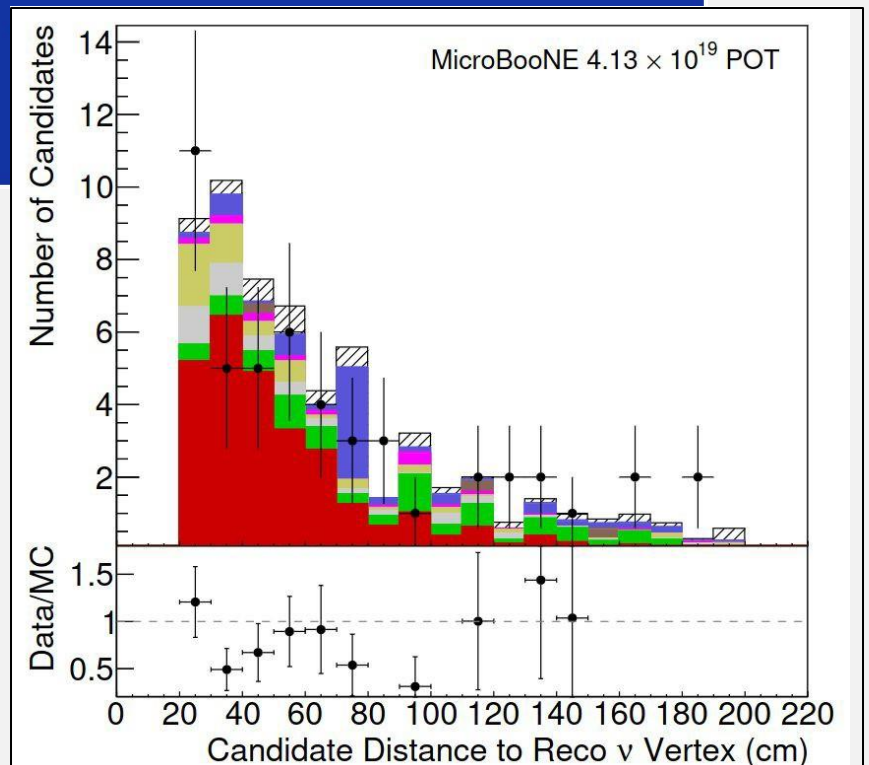
Phys. Rev. Lett. 130, 231802

Update to the NuWro generator to aid this analysis: Phys. Rev. C 104, 035502

# Neutron identification



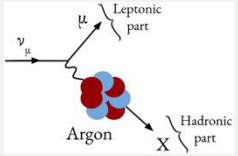



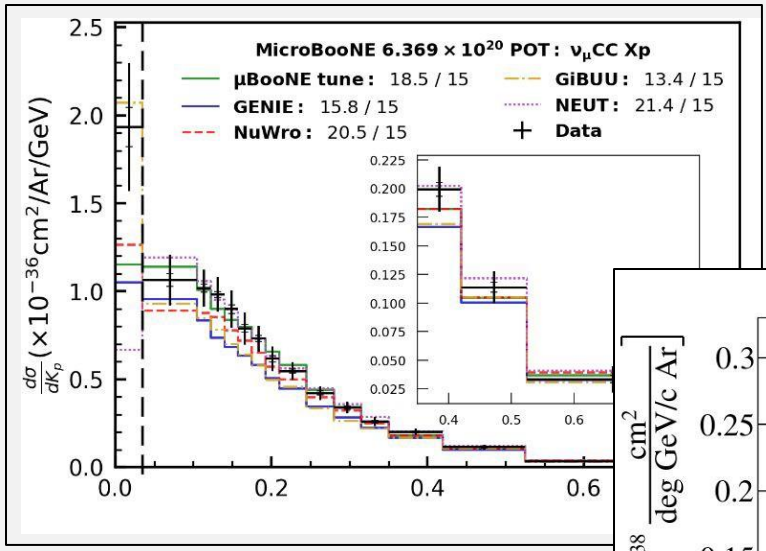

- Challenging identification since neutrons mostly escape the detector without any visible signature
- Detection capability demonstrated using secondary protons, applicable to any LArTPC
- Accounting for missing energy due to neutrons can reduce biases in neutrino energy reconstruction

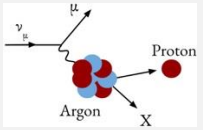
arXiv:2406.10583

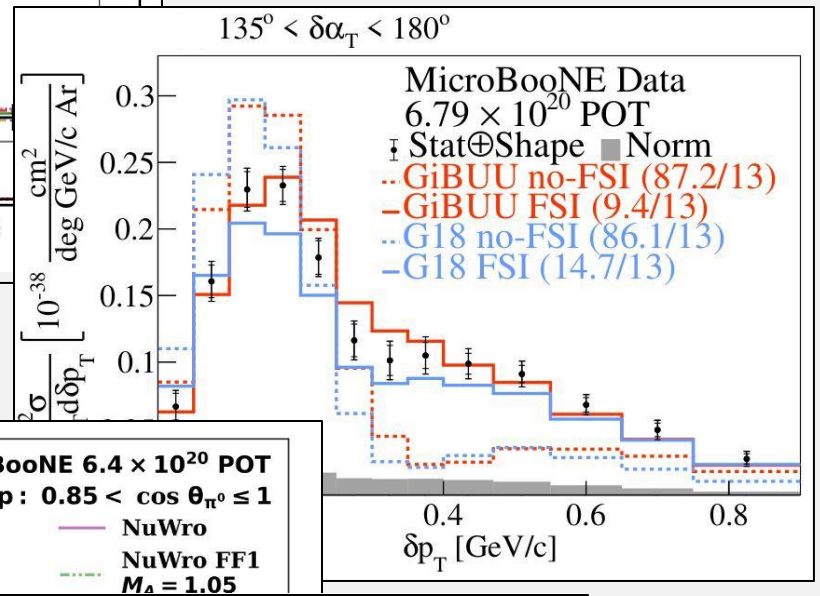
# Summary

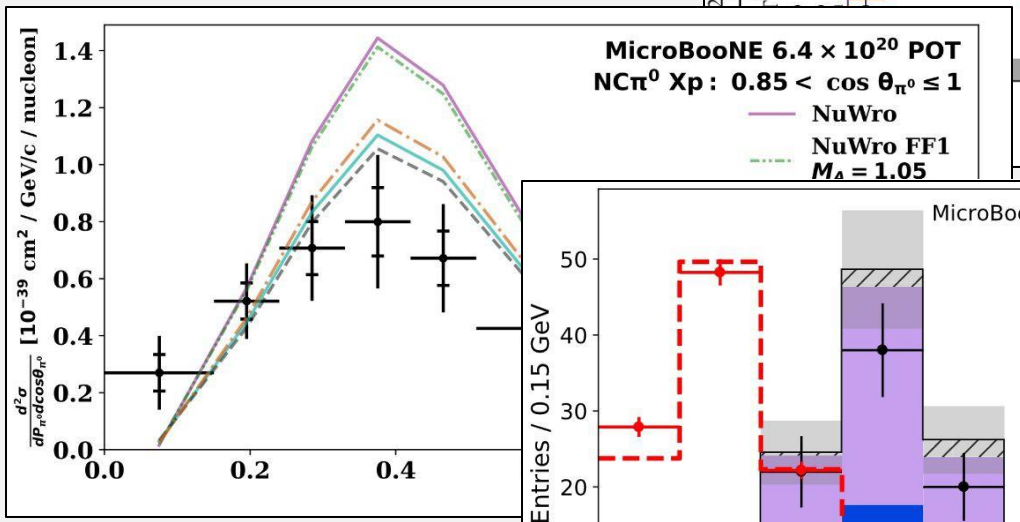
- Diverse MicroBooNE cross-section program with novel high-precision measurements
- Exploring variety of analysis techniques and demonstrating sensitivity to expose mismodeling effects
- Analyses using our full data set (2x stats), electron neutrinos, and charged pions to follow soon!

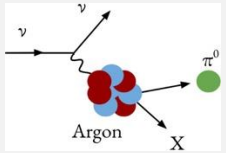


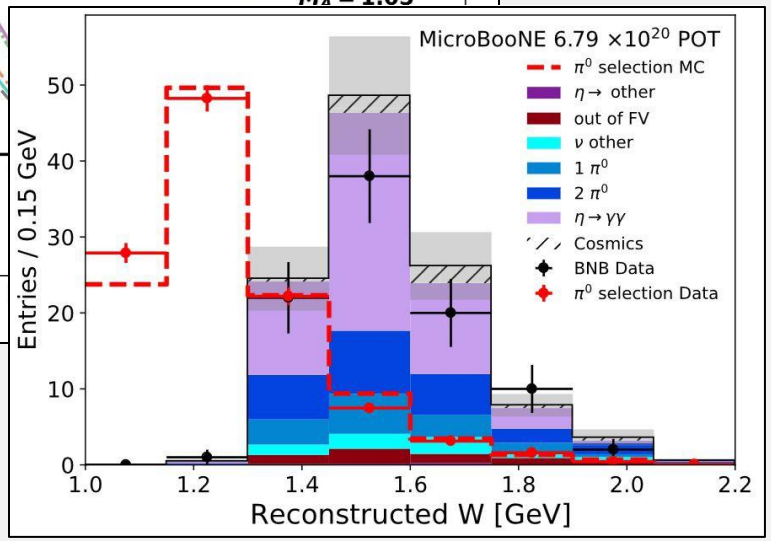



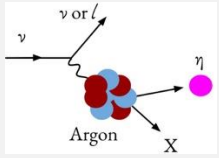




# Already Public Results

**CC inclusive**

- 1D $\nu_\mu$ CC inclusive @BNB, Phys. Rev. Lett. 123, 131801
- 1D $\nu_\mu$ CC $E_\nu$ @BNB, Phys. Rev. Lett. 128, 151801
- 3D CC $E_\nu$ @BNB, arXiv:2307.06413
- 1D $\nu_e$ CC inclusive @NuMI, Phys. Rev. D104, 052002 Phys. Rev. D105, L051102
- 2D $\nu_\mu$ CC0pNp inclusive @BNB, arXiv:2402.19216, arXiv:2402.19281

**Pion production**

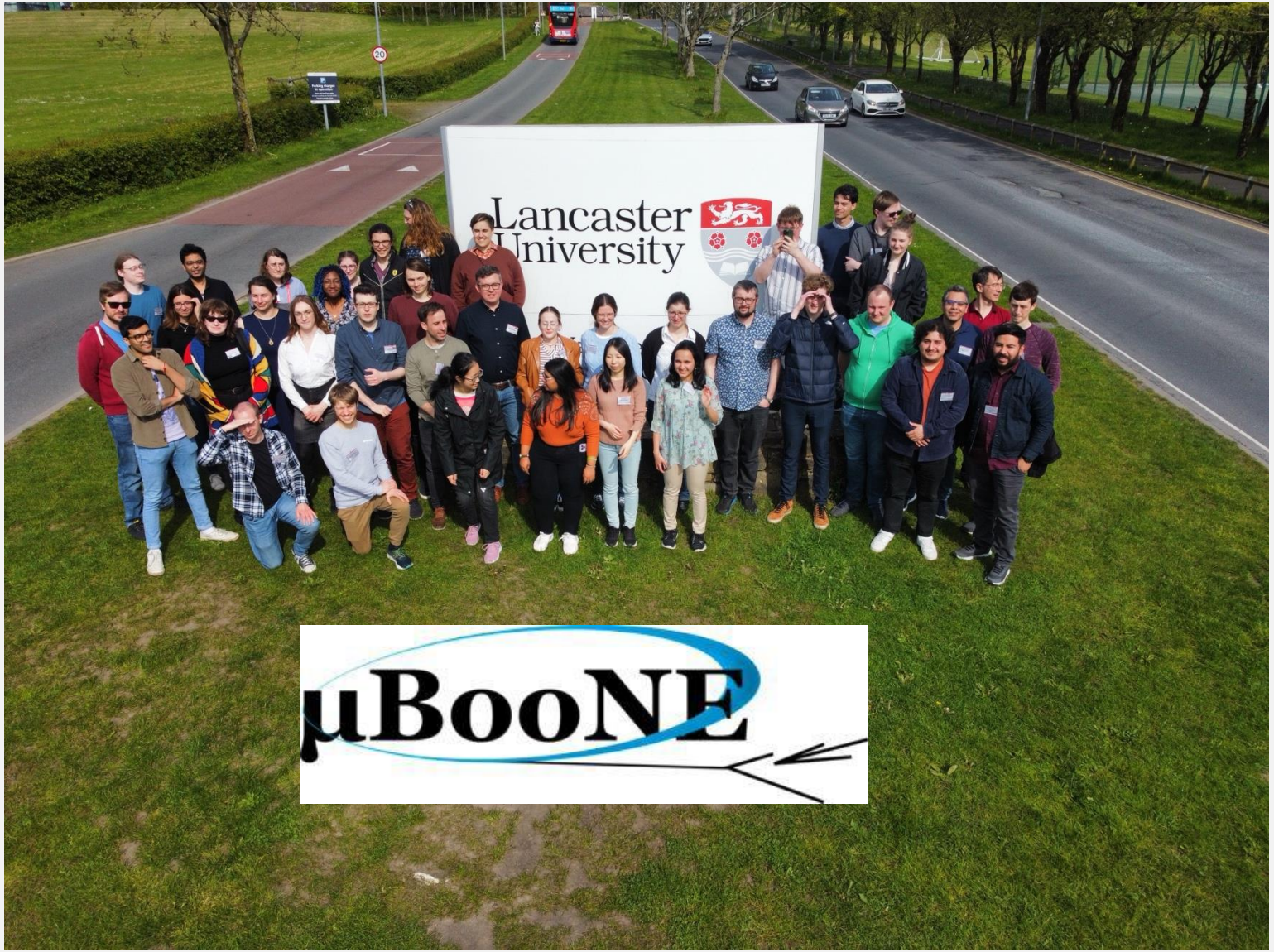
- $\nu_\mu$ NC$\pi^0$ @BNB, Phys. Rev. D 107, 012004
- 2D $\nu_\mu$ NC$\pi^0$ @BNB, arXiv:2404.10948
- $\nu_\mu$ CC$\pi^0$ @BNB, arXiv:2404.09949

**CC0π**

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


Lancaster University
μBooNE