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# Neutrino-argon cross-section measurements from the MicroBooNE experiment

*Liang Liu on behalf of the MicroBooNE Collaboration*  
Postdoc at Fermilab



U.S. DEPARTMENT  
of **ENERGY**

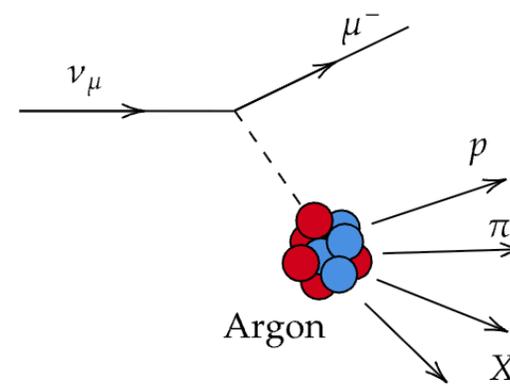
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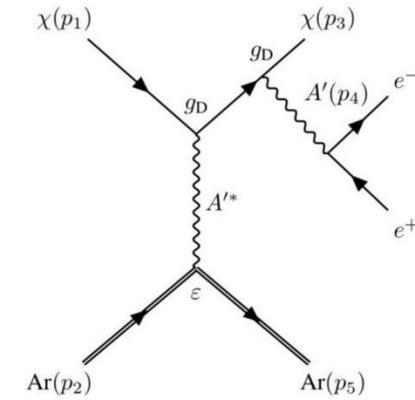
# MicroBooNE

A large liquid-argon time projection chamber (LArTPC) neutrino experiment at Fermilab.

- **LArTPC Technology:** MicroBooNE is the first detector in the Short-Baseline Neutrino (SBN) program at Fermilab, contributing crucial input towards the future DUNE.
- **Cross-Section Measurements:** MicroBooNE has collected a large dataset of neutrino-argon interactions and is pursuing a broad program of cross-section measurements.
- **Short-Baseline Anomalies and BSM:** MicroBooNE can search for physics beyond the Standard Model with the excellent capabilities of the LArTPC detector.



Neutrino cross-section

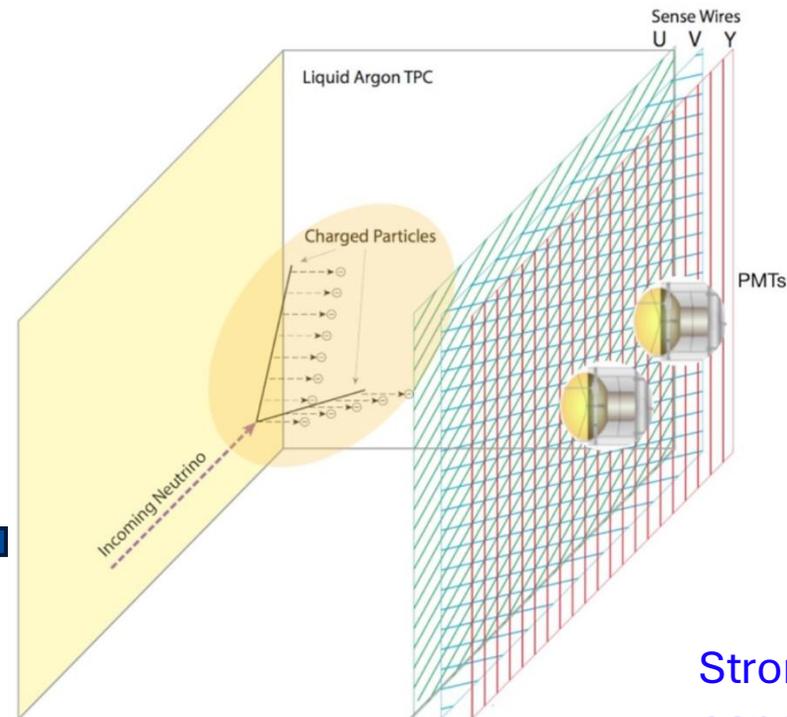
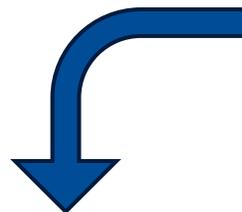


BSM physics

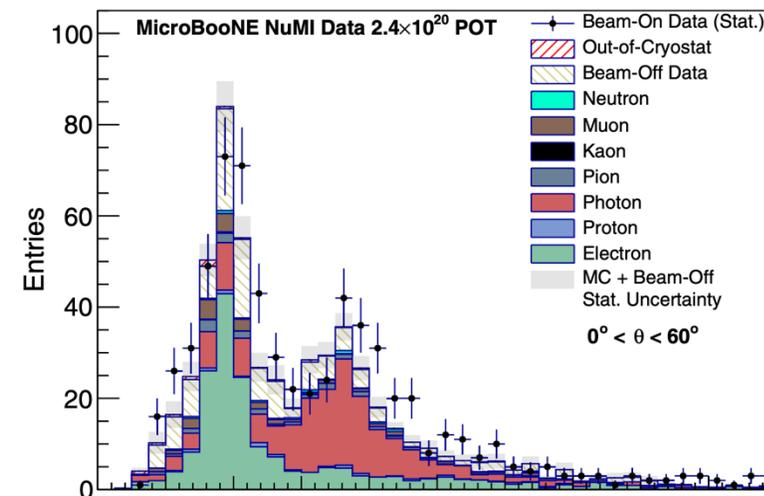
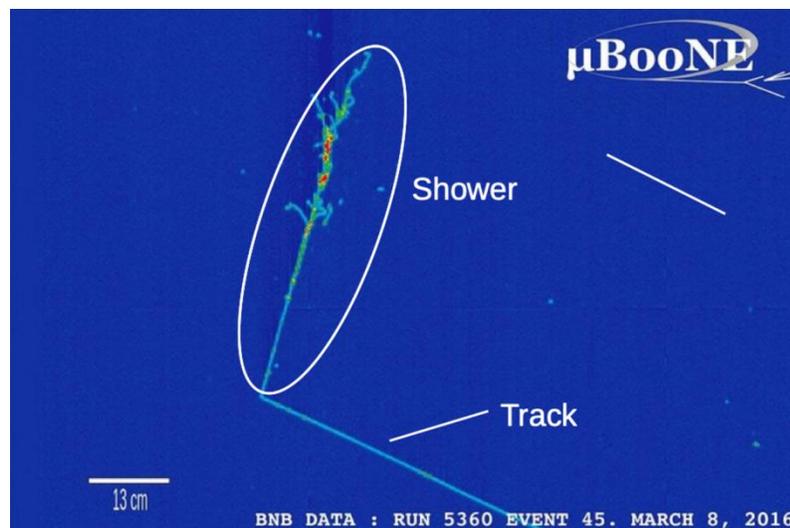
# MicroBooNE detector

- MicroBooNE detector
  - Low energy threshold: few to tens of MeV
  - High spatial/time resolution
  - Pattern recognition: track/shower
  - High energy precision
- Liquid argon time projection chamber
  - TPC field cage  $2.3 \times 2.6 \times 10.4 \text{ m}^3$ , 80 tons
  - Electric field 273 V/cm; drift velocity 114 cm/ms
  - Inter-plane distance 3 mm
- Light collection system
  - 32 PMT behind the TPC wire planes

With drift charge and scintillation light information



Strong particle ID capabilities, e.g.  $\gamma/e$



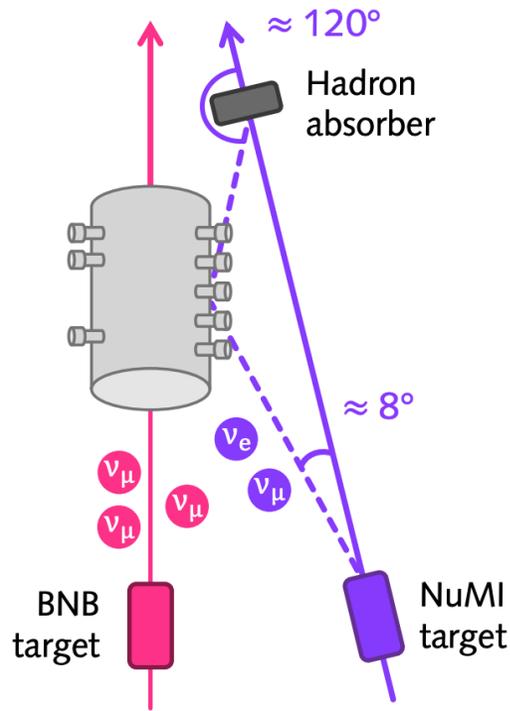
PRD 104, 052002 (2021)

# Neutrino flux

On-axis Booster Neutrino Beam at ~500 m baseline.

## Booster neutrino beam (BNB)

- 8 GeV protons, primary beam
- On-axis
- $\langle E_\nu \rangle = 800$  MeV



*Not to scale*

## Neutrino at the Main Injector (NuMI)

- 120 GeV protons,
- off-axis,  $\sim 8^\circ$
- $\langle E_\nu \rangle = 500$  MeV
- $\nu_\mu/\nu_{\bar{\mu}}$  modes

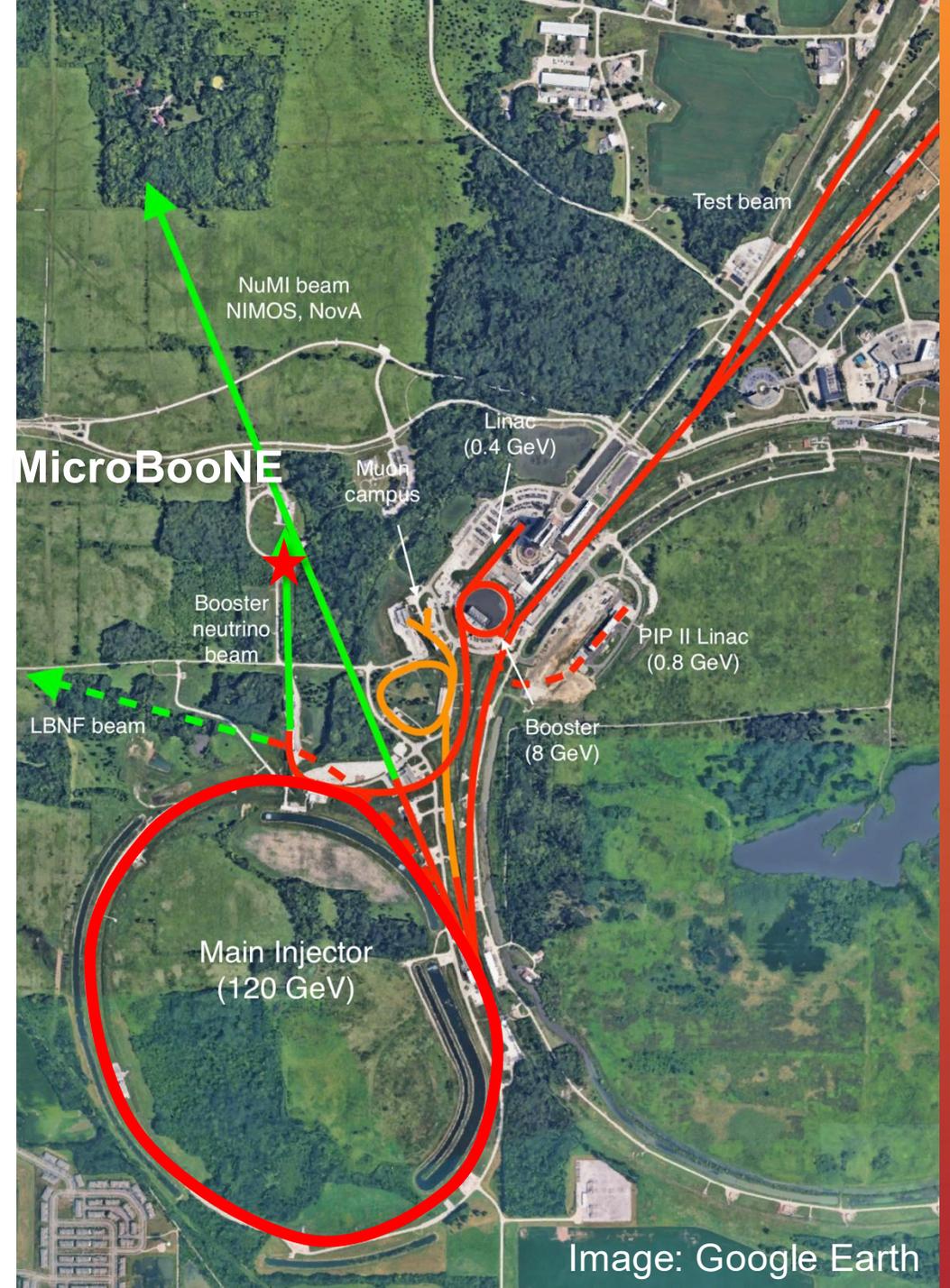


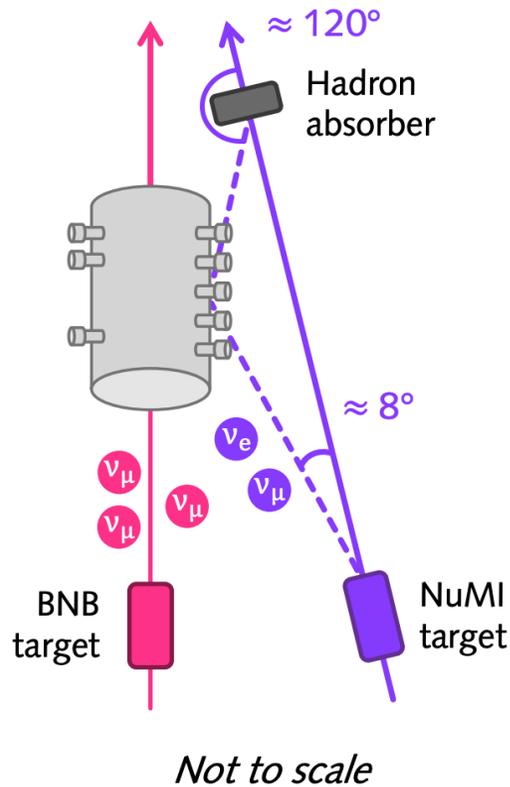
Image: Google Earth

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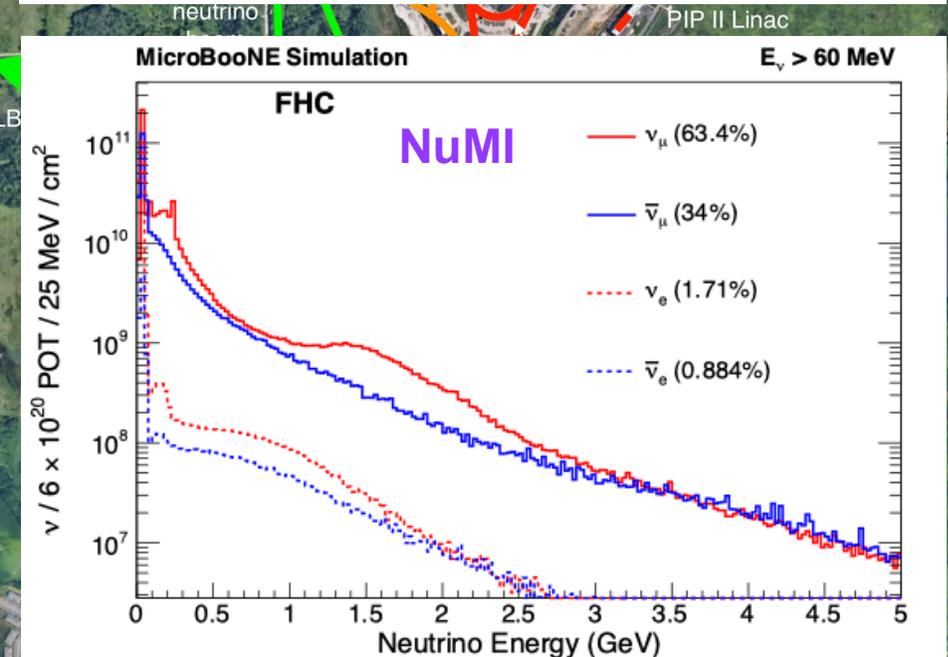
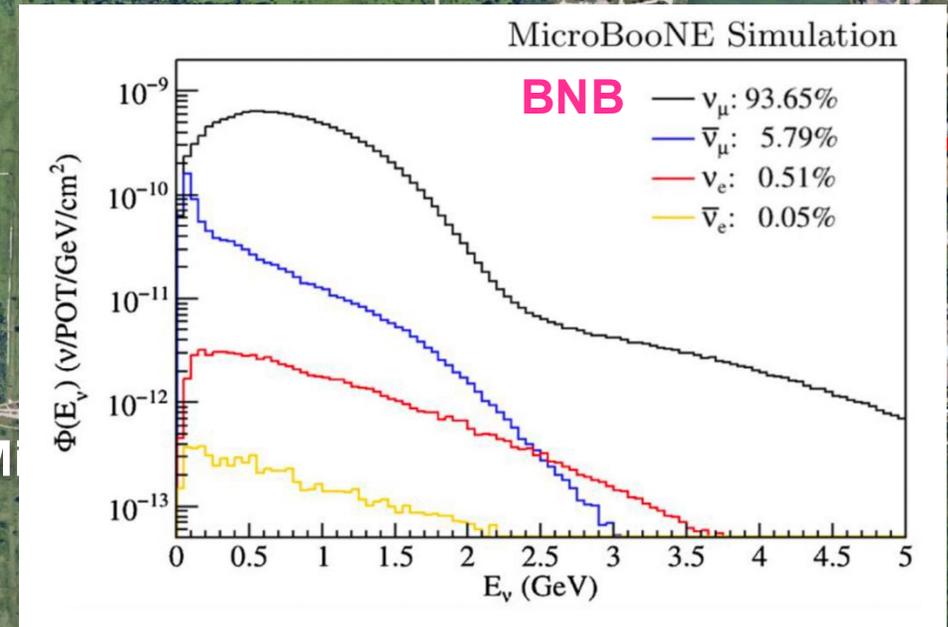
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- 8 GeV protons, primary beam
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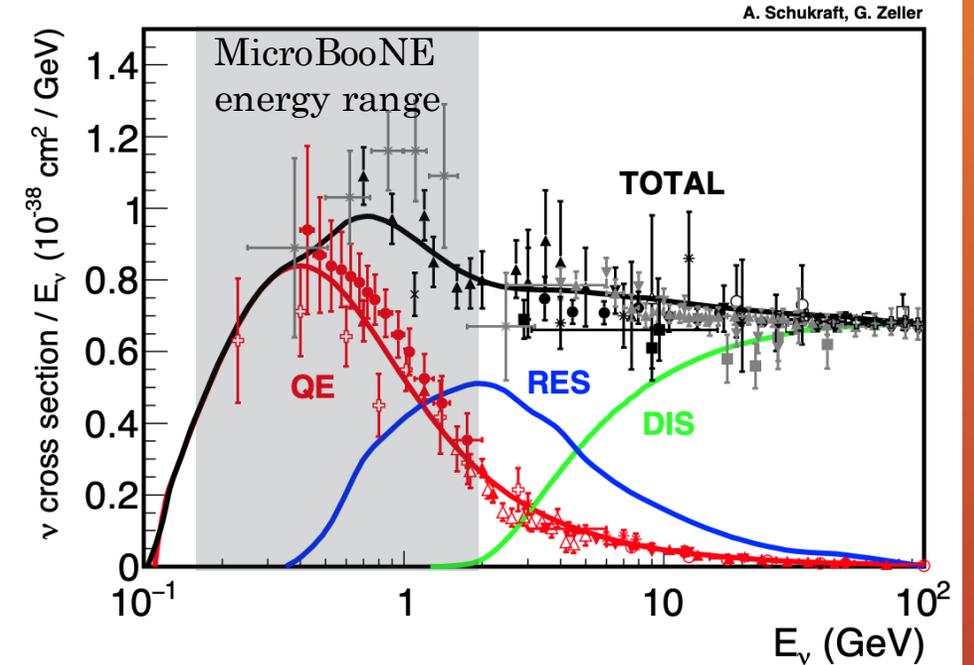
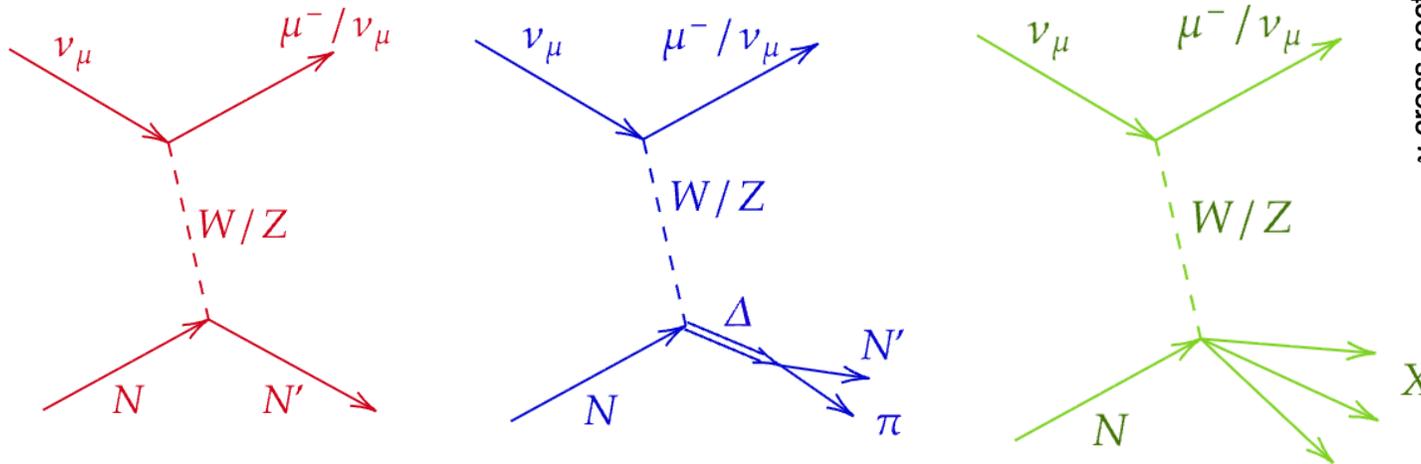
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- 120 GeV protons,
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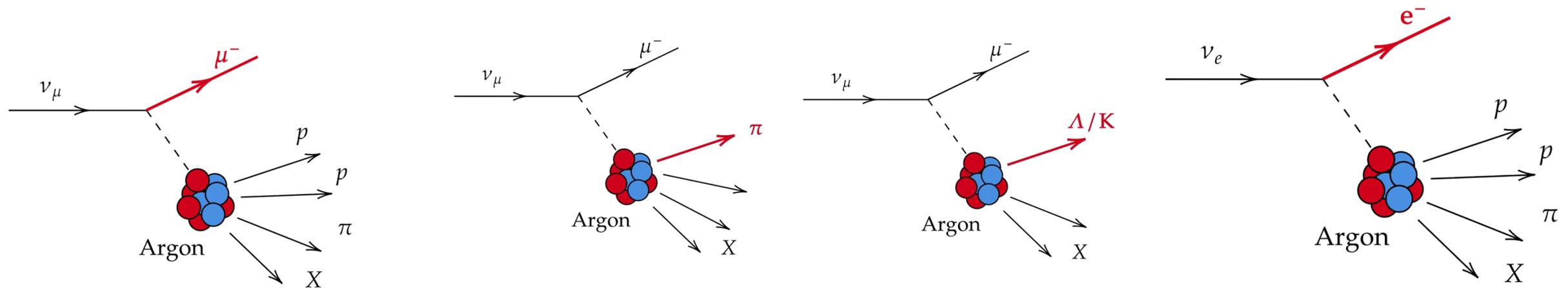
# Cross-section at MicroBooNE

- The energy range of neutrino flux at the MicroBooNE covers **quasi-elastic(QE)**, **resonance (RES)** and **deep inelastic scattering (DIS)** (0.5-2.0 GeV).
  - QE and RES are the dominant ranges.
  - DIS process can also be observed.



# Cross-section at MicroBooNE

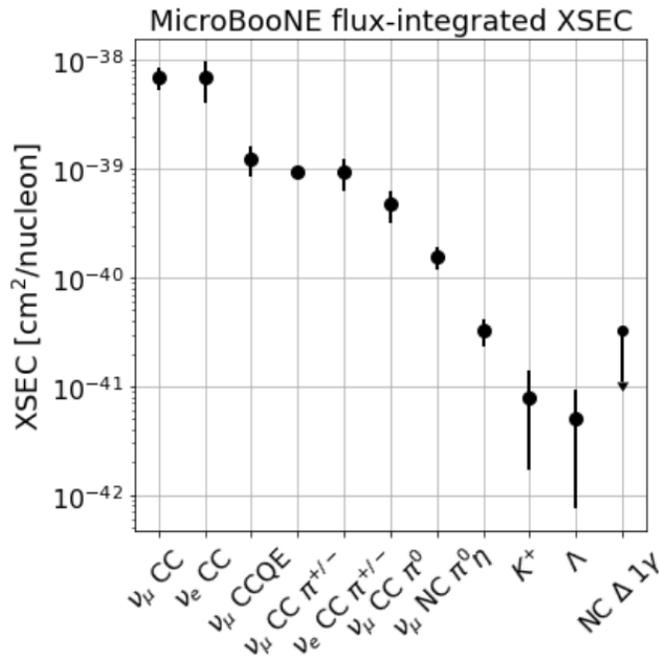
- Neutrino-nucleus cross-section model is one of the most critical source of systematic uncertainties in the measurement of neutrino oscillation.
  - inclusive/exclusive proton final-states to study nuclear effects in CC channels.
  - Neutral pion production: crucial for neutrino oscillation and BSM programs.
  - Rare channels & signatures including neutrons for precision tests of generators and better understanding of missing energy.
  - $\nu_e$ : poorly constrained with data, crucial for oscillation program.





# Cross-section at MicroBooNE

- Many cross-section measurements have been accomplished.
- These measurements will be a crucial inputs for **constraining models** and the physics research at **future SBN and DUNE** experiments.



## Inclusive Measurements

- 1D  $\nu_\mu$  CC Inclusive @ BNB: PRL 123 131801 (2019), PRL 128 151801 (2022)
- 2D  $\nu_\mu$  CC Inclusive @ BNB: PRL 133 041801 (2024), **PRD 110 L013006 (2024)**
- 3D  $\nu_\mu$  CC Inclusive @ BNB: arXiv:2307.06413
- 1D  $\nu_e$  CC Inclusive @ NuMI: PRD 104 052002 (2021), PRD 105 051102 (2022)

## Pionless Measurements

- 1D, 2D  $\nu_\mu$  CC  $0\pi$  Np @ BNB: PRD 102 112013 (2020), arXiv:2403.19574, **arXiv:2507.00921 (2025)**
- 1D  $\nu_\mu$  CC  $0\pi$  1p @ BNB: PRL 125 201803 (2020)
- 1D, 2D  $\nu_\mu$  CC  $0\pi$  1p TKI @ BNB: PRL 131 101802 (2023), PRD 108 053002 (2023)
- 1D, 2D  $\nu_\mu$  CC  $0\pi$  1p GKI @ BNB: PRD 109 092007 (2024)
- 1D, 2D  $\nu_\mu$  CC  $0\pi$  1p AKI @ BNB: **PRD 111 113007 (2025)**
- 1D  $\nu_\mu$  CC  $0\pi$  2p @ BNB: arXiv:2211.03734
- 1D  $\nu_e$  CC  $0\pi$  Np @ BNB: PRD 106 L051102 (2022)

## Pion Production Measurements

- 1D  $\nu_\mu$  CC  $1\pi^0$  @ BNB: PRD 99 091102 (2019), PRD 110 092014 (2024)
- 1D, 2D  $\nu_\mu$  NC  $1\pi^0$  @ BNB: PRD 107 012004 (2023), **PRL 134 161802 (2025)**
- 1D  $\nu_e$  CC  $1\pi^\pm$  @ NuMI: **PRL 135, 061802 (2025)**

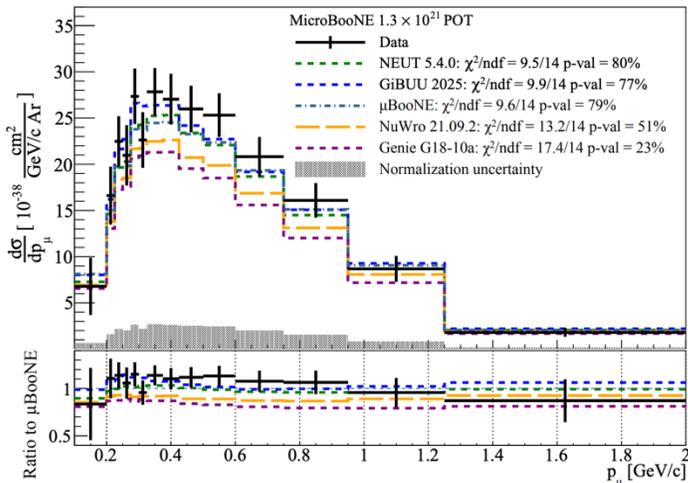
## Rare Channels and Novel Techniques

- $\Lambda$  Production @ NuMI: **PRL 130 231802 (2023)**
- $\eta$  Production @ BNB: **PRL 132 151801 (2024)**
- $K^+$  Production @ BNB: **arXiv:2503.00291 (2025)**
- Neutrons Identification: EPJC 84 1052 (2024)
- Model Validation: PRD 111 092010 (2025)



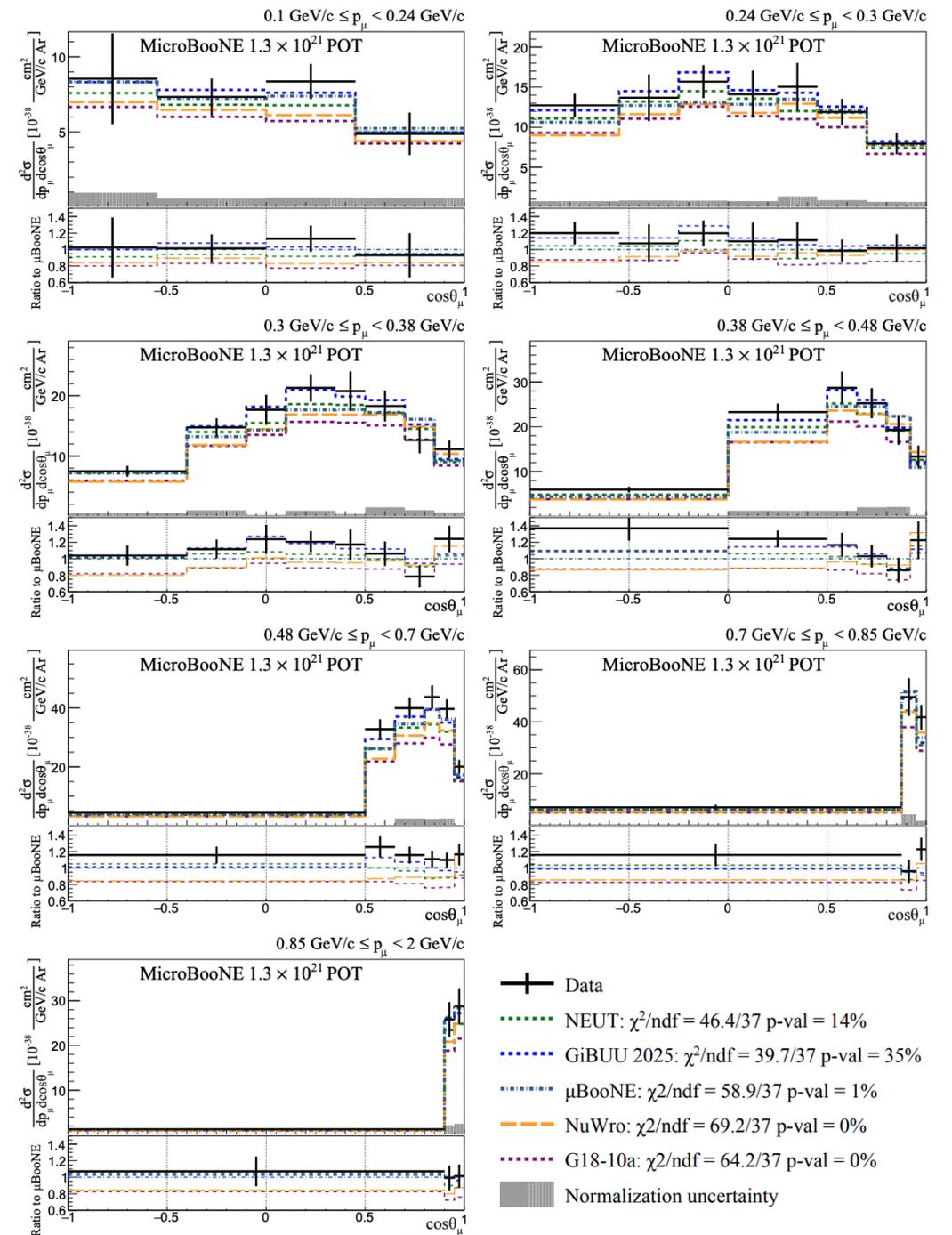
# Pionless CC inclusive

- 1D/2D  $\mu$  momentum and angular distribution without pions.
- Average total uncertainty below 20%
- A joint analysis with ANNIE on-going, multi-target cross-section extraction with a water Cherenkov detector in the same beam.
- Only a subset of models is in agreement with the data across the correlated 2D measurement space.



(a)  $p_\mu$  differential cross section.

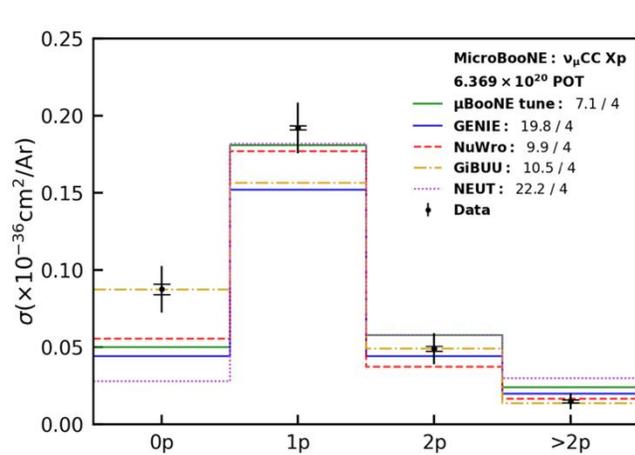
arXiv:2507.00921



- Data
- NEUT:  $\chi^2/\text{ndf} = 46.4/37$  p-val = 14%
- GiBUU 2025:  $\chi^2/\text{ndf} = 39.7/37$  p-val = 35%
- $\mu\text{BooNE}$ :  $\chi^2/\text{ndf} = 58.9/37$  p-val = 1%
- NuWro:  $\chi^2/\text{ndf} = 69.2/37$  p-val = 0%
- G18-10a:  $\chi^2/\text{ndf} = 64.2/37$  p-val = 0%
- Normalization uncertainty

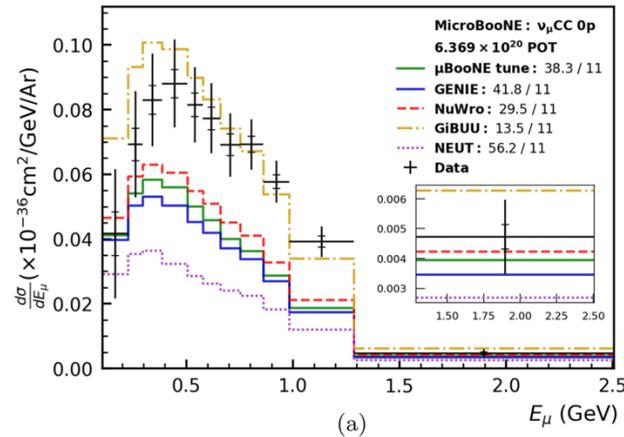
# CC inclusive 0p/Np

- Understanding the 0p and Np final states in  $\nu_\mu$  CC channel is essential in constraining the prediction and systematics for  $\nu_e$  CC in  $\nu_e$  appearance measurement.
- Modeling better in Np, prefers GiBUU modeling in 0p.
- Data sensitive to proton reinteractions within nucleus.

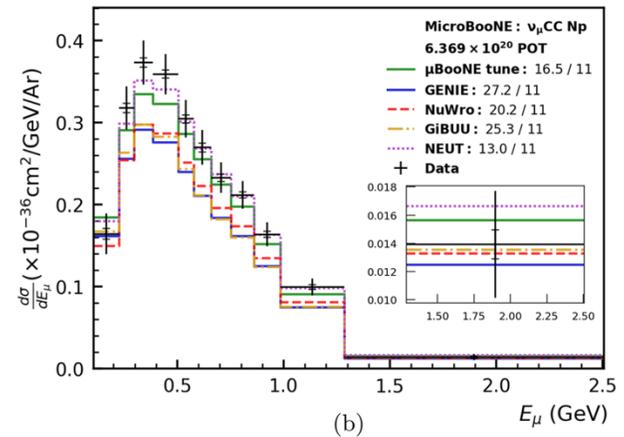


PRD 111, 013006 (2024)

0pNp  $\chi^2$  ( $ndf = 22$ ):  $\mu$ BooNE tune = 50.8, GENIE = 61.5, NuWro = 46.4, GiBUU = 37.6, NEUT = 65.7



(a)

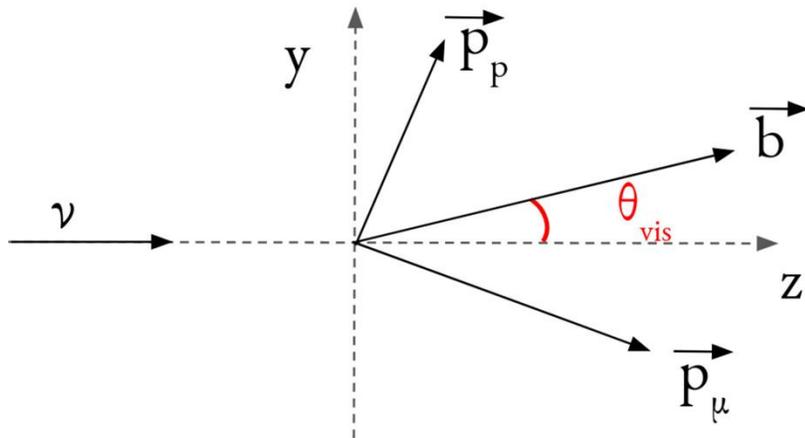


(b)

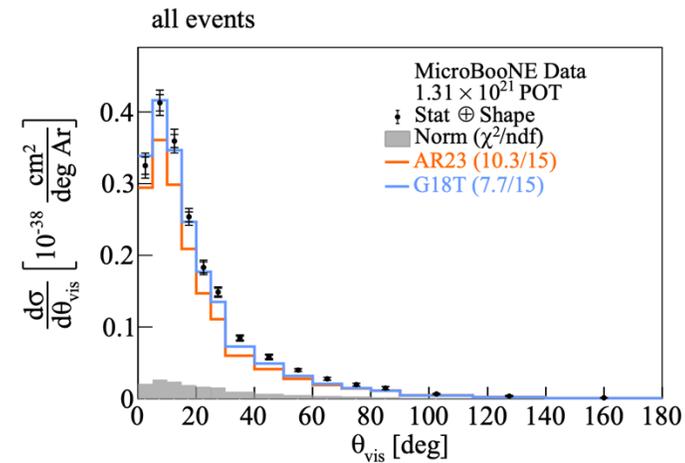


# Neutrino angle reconstruction

- A precise reconstruction of the incoming neutrino direction is essential for DUNE to study atmospheric neutrino oscillations.
- First study of using charged-current quasi-elastic-like (CCQE-like) interaction to extract the angle between muon-proton system and the incoming neutrino direction.
  - BNB neutrino direction is known.
- Direction reconstruction in single-proton selection has a good resolution.



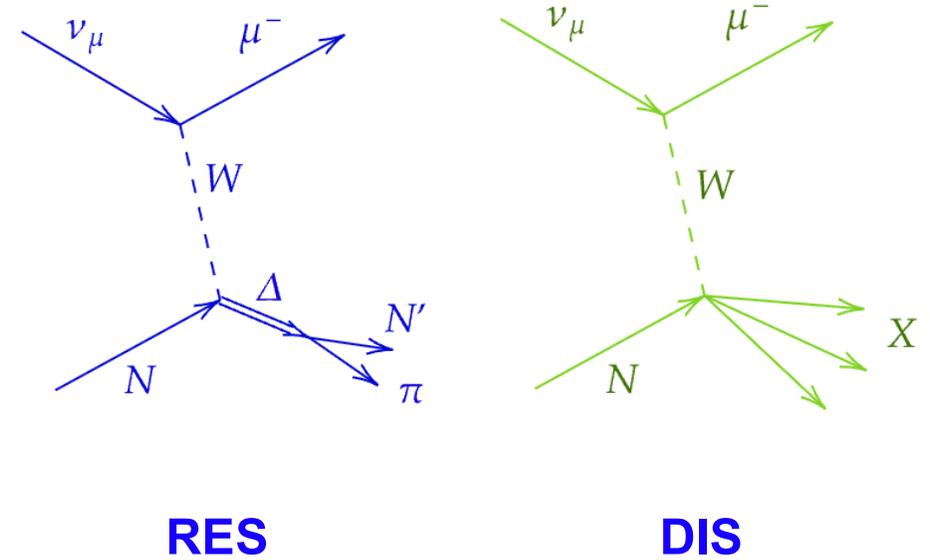
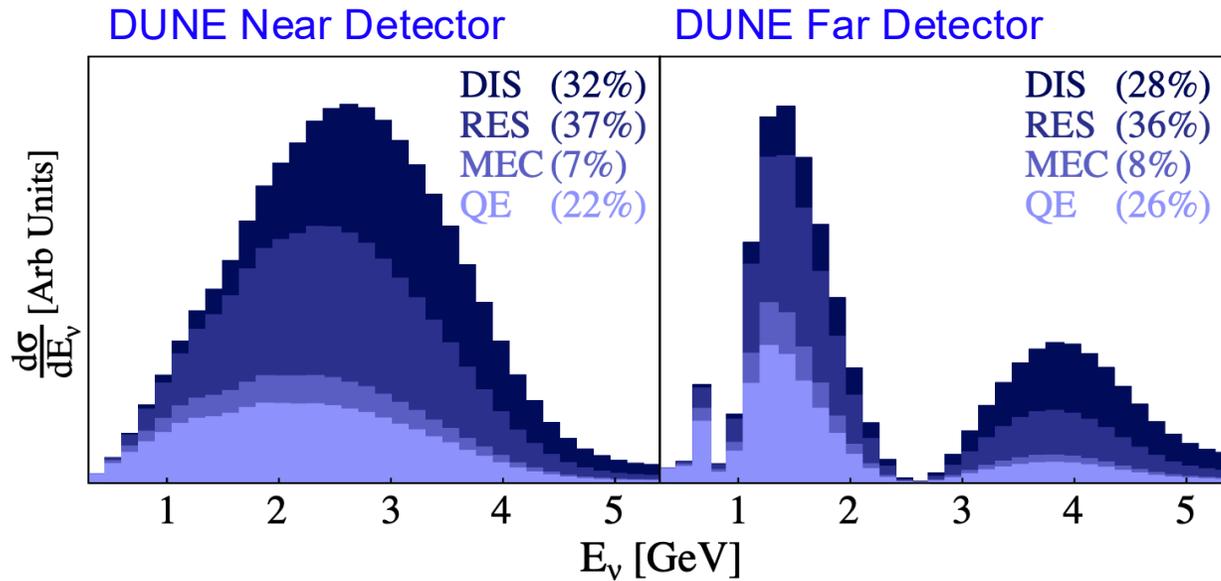
PRD 111, 113007 (2025)



Smearing dominant by nuclear effects.

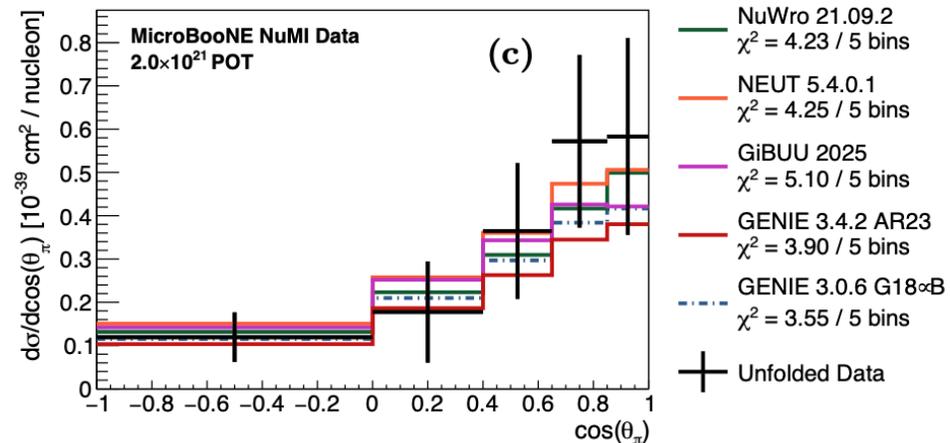
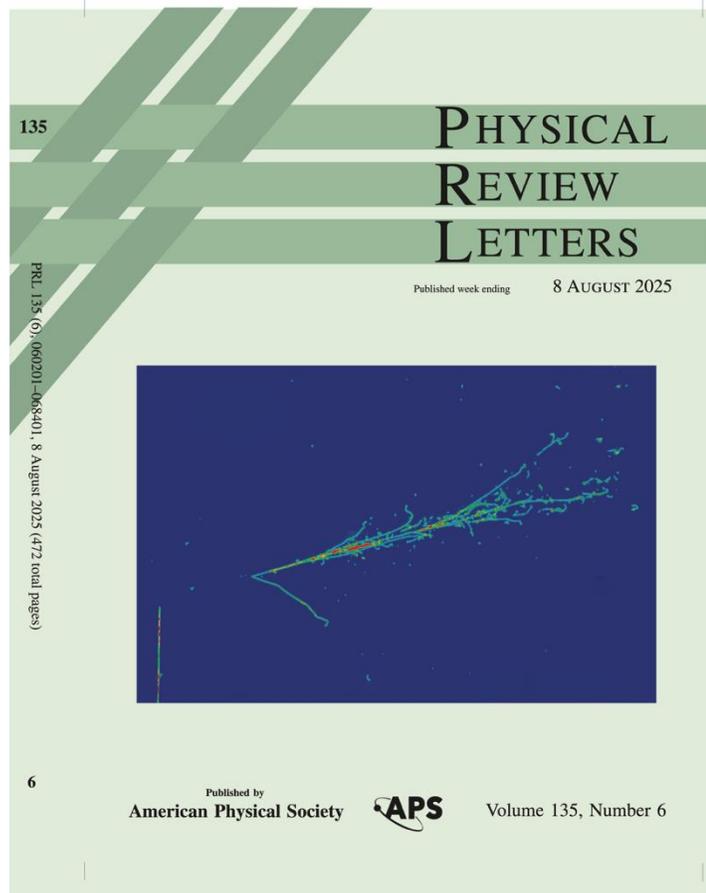
# Pion production

- Resonance and deep in-elastic channel are dominant interaction modes at DUNE.
- These channels lead to pion-containing final states that we can measure in the MicroBooNE.



# $\nu_e + \bar{\nu}_e$ CC pion production (NuMI)

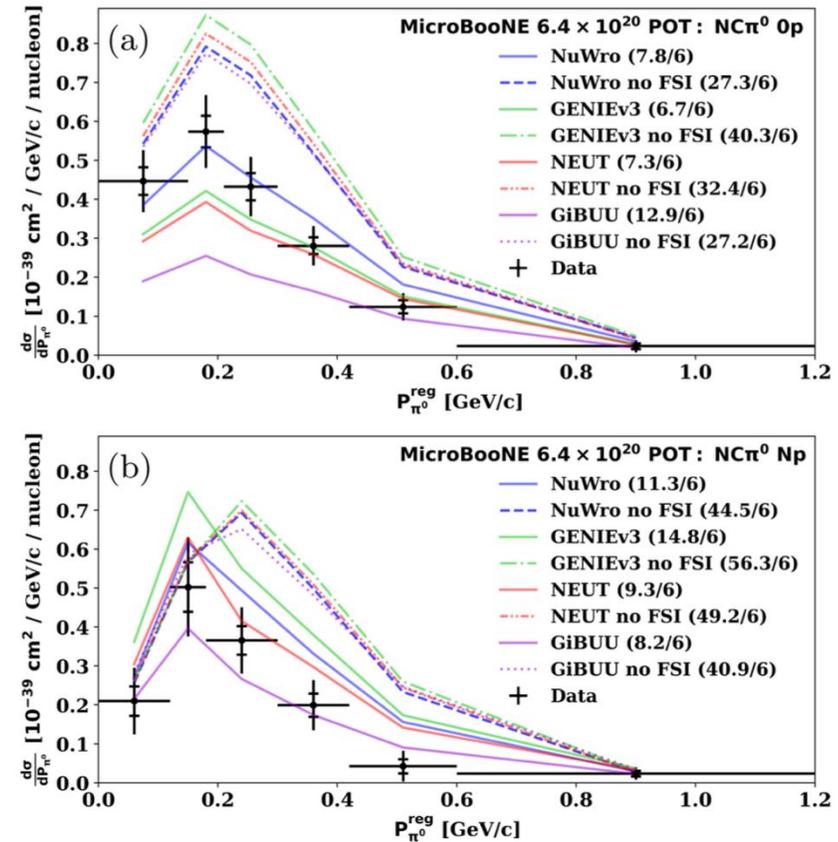
- Precise understanding of  $\nu_e$  interactions on argon is essential for measurement of electron neutrino appearance.
- The first measurement of cross-section of  $\nu_e + \bar{\nu}_e$  CC pion production is found to be in good agreement with generator prediction.



PRL 135, 061802 (2025)

# NC $\pi^0$ production (BNB)

- NC $\pi^0$  channel is a critical background in oscillation analyses and BSM search.
- The first double-differential cross section measurement of NC $\pi^0$  production in neutrino-argon scattering
- Models without Final State Interaction (FSI) overestimate the measured NC $\pi^0$  cross section. These results are constraint for improving the modeling.



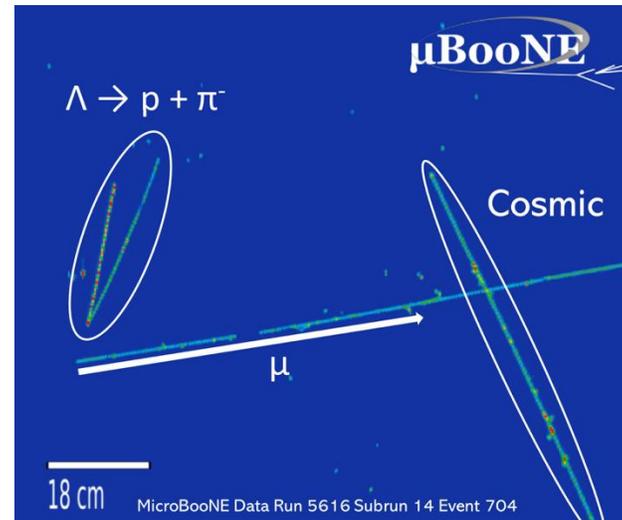
PRL 134 161802 (2025)

# Rare process

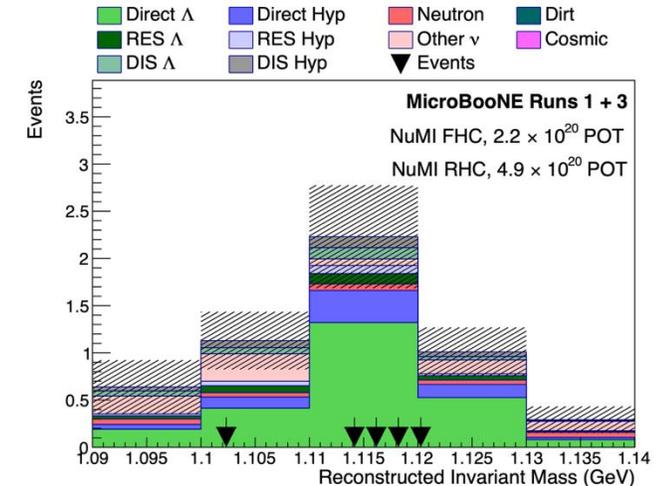
- Strange-hadron production is sensitive to the physics of the underlying neutrino interaction and nuclear effects
  - Nucleon form factors and axial masses, hyperon-nucleus potentials, final state interactions
  - A potential source of background in proton decay

## $\Lambda$ Production (NuMI)

- $\bar{\nu}_\mu + \text{Ar} \rightarrow \mu^+ + \Lambda + X$
- 5 candidate signal events
- $\sigma = 2.0_{-1.7}^{+2.2} \times 10^{-40} \text{ cm}^2/\text{Ar}$



PRL **130**, 231802 (2023)

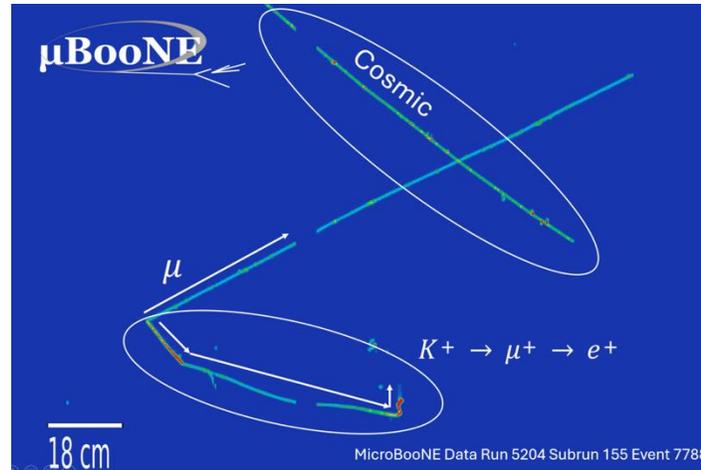


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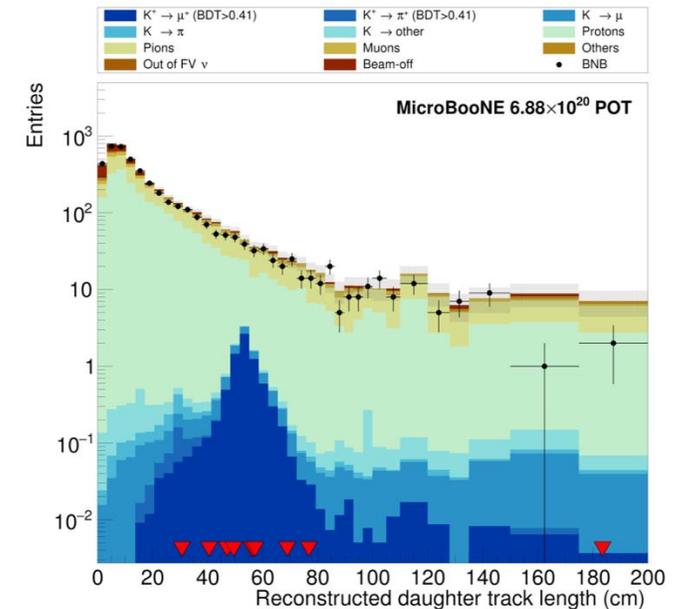
## $K^+$ Production (BNB)

- $\nu_\mu + \text{Ar} \rightarrow \mu^- + K^+ + X$
- 10 candidate signal events



[arXiv:2503.00291](https://arxiv.org/abs/2503.00291)

$$\sigma = 7.93 \pm 3.27 \text{ (stat.)} \pm 2.92 \text{ (syst.)} \times 10^{-42} \text{ cm}^2/\text{nucleon}$$

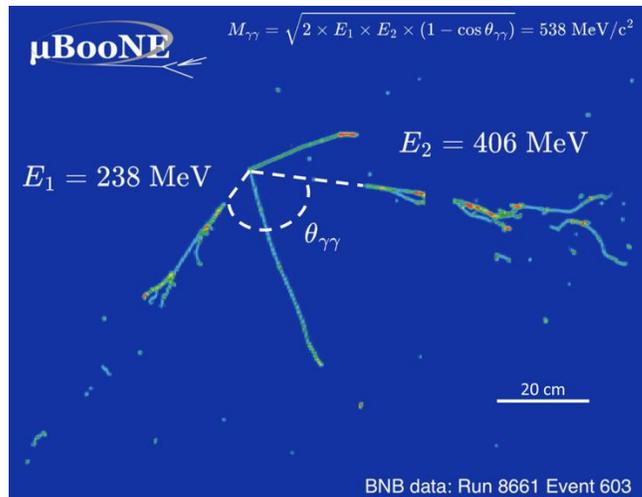




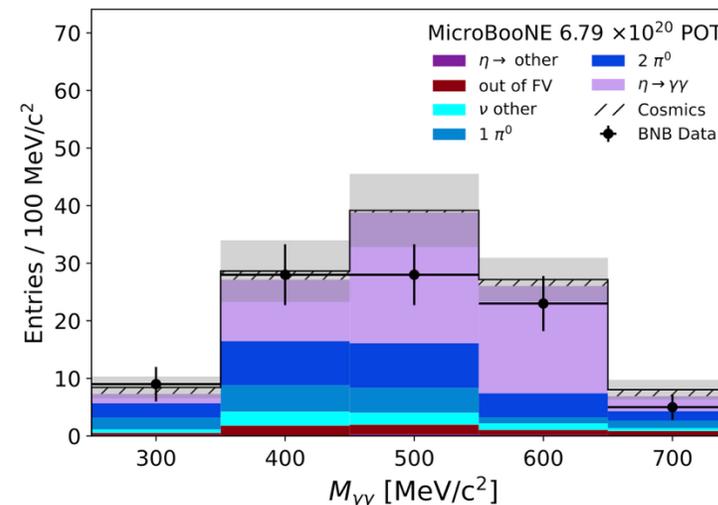
# Rare process

## $\eta$ Production (complementary to pion) (BNB)

- Probe neutrino-induced higher order resonances beyond the  $\Delta(1232)$ , e.g.  $N(1535)$ ,  $N(1650)$ ,  $N(1710)$
- A novel calibration technique for electromagnetic showers in GeV range in LArTPC.
- Background to proton decay in the  $p \rightarrow e^+ + \eta$ ,  $p \rightarrow \mu^+ + \eta$
- $\sigma(\nu \rightarrow 1\eta + X) = 3.22 \pm 0.84$  (stat)  $\pm 0.86$  (syst)  $\times 10^{-41}$  cm<sup>2</sup>/nucleon



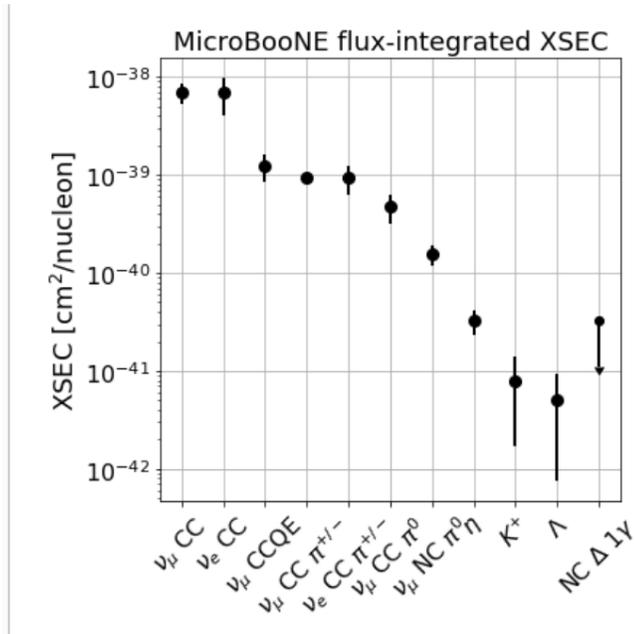
PRL 132, 151801 (2024)



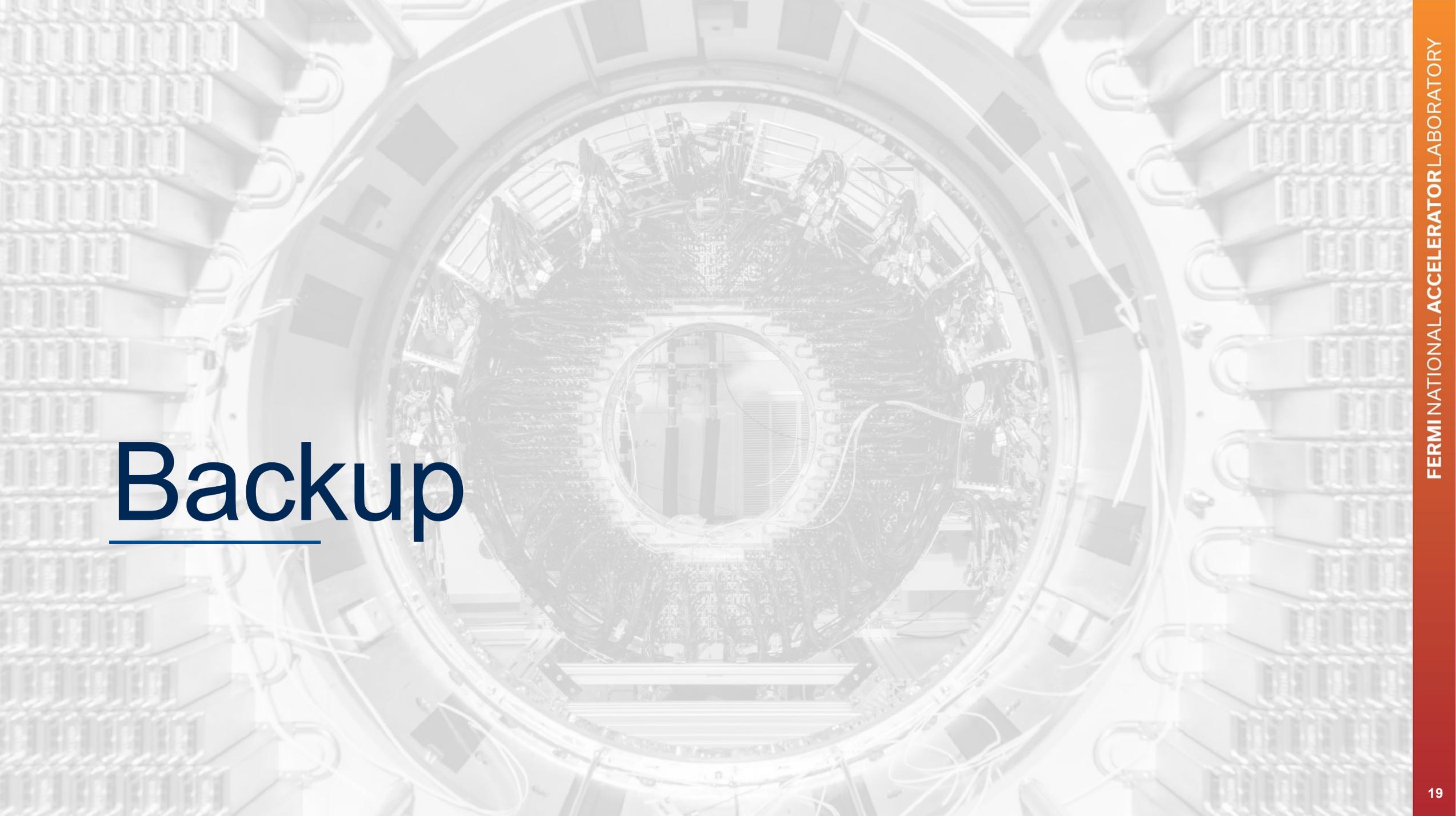


# Summary

- The MicroBooNE has reported measurements of neutrino-argon cross-section.
  - Precise measurement neutrino-argon interaction
  - Observe processes with cross-section less than  $\sim 10^{-41}$  cm<sup>2</sup>/nucleon
- Current & upcoming MicroBooNE cross section results will provide important model constraints for future oscillation measurements



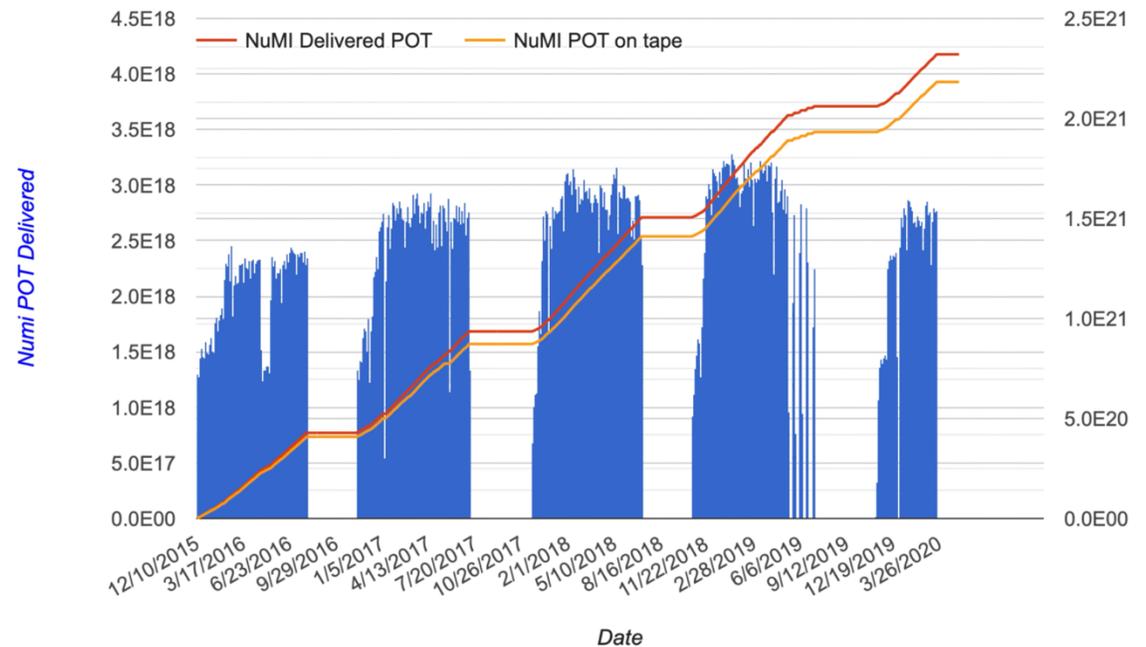
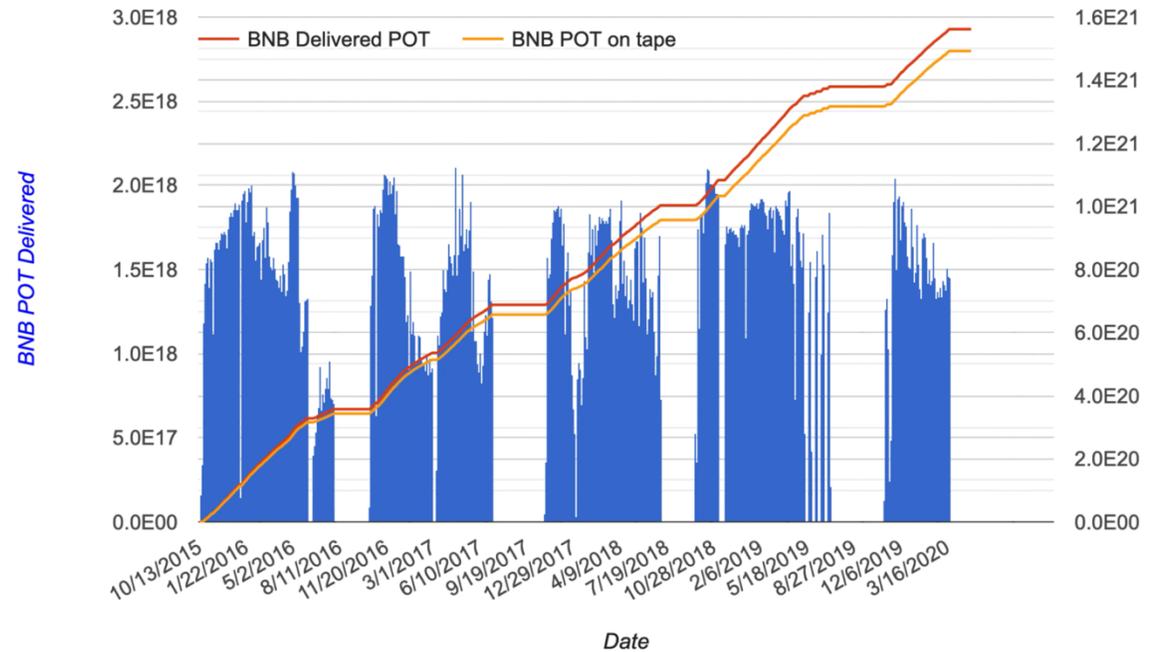
# Backup

A grayscale photograph of the interior of a large particle accelerator tunnel. The view is from a high angle looking down into a circular opening. The tunnel walls are lined with a grid of metal panels, each featuring a circular access point. In the center, a complex array of machinery, including cables and structural supports, is visible. A prominent circular opening is located in the middle of the tunnel's length.



# MicroBooNE datasets

- The MicroBooNE collected beam data from 2015-2020
  - Accumulating  $\sim 1.3 \times 10^{21}$  POT from the **BNB**
  - Accumulating  $\sim 2.0 \times 10^{21}$  POT from the **NuMI**
- Many measurements of cross-section of neutrino-argon interaction have been accomplished based on both exposure.



Cumulative POT

Cumulative POT