

# Latest Results from MicroBooNE

**Jay Hyun Jo**, Brookhaven National Laboratory  
*on behalf of the MicroBooNE collaboration*

February 22, 2023  
Lake Louise Winter Institute



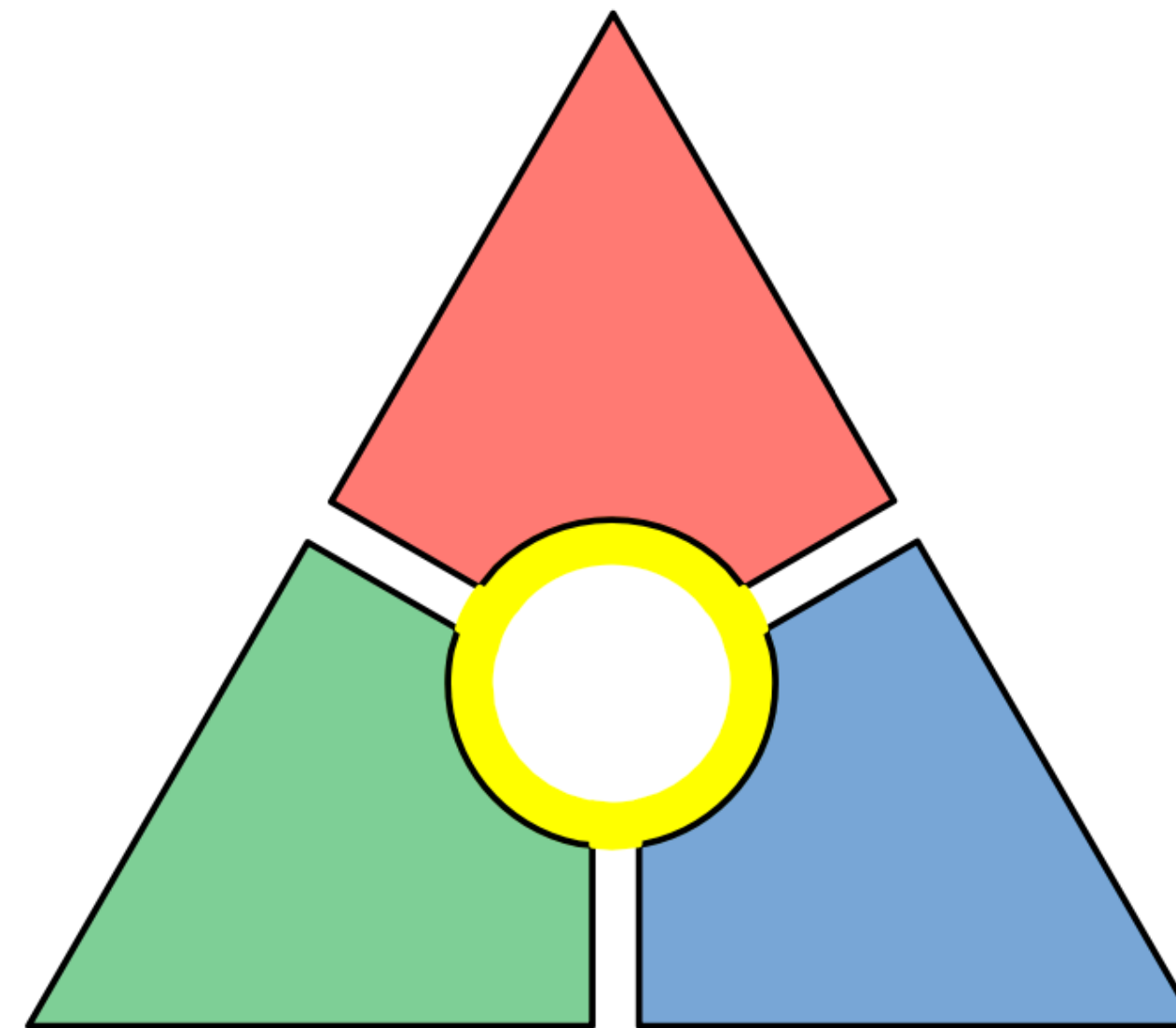
# MicroBooNE science goals

## address MiniBooNE LEE and BSM

- same neutrino beamline & roughly same location as MiniBooNE
- unique electron/photon separation capability
- search for BSM physics

## LArTPC hardware & software R&D

- LArTPC design, cryostat, cold electronics
- noise filtering, TPC signal processing, detector physics,
- event reconstruction



## study $\nu$ -Ar interactions

- one of the largest uncertainties in neutrino oscillation experiments
- provide important input for LArTPC experiments



# MicroBooNE science output

2017 2018 2019 2020 2021 2022 2023

55 papers:  
~1/2 detector R&D  
~1/2 physics

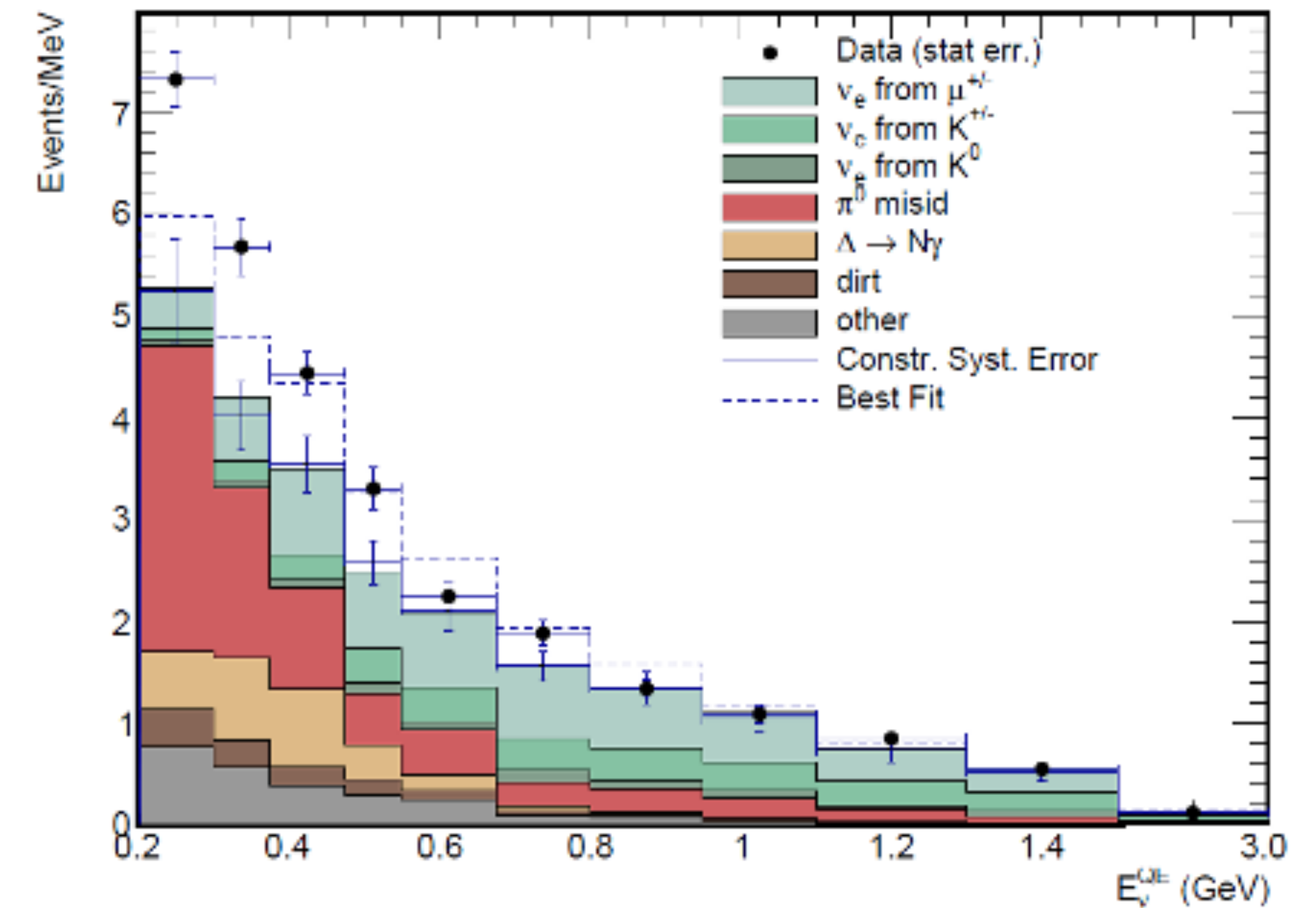
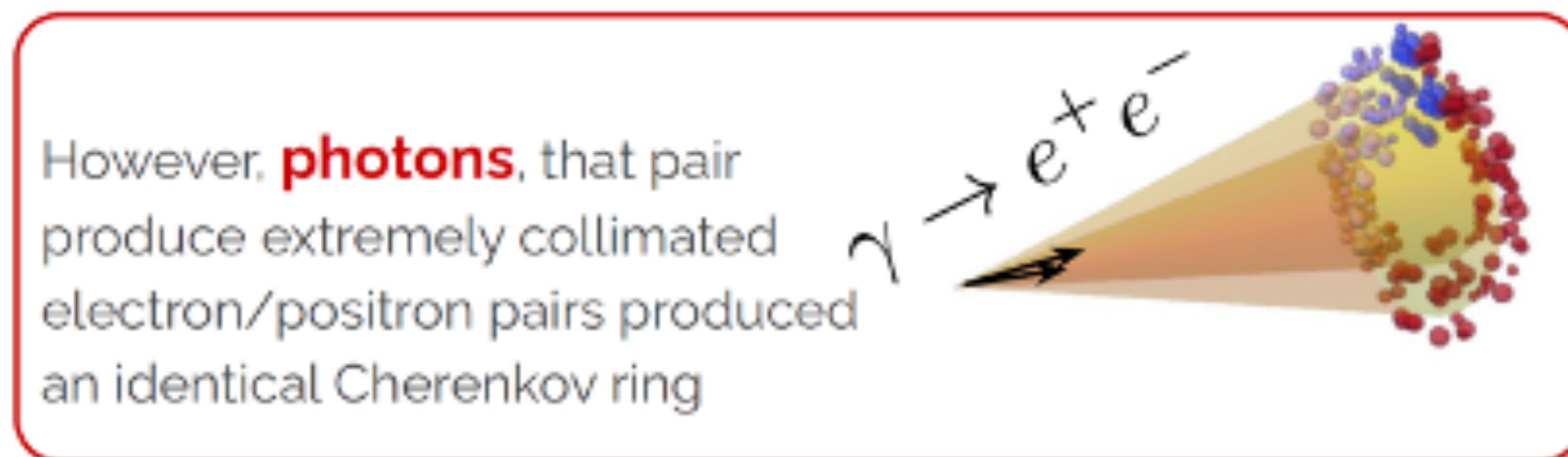
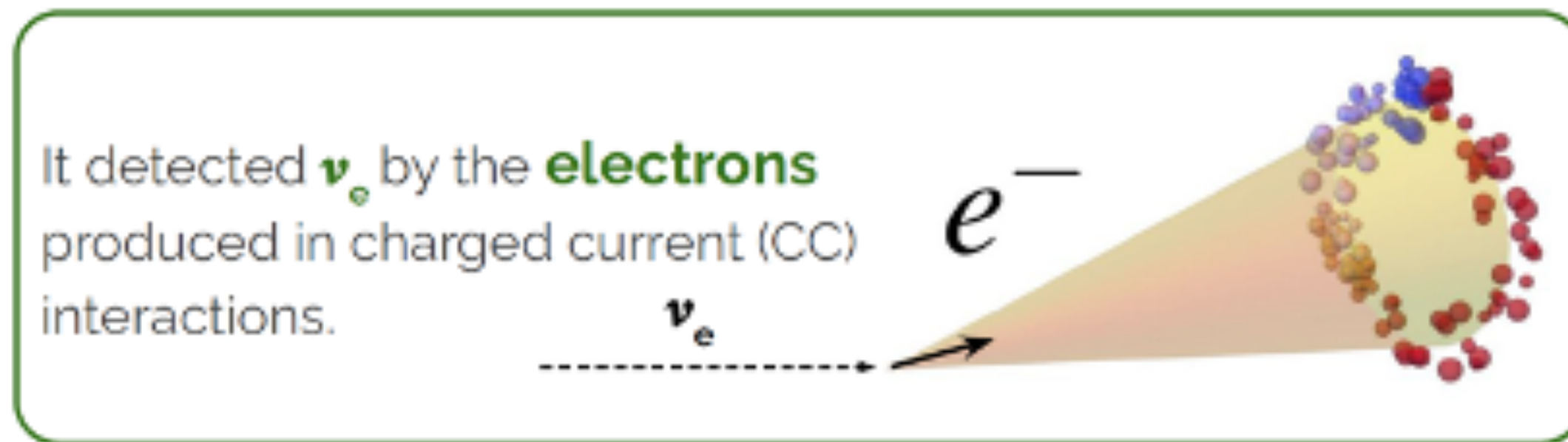
- Multi-Differential Cross Section Measurements of Muon-Neutrino-Argon Quasielastic-like Reactions with the MicroBooNE Detector
- First double-differential measurement of kinematic imbalance in neutrino interactions with the MicroBooNE detector
- First measurement of quasi-elastic  $\Lambda$  baryon production in muon anti-neutrino 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  $\nu_e$  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  $\pi^0$  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  $\nu_e$  interactions without pions in the final state with the MicroBooNE experiment
- Search for an anomalous excess of charged-current quasi-elastic  $\nu_e$  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  $\nu_e$  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  $\pi^0$  samples for the deep-learning-based analyses in MicroBooNE
- Search for neutrino-induced NC  $\Delta$  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  $E_{\nu} \sim 0.8$  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



# MiniBooNE anomaly

Phys. Rev. D **103**, 052002

- MiniBooNE (2002-2019) observed a low energy excess (LEE) of electromagnetic events with  $4.8\sigma$  significance



- MiniBooNE Cherenkov detector unable to distinguish between **electrons** and **photons**
- MiniBooNE also unable to detect hadronic final-state particles below Cherenkov threshold



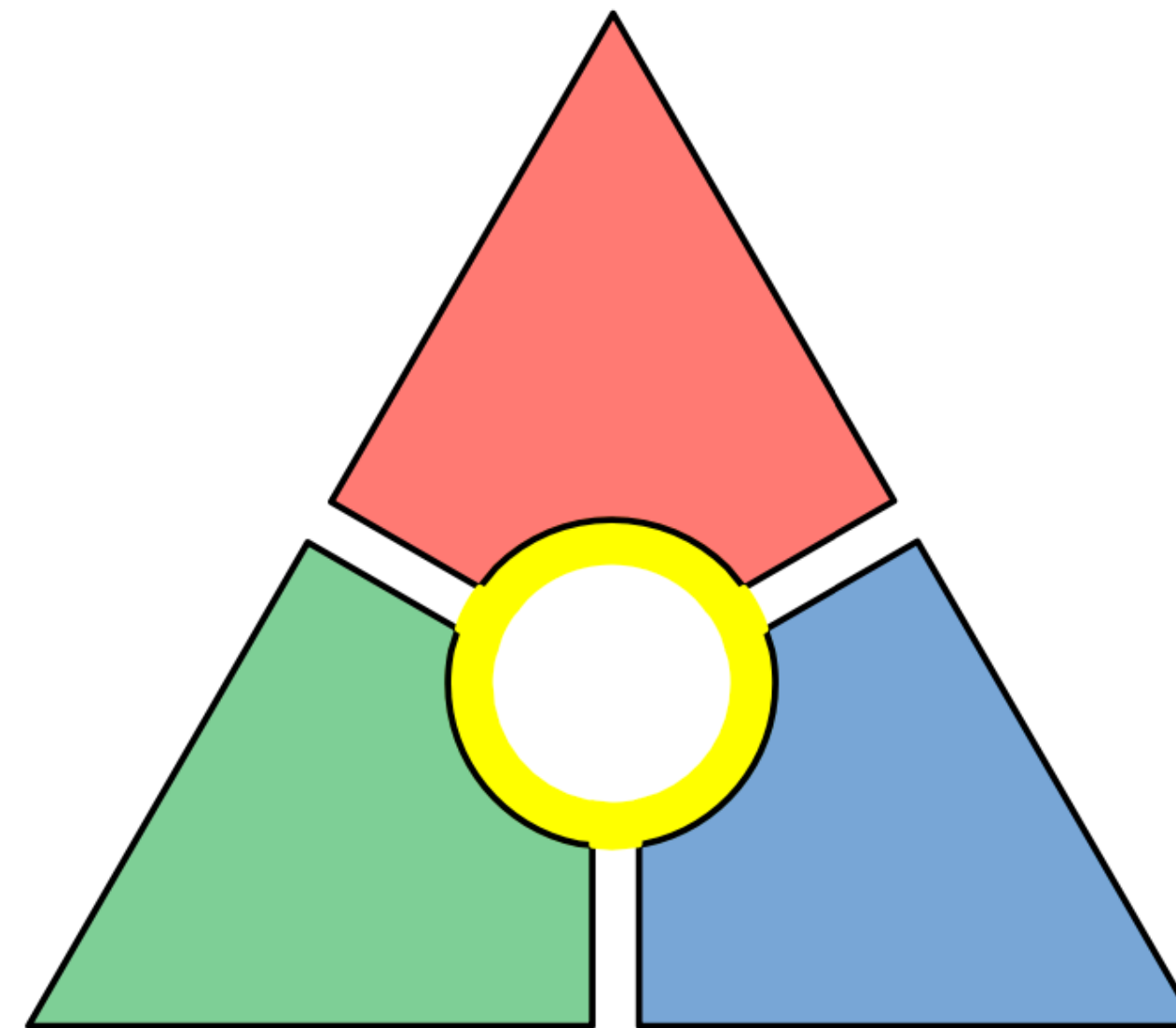
# MicroBooNE science goals

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## LArTPC hardware & software R&D

- LArTPC design, cryostat, cold electronics
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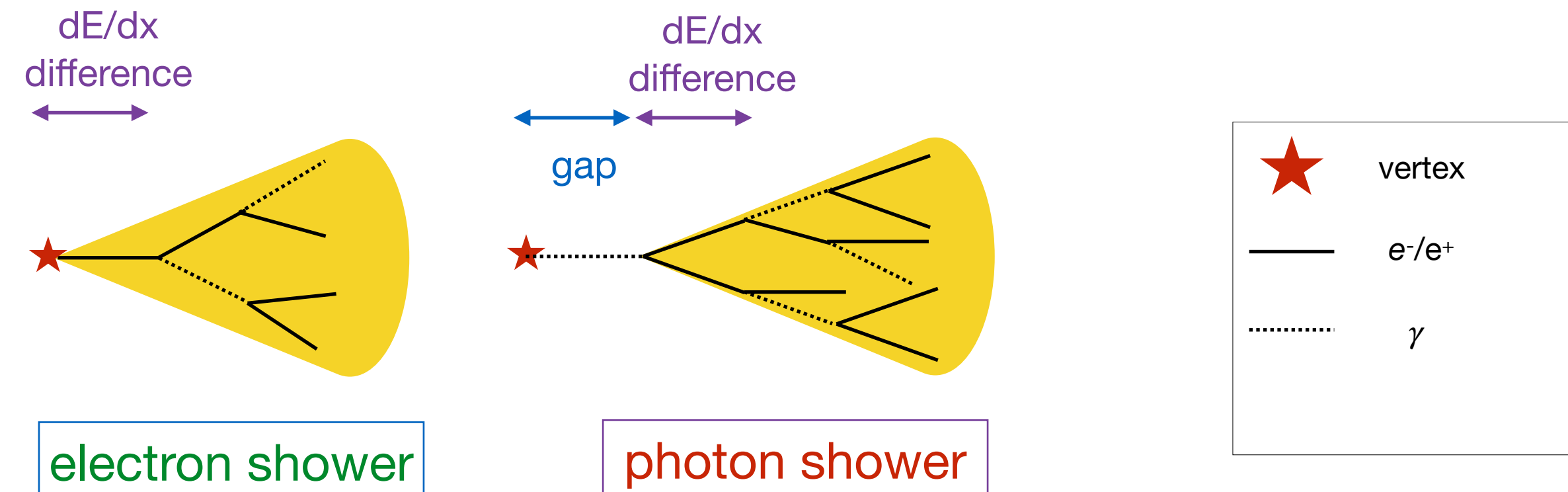
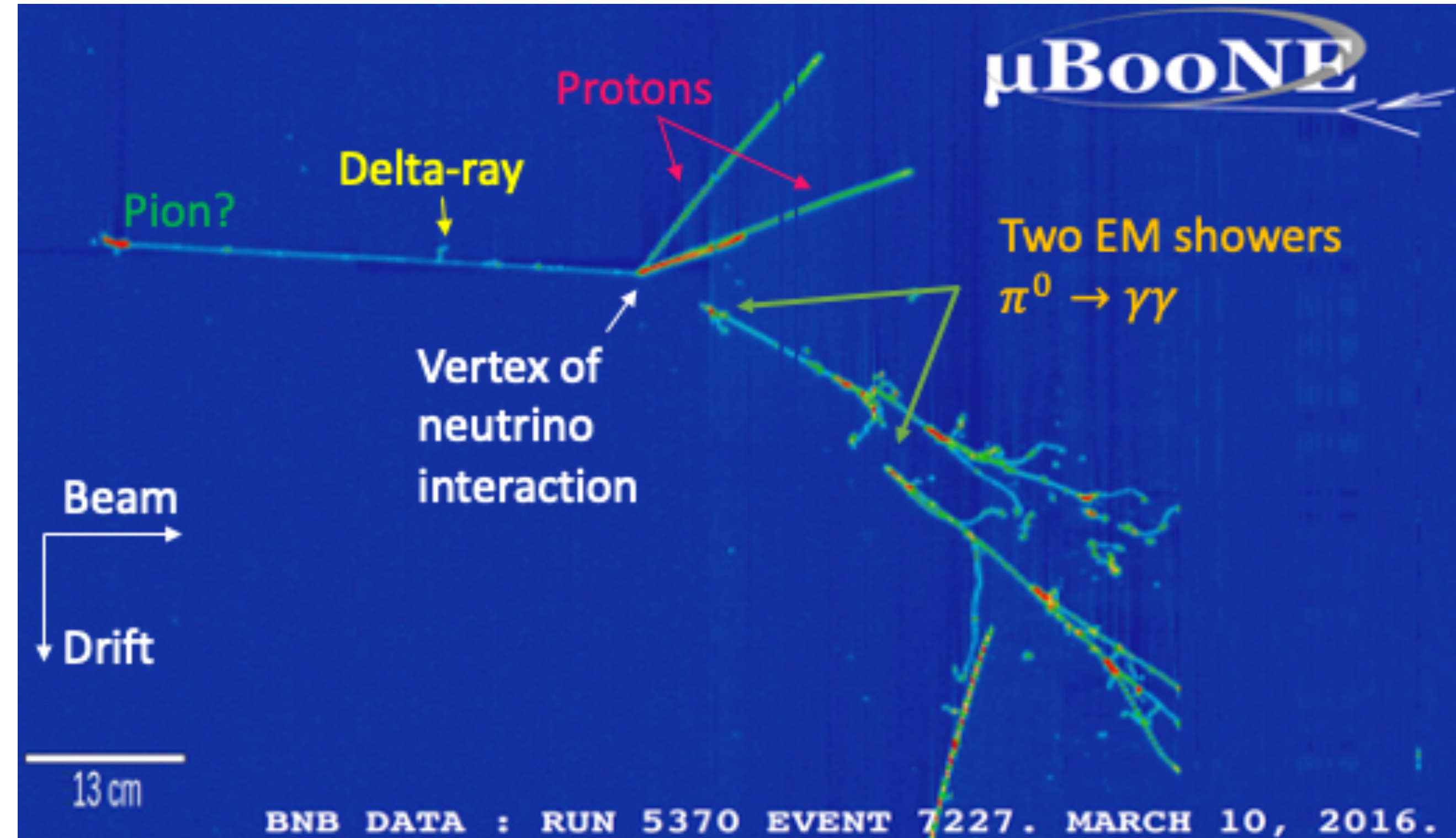
## study $\nu$ -Ar interactions

- one of the largest uncertainties in neutrino oscillation experiments
- provide important input for LArTPC experiments



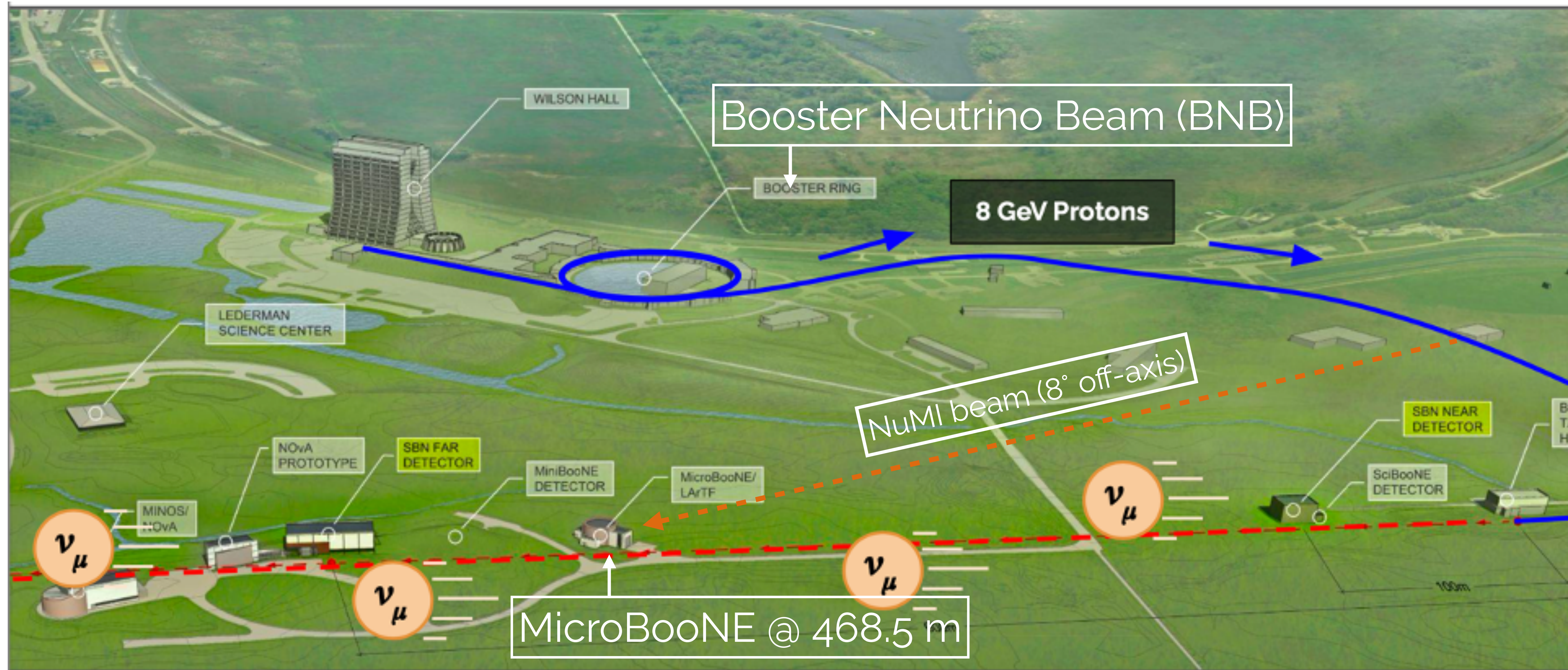
# Liquid Argon Time Projection Chamber

- LArTPC is capable of identifying different species of particles and reconstructing 3D images with fine-grained information
  - neutrino vertex
  - particle flow (mother-daughter particle relationship)
  - track vs. shower separation
  - electron vs. photon ( $e^+e^-$  pair production) separation





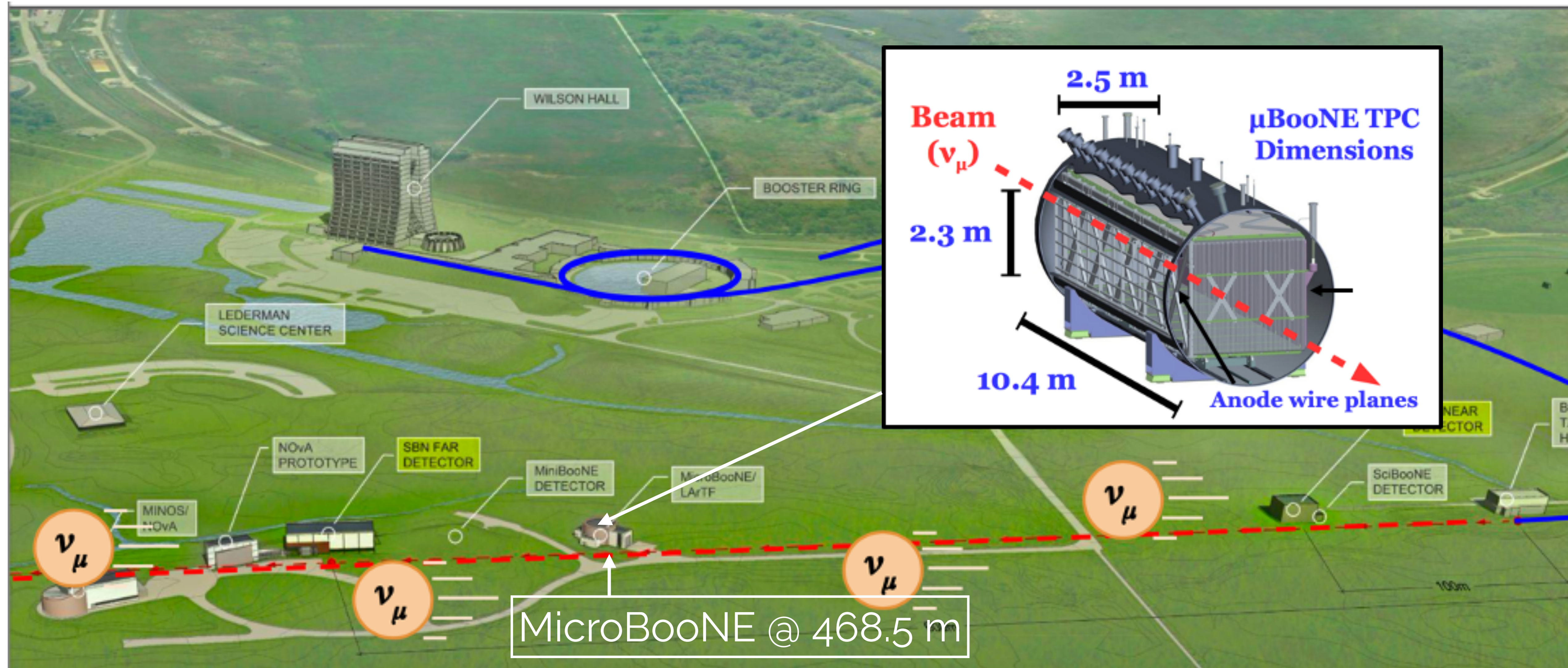
# MicroBooNE @ Fermilab





# MicroBooNE @ Fermilab

170 (85) tonne liquid argon in cryostat (TPC)

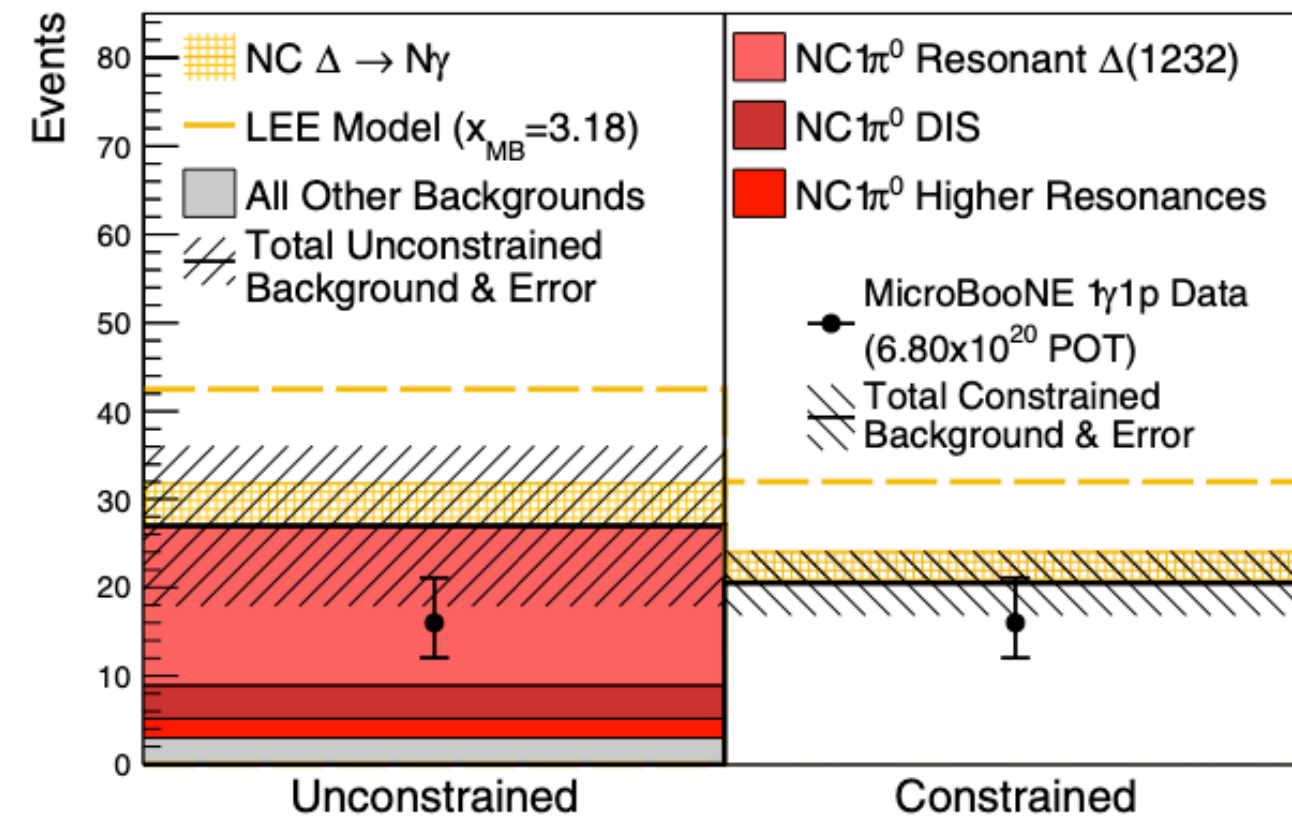




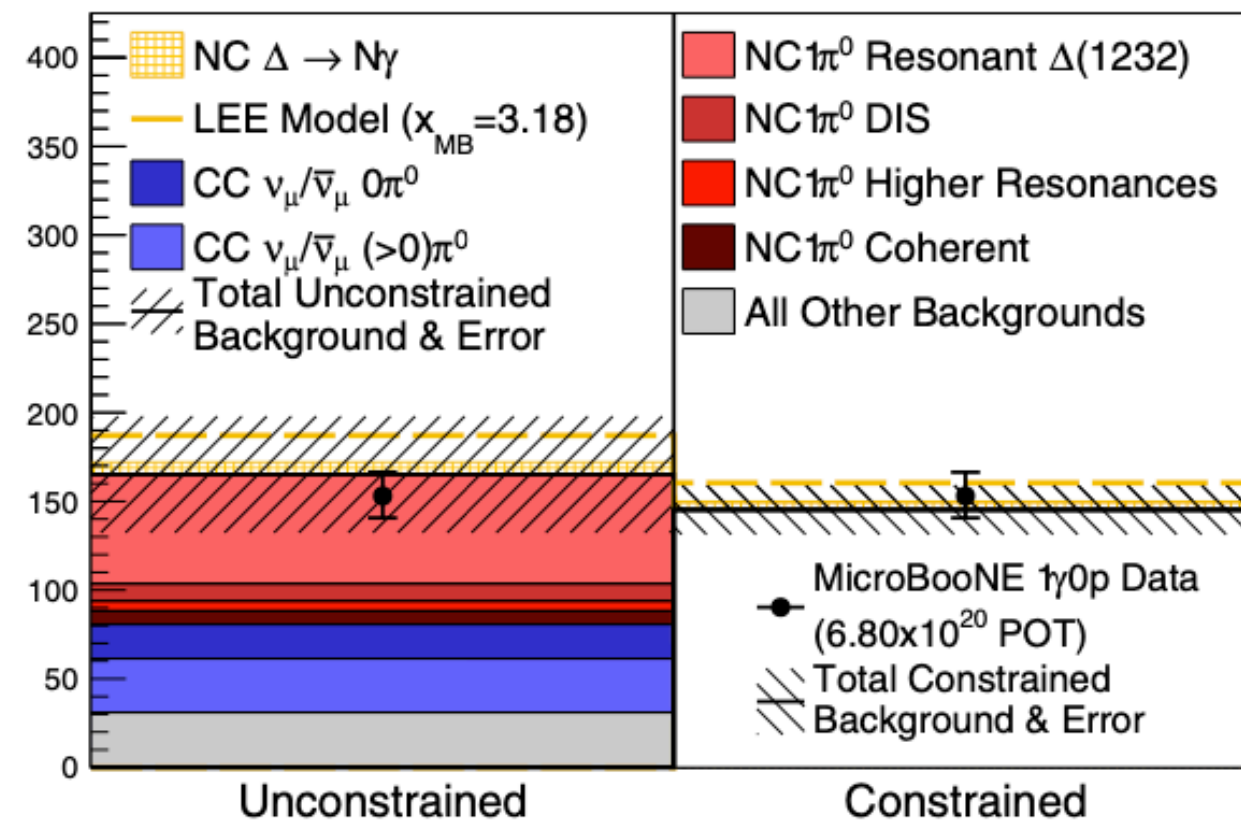
# First LEE results 2021

“Q: is LEE coming from underestimated NCA  $\Delta$  background?”

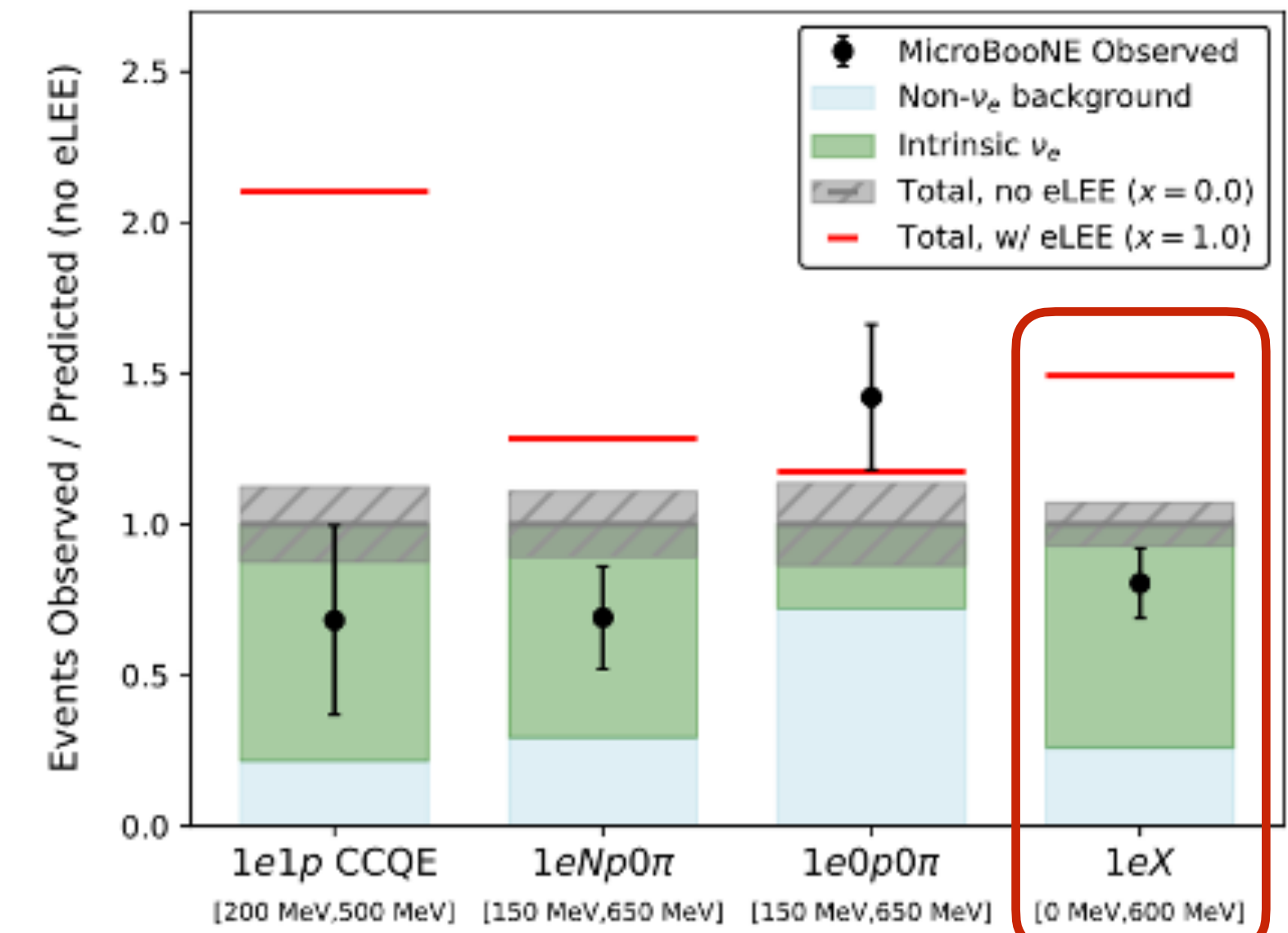
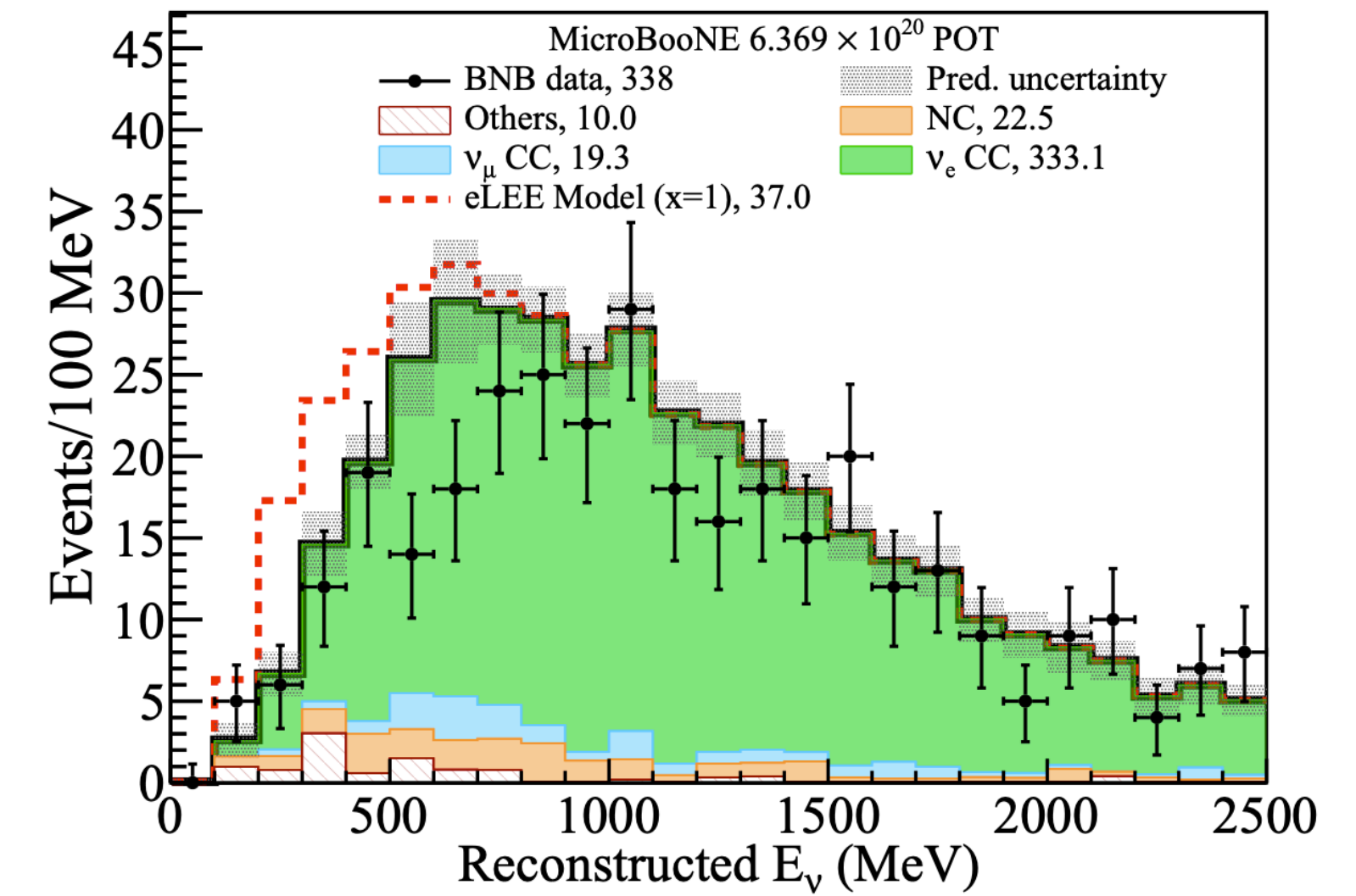
$1\gamma 1p$



$1\gamma 0p$



“Q: is LEE coming from electron neutrinos?”



Phys. Rev. Lett. **128**, 111801

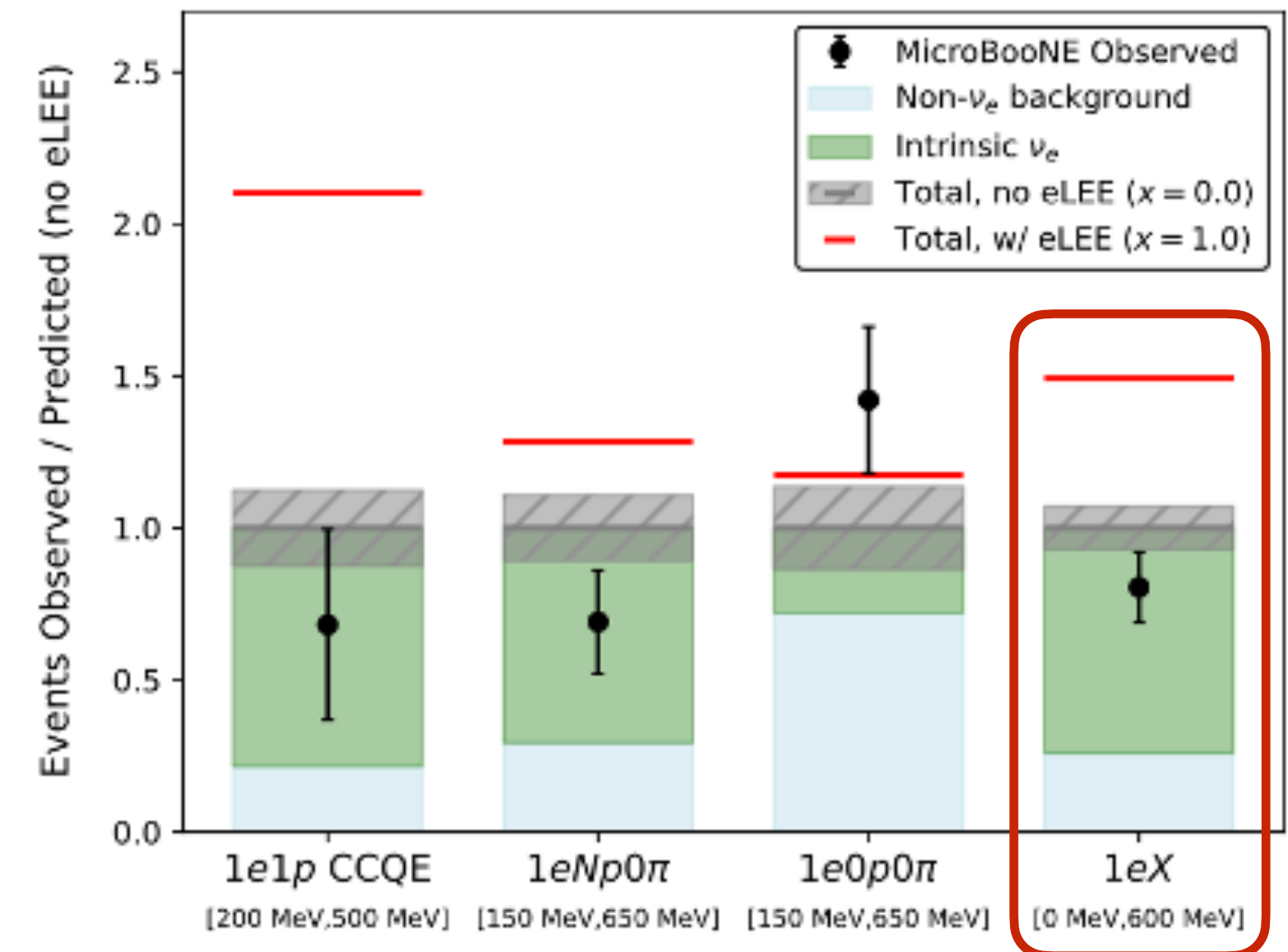
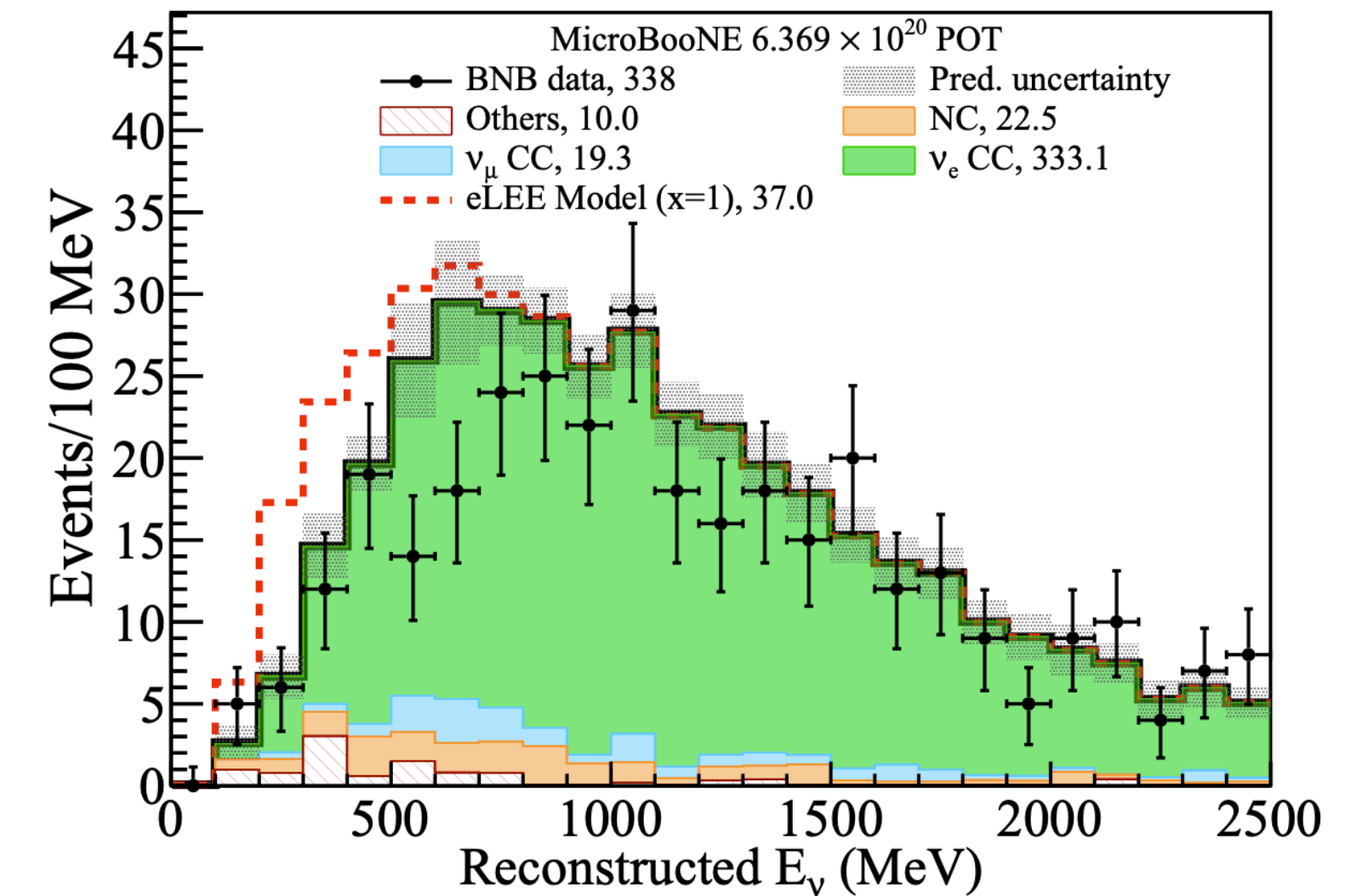
Phys. Rev. Lett. 128, 241801  
 Phys. Rev. D 105, 112005



# What did we learn from the LEE result?

- observed  $\nu_e$  candidate rates are statistically consistent with the predicted background rates in the LEE region
- with exception of the low  $\nu_e$  purity channel  $1e0p0\pi$ , the hypothesis that  $\nu_e$  events are **fully responsible** for the median MiniBooNE LEE is rejected at 97% C.L. and  $>3\sigma$  in the inclusive channel
- however, **this analysis does not address specifically the sterile neutrino hypothesis**, which is a generic low-energy  $\nu_e$  excess search

“Q: is LEE coming from electron neutrinos?”

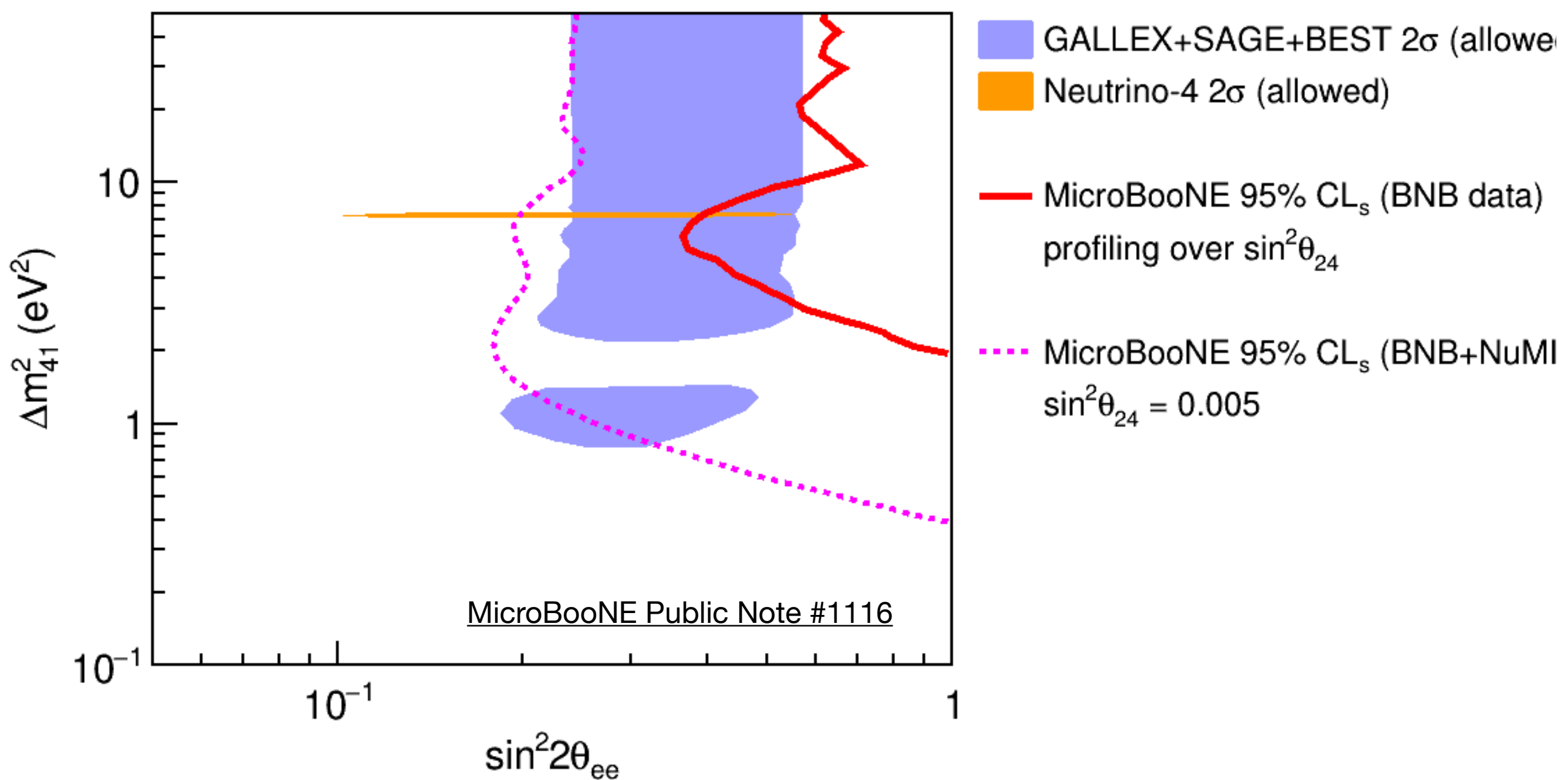


Phys. Rev. Lett. 128, 241801  
Phys. Rev. D 105, 112005

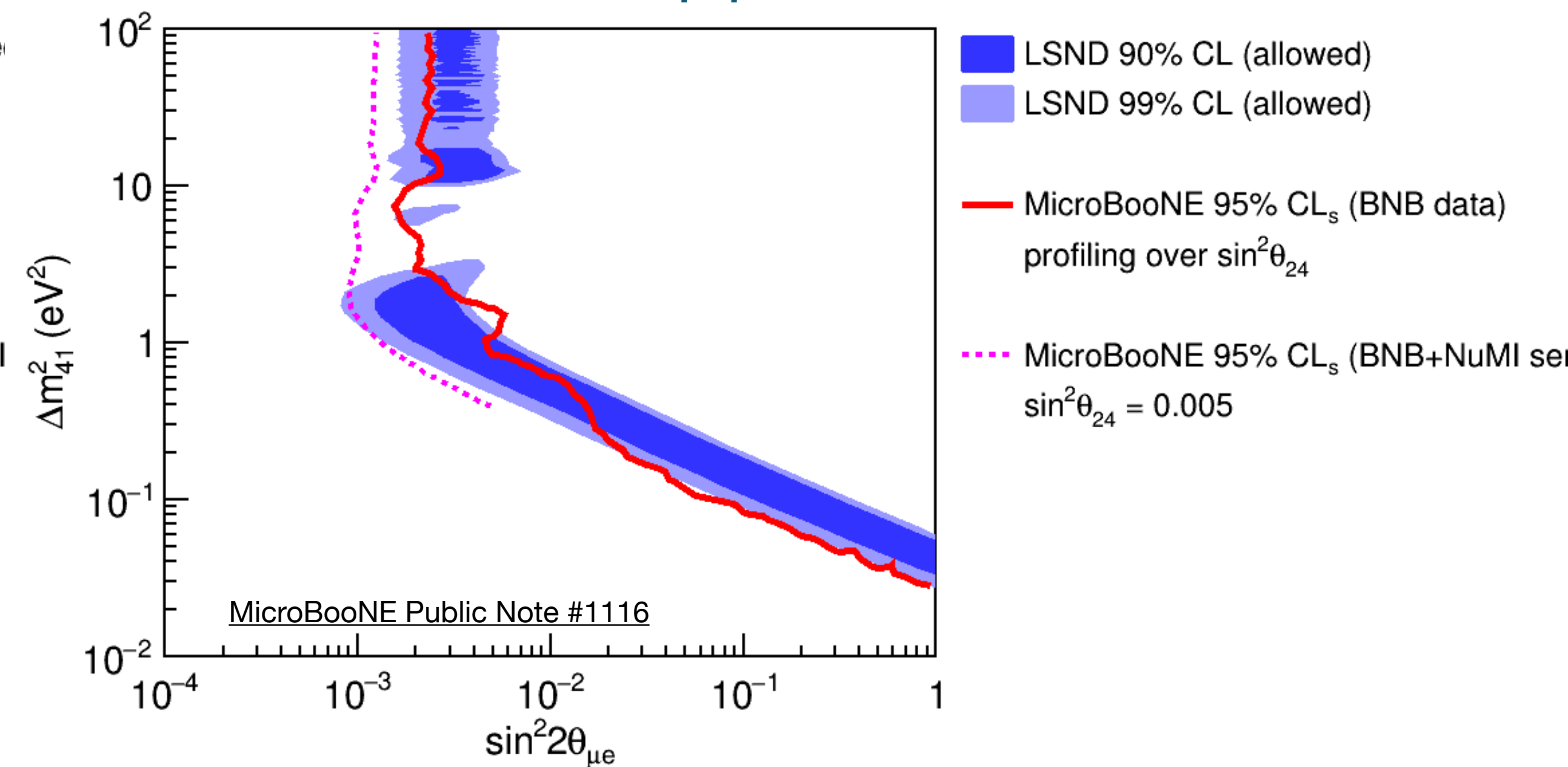


# 3+1 neutrino oscillation analysis

## $\nu_e$ disappearance



## $\nu_e$ appearance



- **competitive limit** on the eV-scale  $\nu_e$  disappearance, first  $\nu$ -Ar scattering data limit

- **part of the LSND allowed region is excluded** by the MicroBooNE 95% C.L.

**sensitivity significantly improved** when combining both BNB and NuMI, mainly due to  $\nu_e$  appearance-disappearance degeneracy mitigation



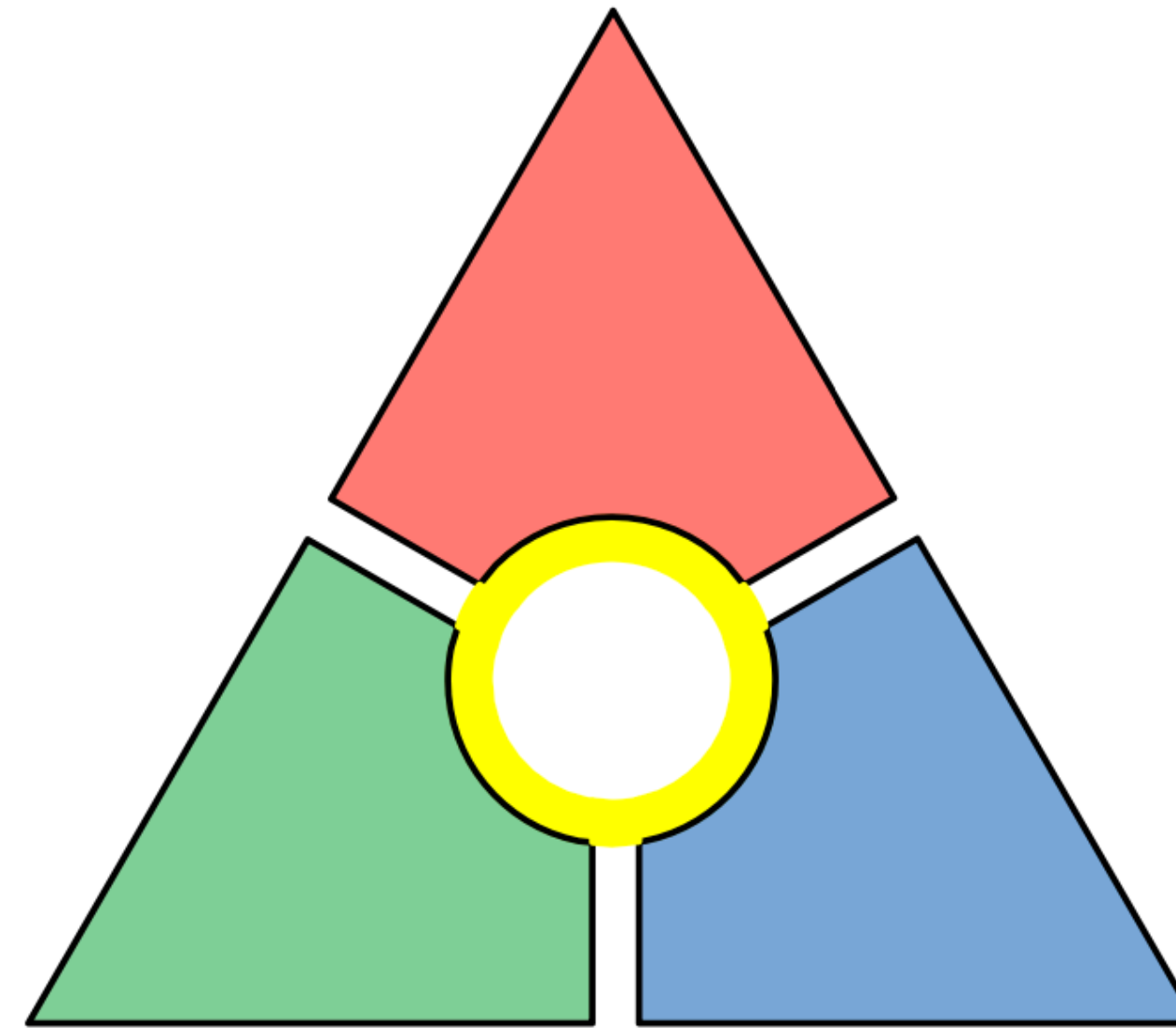
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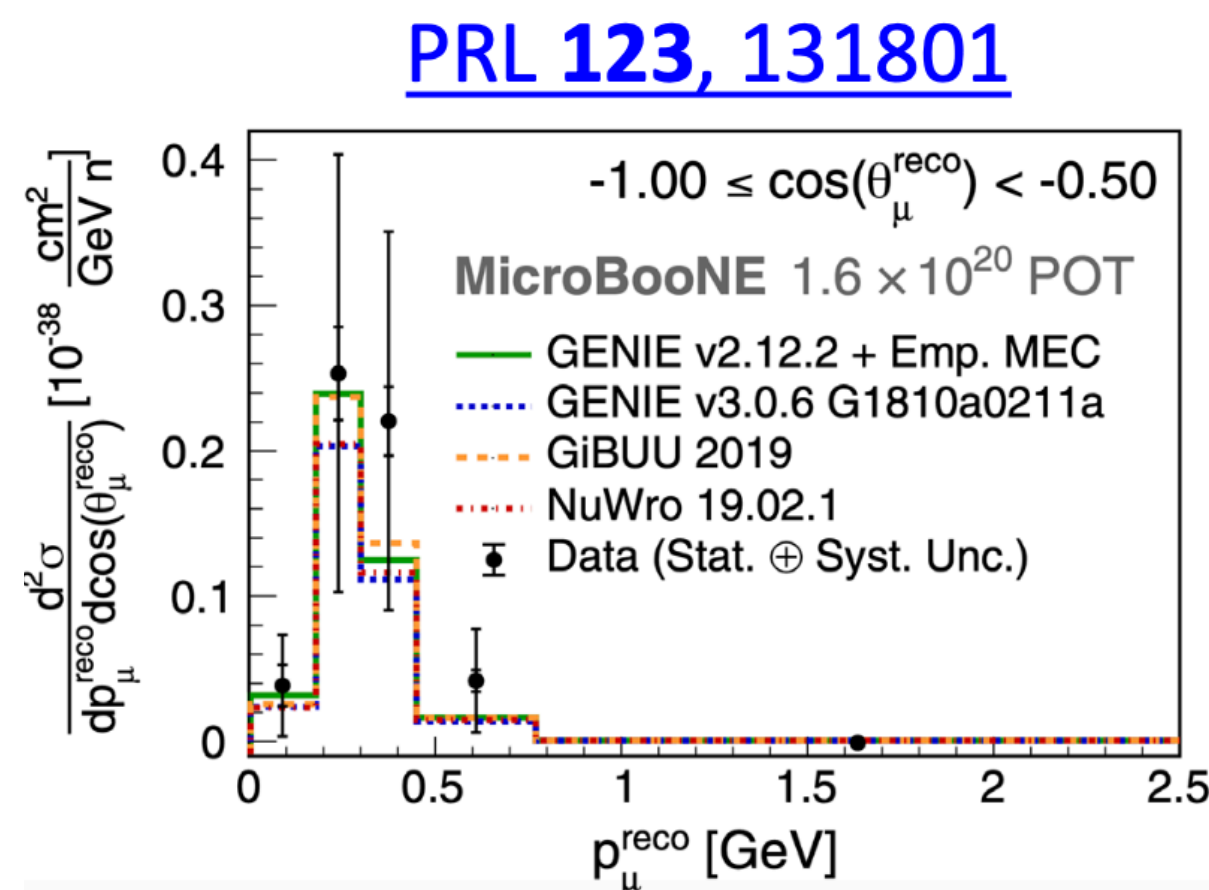
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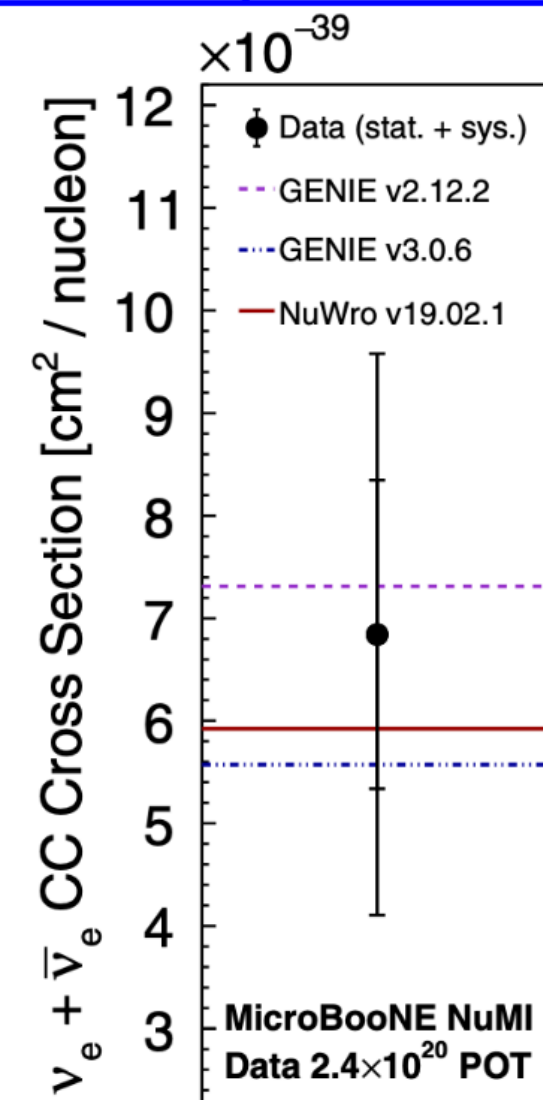


# Studying $\nu$ -Ar cross sections @ MicroBooNE

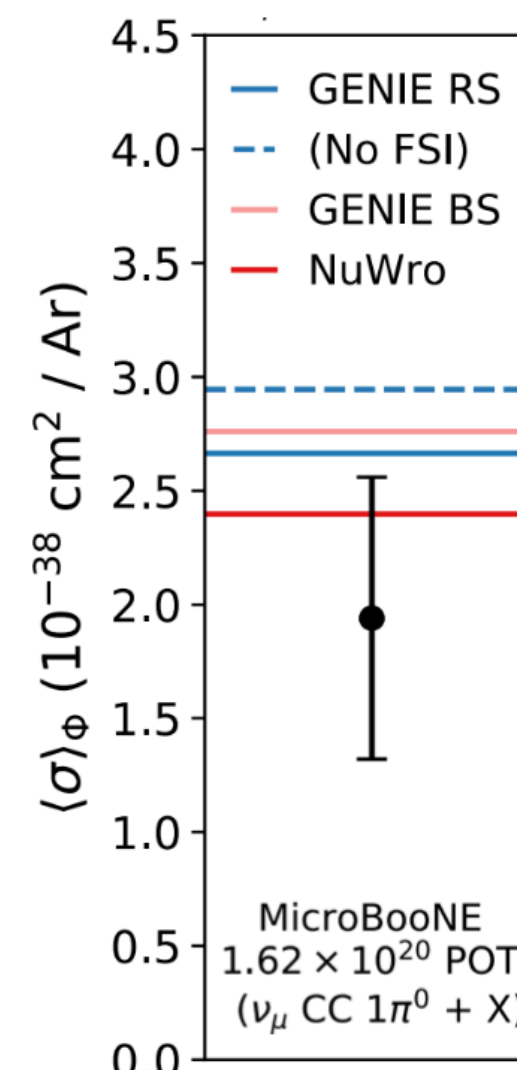
- leveraging LArTPC's excellent capability of tracking calorimetry
  - understanding of charged-current (CC) inclusive and neutral-current (NC)  $\pi^0$  cross section is desired for oscillation measurements
  - exclusive cross sections further guide event generators to pin down underlying reaction mechanism
  - "1st generation" results covered wide range of channels, providing foundation for next set of results



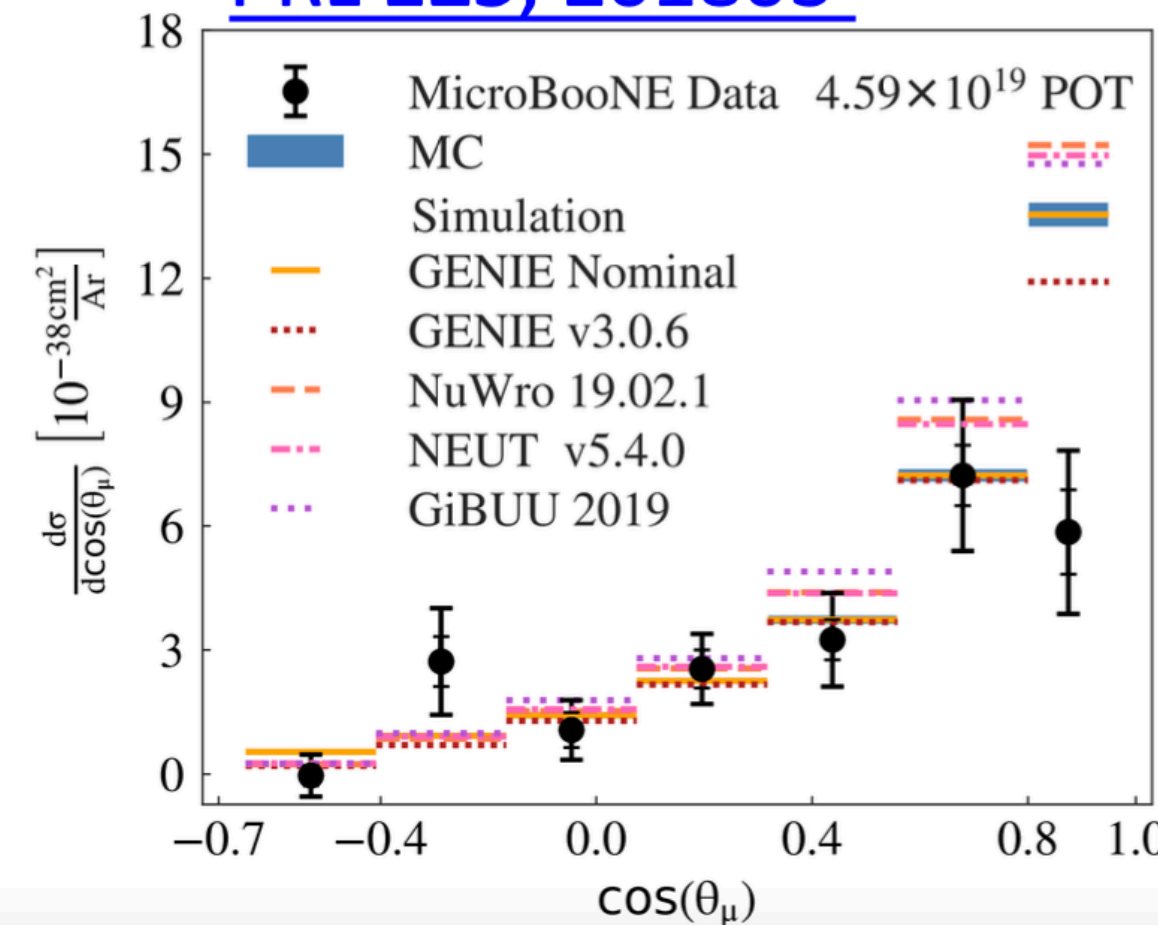
**PRD 104, 052002**



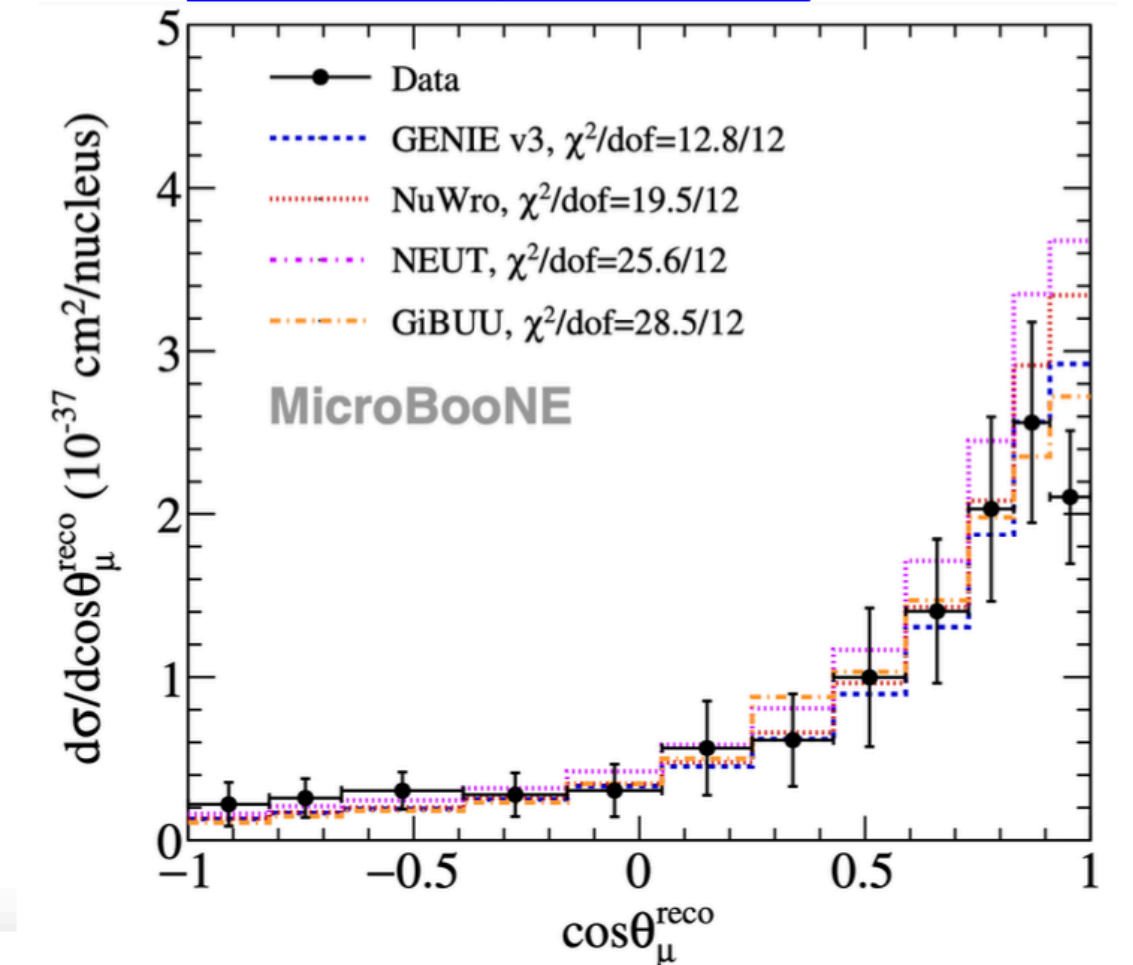
**PRD 99, 091102**



**PRL 125, 201803**



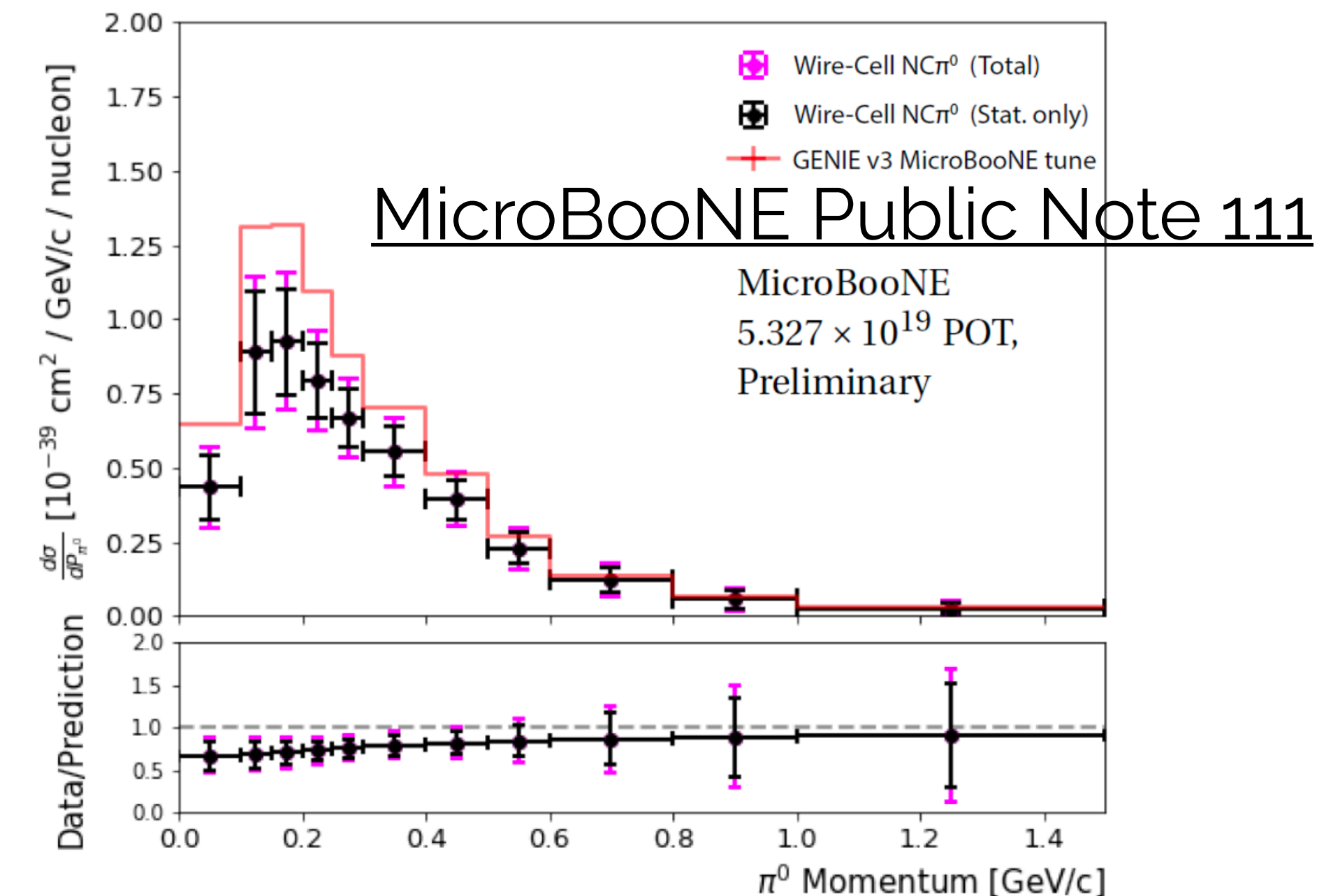
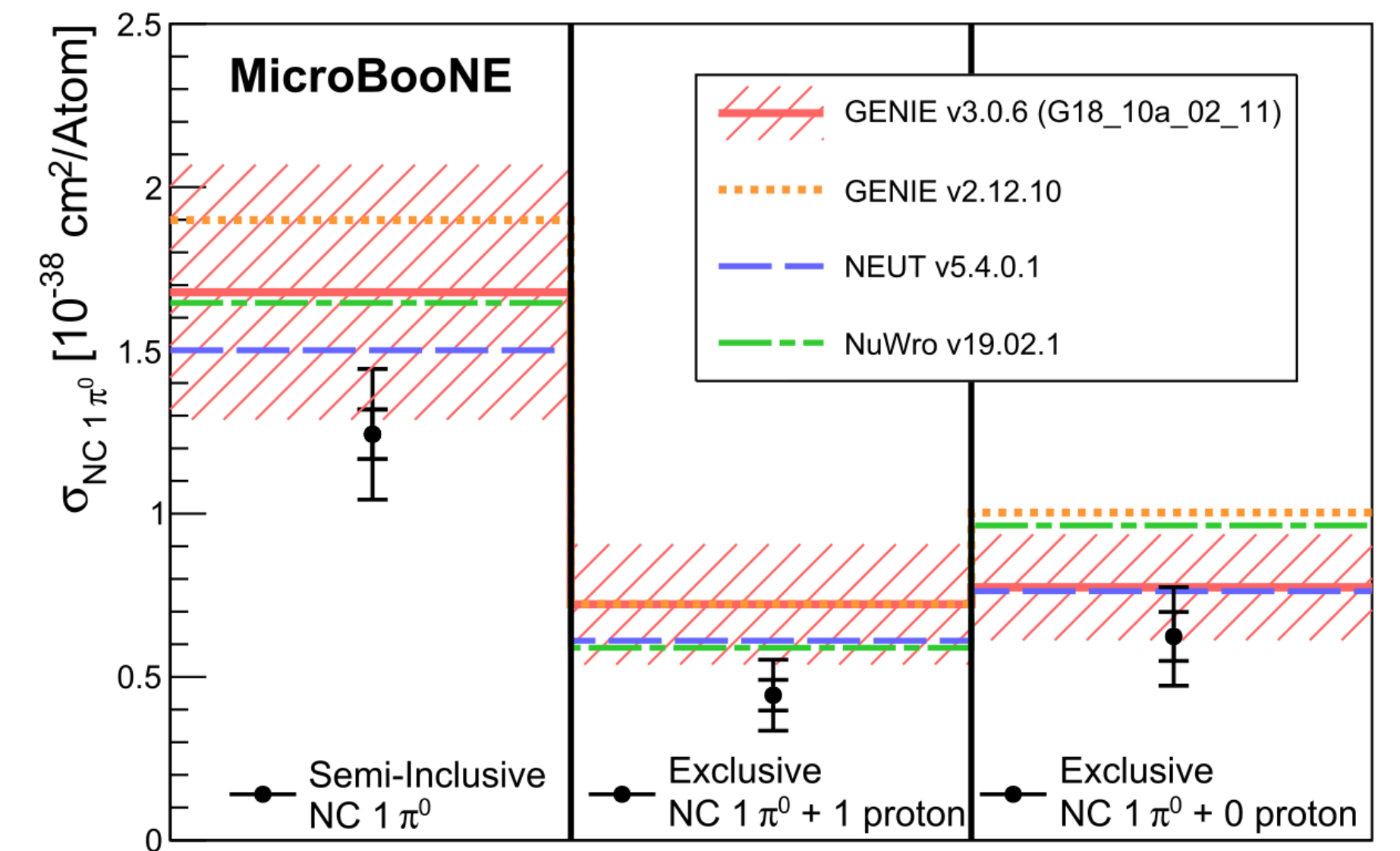
**PRD 102, 112013**



X. Qian, NuINT 2022



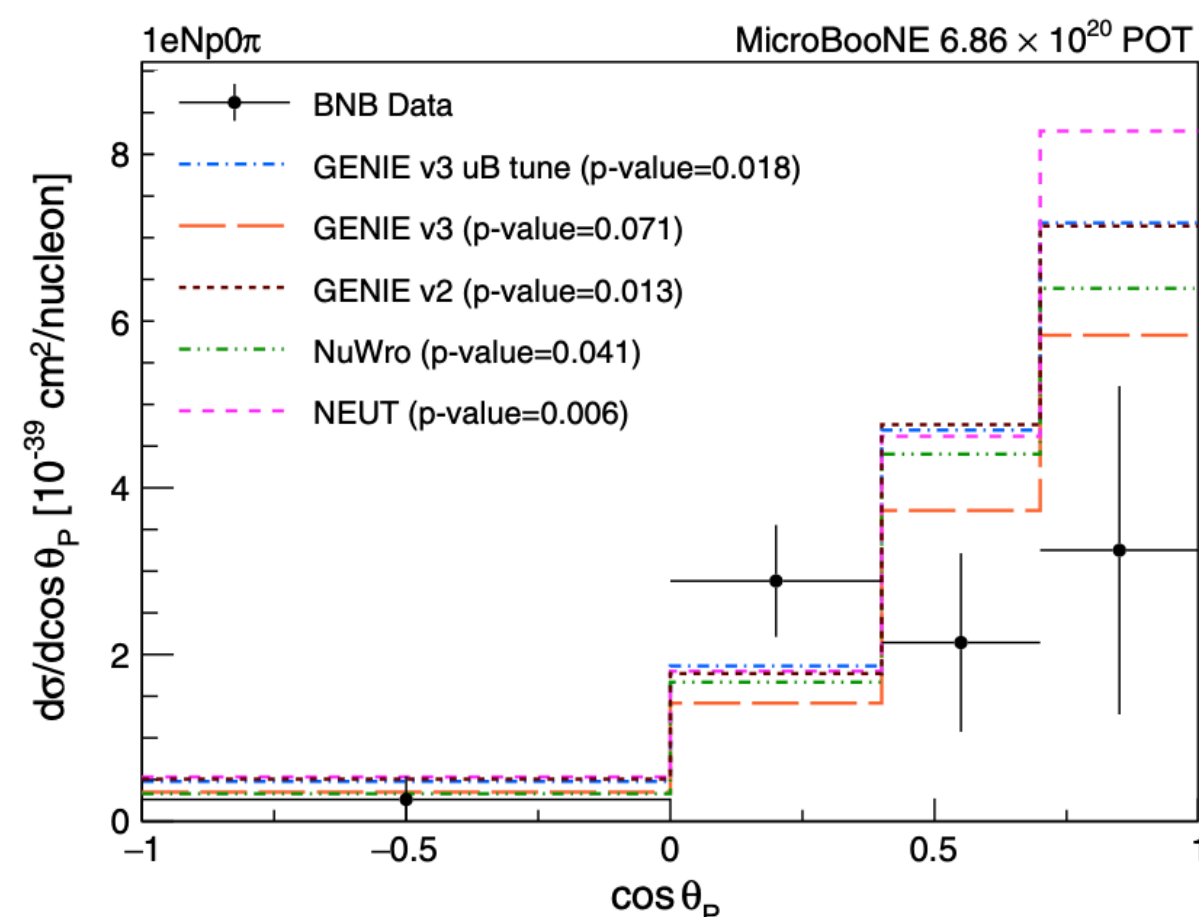
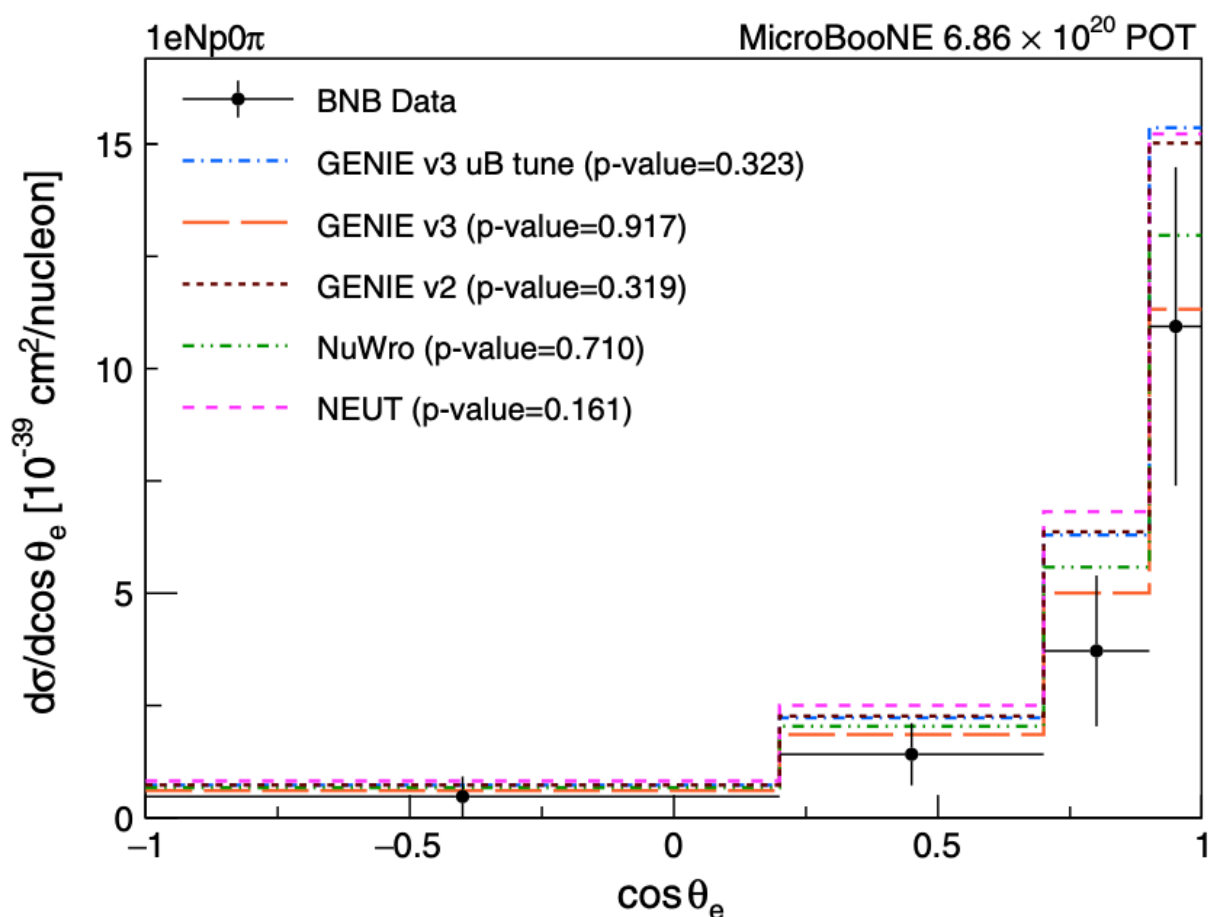
- inclusive NC  $1\pi^0$  measurement on argon
  - first exclusive measurement in the  $0p$  and  $1p$  channels
- deficit seen compared to all model studied
- ongoing analysis to extract differential cross sections
- $\sim 1\sigma$  deficit over much of the phase space in  $\pi^0$  momentum with an interesting slope



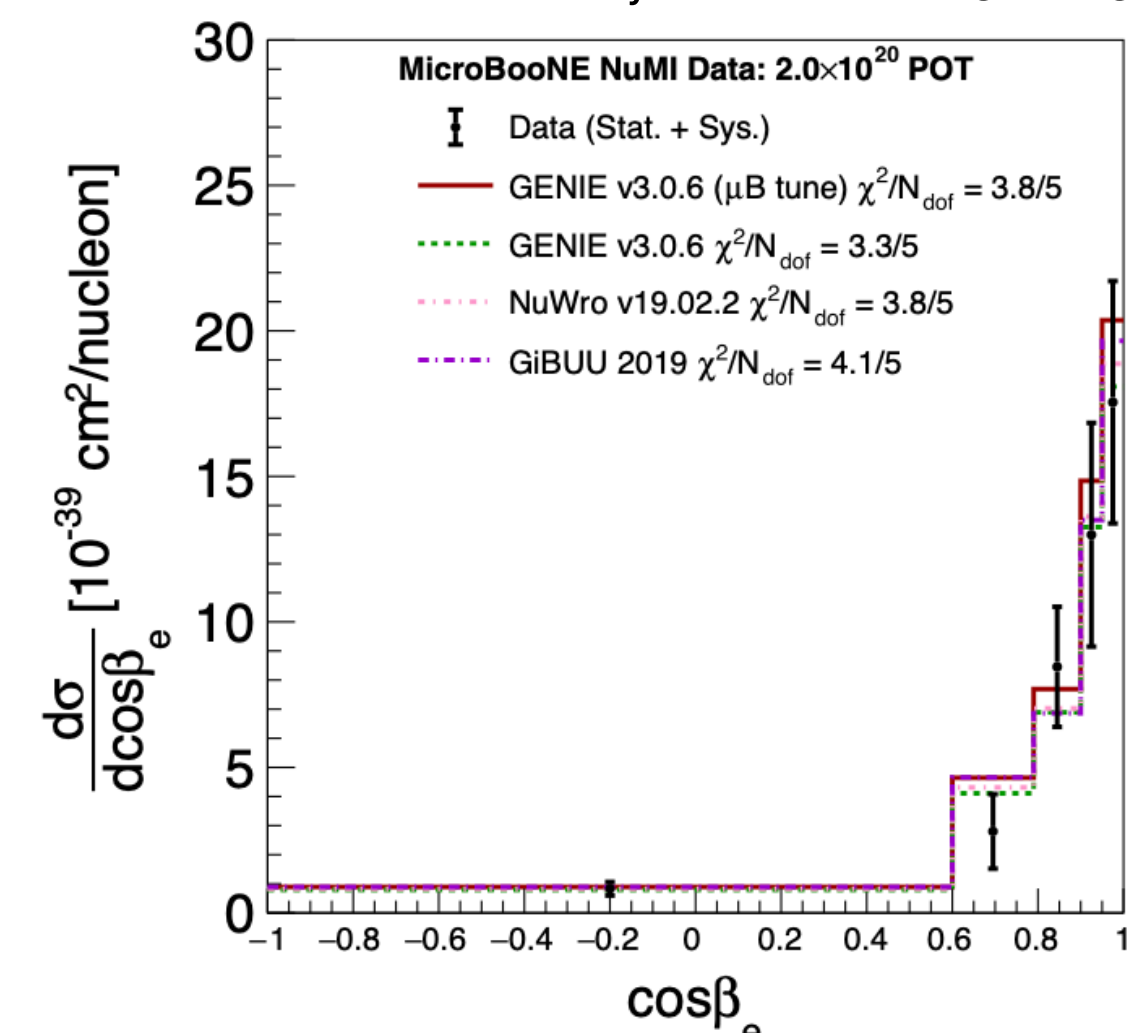
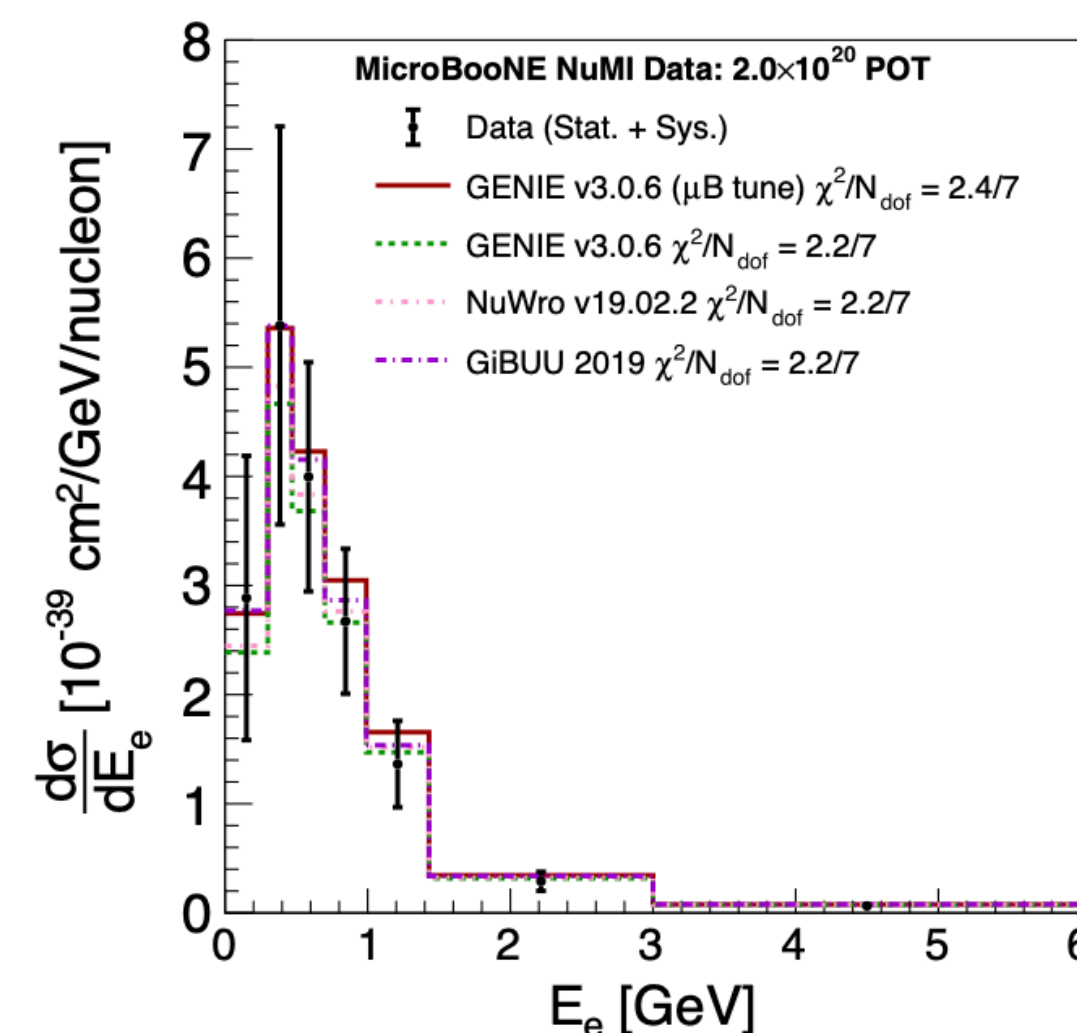


# $\nu_e$ CC cross section analyses (BNB vs. NuMI)

Phys. Rev. D 106, L051102



Phys. Rev. D 105, L051102



- first differential exclusive  $\nu_\mu$ CC cross section without pions
  - categorize the proton final state with low energy threshold
  - **consistent result with model predictions within uncertainties**, slightly favor predictions of a lower overall cross section

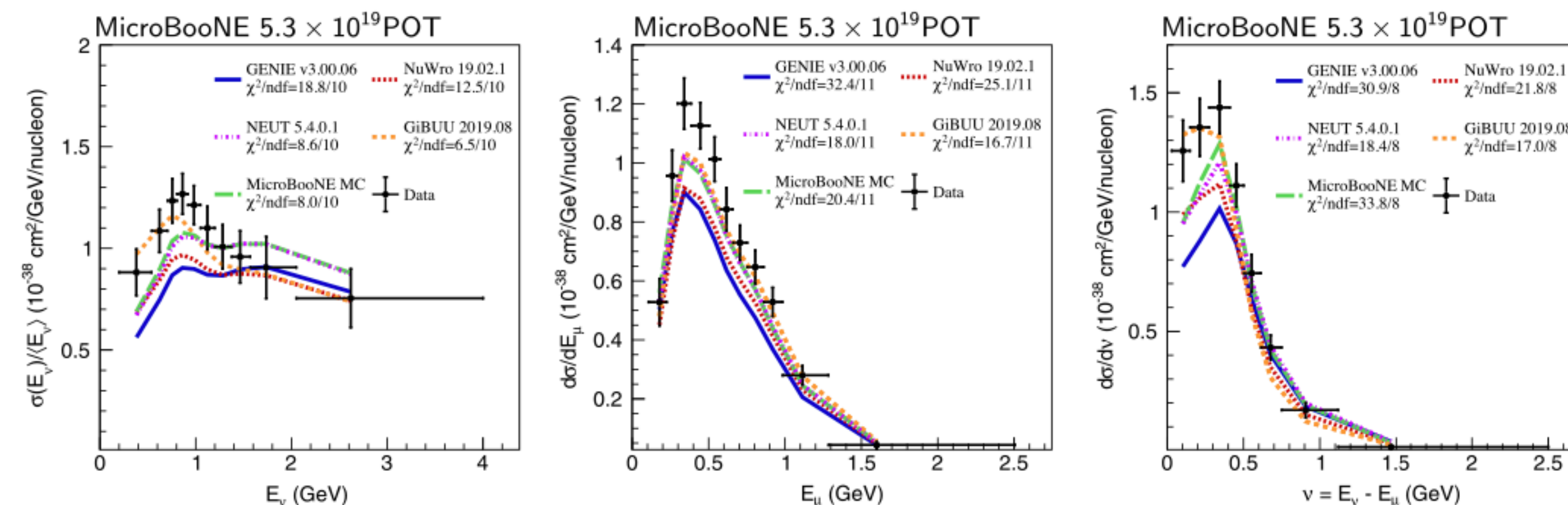
- differential inclusive  $\nu_e + \bar{\nu}_e$  cross section
  - enhanced event selection efficiency and purity
  - **consistent results with model predictions within uncertainties**



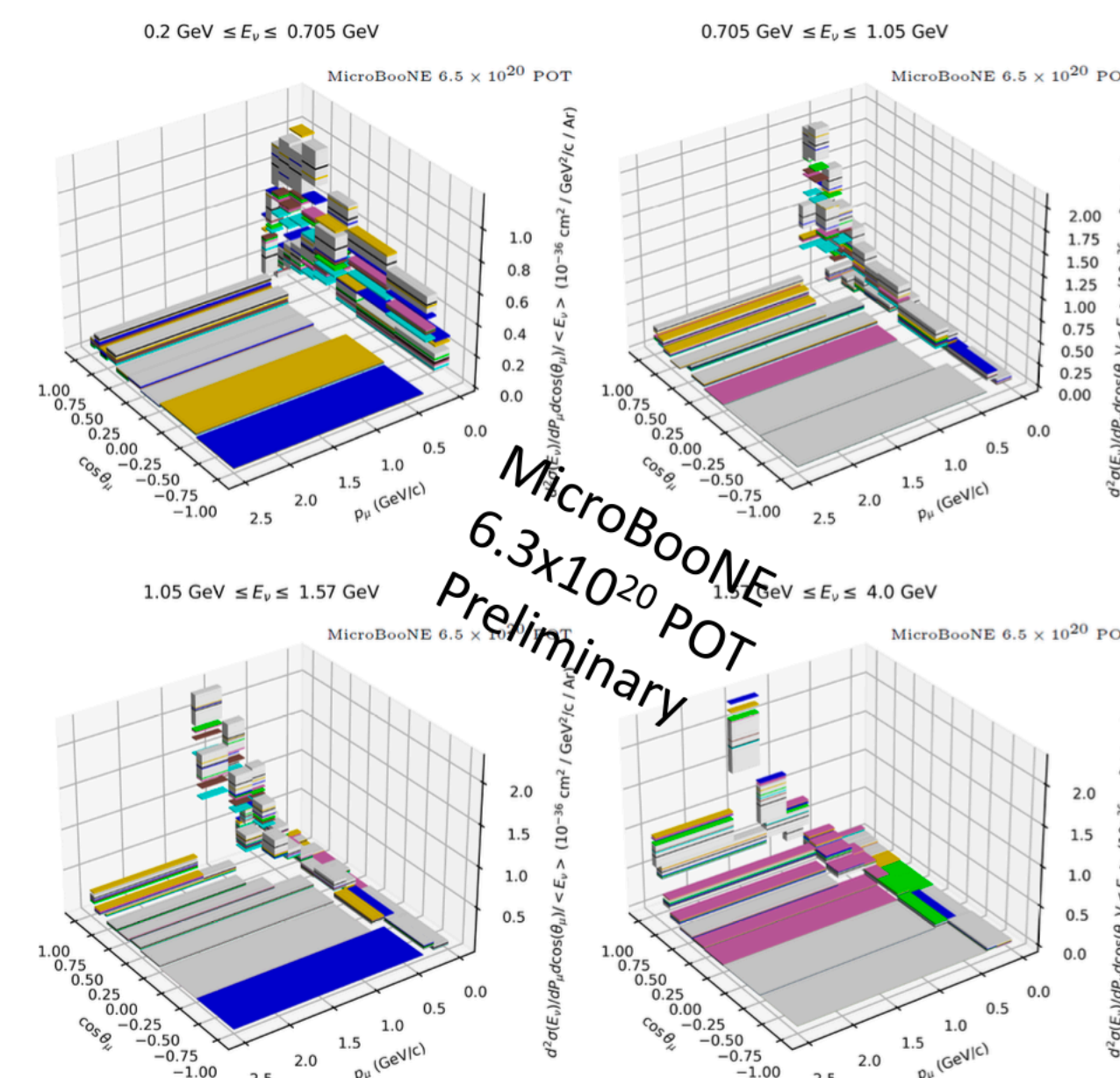
# Inclusive $\nu_\mu$ CC cross section analyses

Phys. Rev. Lett. 128, 151801 (2022)

- energy-dependent cross section has been performed
- using new model validation procedure based on the conditional covariance matrix formalism



- extended to triple differential cross sections for inclusive  $\nu_\mu$ CC in  $\{E_\nu, P_\mu, \cos\theta_\mu\}$ , rich information can be extracted



- uBooNE Data CV
- uBooNE Data Uncertainty
- GiBUU
- GENIE v2
- GENIE v3
- Neut
- NuWro
- uBooNE MC

Model Generator	$\chi^2/\text{ndf}$
Genie v2	740.8/138
Genie v3 (MicroBooNE Tune)	313.9/138
Genie v3 (Default Tune)	309.7/138
GIBUU	265.6/138
NEUT	233.1/138
NuWro	200.9/138

MicroBooNE Public Note 1122



# And much more XS measurements coming

## CC inclusive

- $\nu_e$  CC inclusive @ NuMI
- $\nu_\mu$  CC inclusive @ NuMI
- $\nu_e/\nu_\mu$  ratios @ NuMI
- $E_{\nu_e}, E_{\nu_\mu}$ , hadronic energy @ NuMI & BNB

## Much more coming from 30+ active analyses

## Pion production

- $\nu_\mu$  CC1 $\pi^+$  @ BNB
- $\nu_\mu$  CC-Coherent @ BNB
- $\nu_\mu$  CC $\pi^0$  @ BNB
- $\nu_\mu$  NC $\pi^0$  @ BNB
- $\nu_\mu$  CC/NC  $\pi^0$  @ BNB



## CC0 $\pi$

- $\nu_\mu$  Single Transverse Variables @ BNB
- $\nu_\mu$  CC2p topologies @ BNB
- $\nu_\mu$  CC0 $\pi$  inclusive @ BNB
- $\nu_\mu$  CC0 $\pi$ 0p @ BNB
- $\nu_e$  CC0 $\pi$ Np @ NuMI

## Rare channels

- $\nu_\mu$  CC Kaon @ BNB
- $\nu_\mu$  CC Kaon @ NuMI
- $\eta$  production @ BNB
- Hyperon ( $\Lambda, \Sigma$ ) production @ NuMI
- MeV-scale Physics in MicroBooNE



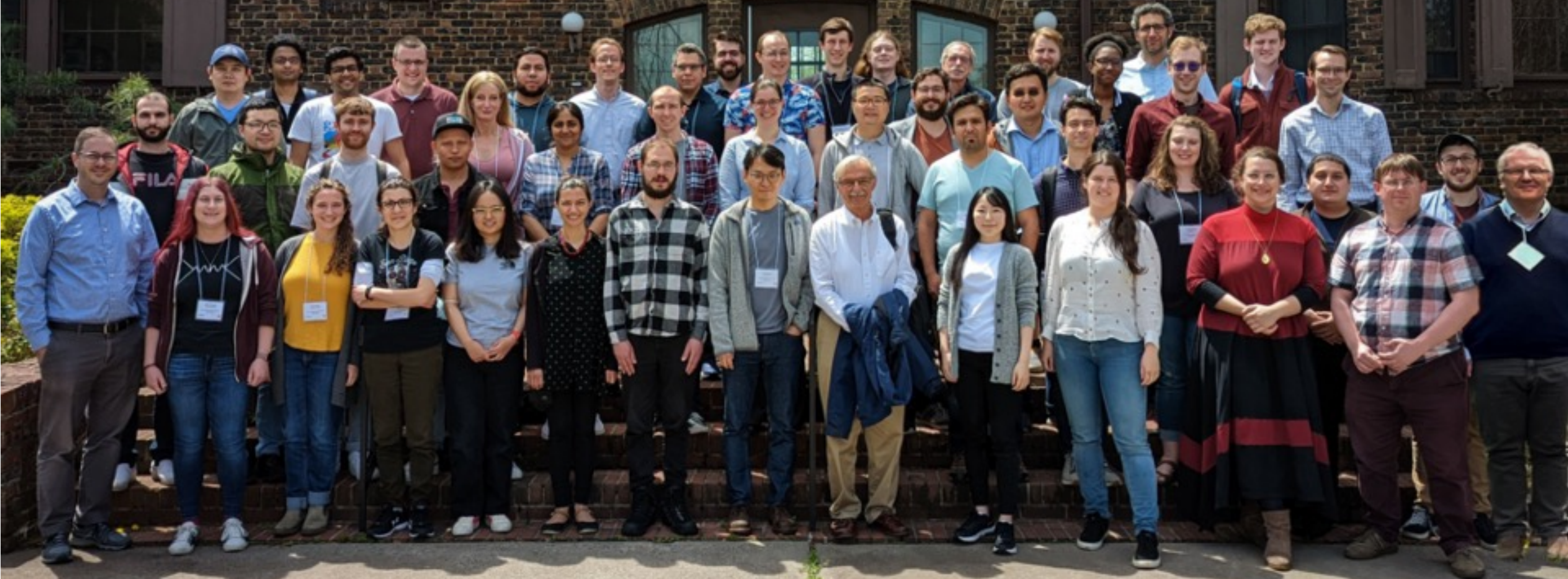
# Summary

- MicroBooNE is the first neutrino experiment to fully realize and exploit the power of LArTPC
- MicroBooNE found no evidence of excessive  $\nu_e$  and NC  $\Delta$  radiative decay as a sole source of the MiniBooNE anomaly
- a full 3+1 oscillation analyses were carried out to interpret the MicroBooNE eLEE results under a sterile neutrino oscillation hypothesis
  - the data (~50% BNB dataset) was found to be consistent with 3-flavor hypothesis
- with well-understood LArTPC detector, simulation, and dataset, wealth of cross section measurements are being carried out, including NC $\pi^0$ , inclusive & exclusive  $\nu_e$  CC/ $\nu_\mu$ CC, and many others
  - already benefiting the community with better understanding of  $\nu$ -Ar interactions, providing inputs for current/future LArTPC experiments



# $\mu$ BooNE

# Thank You!



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Facilities Council



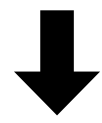


Backup slides

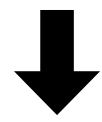


# LArTPC: Liquid Argon Time Projection Chamber

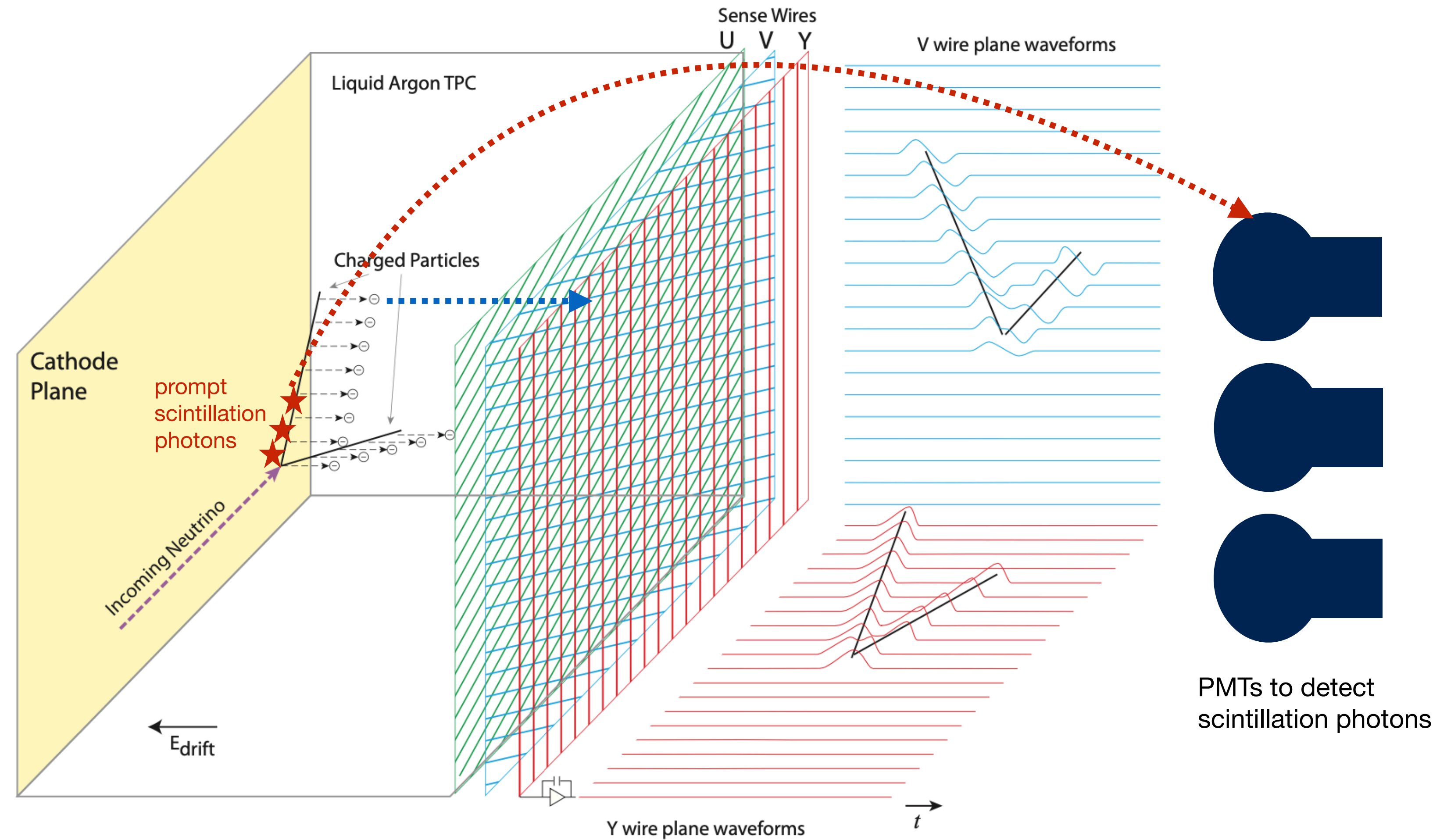
charged particle enters detector



scintillation light emitted by excited Ar, detected by PMTs

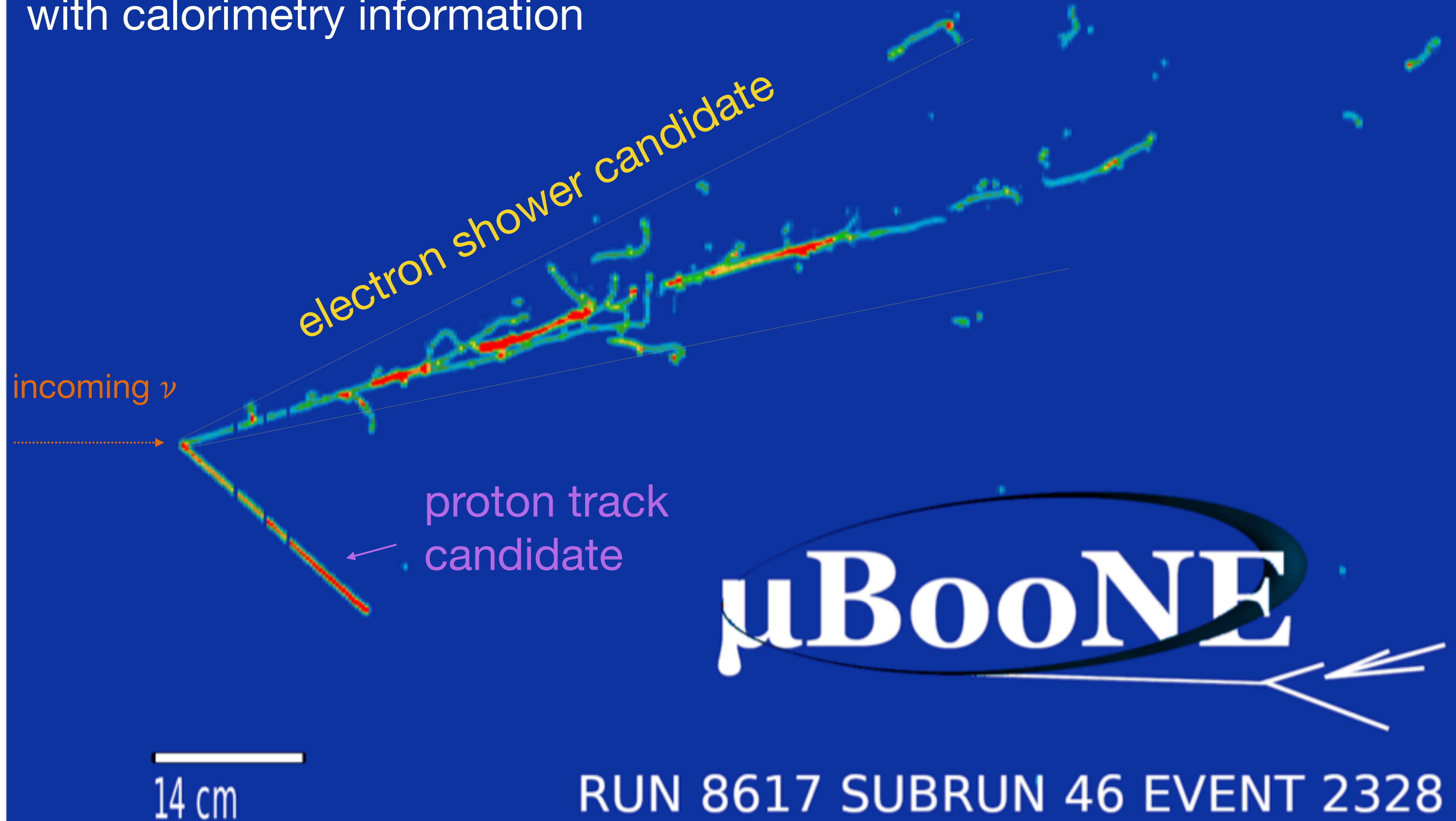


ionization electrons drift to anode plane, detected by sense wires





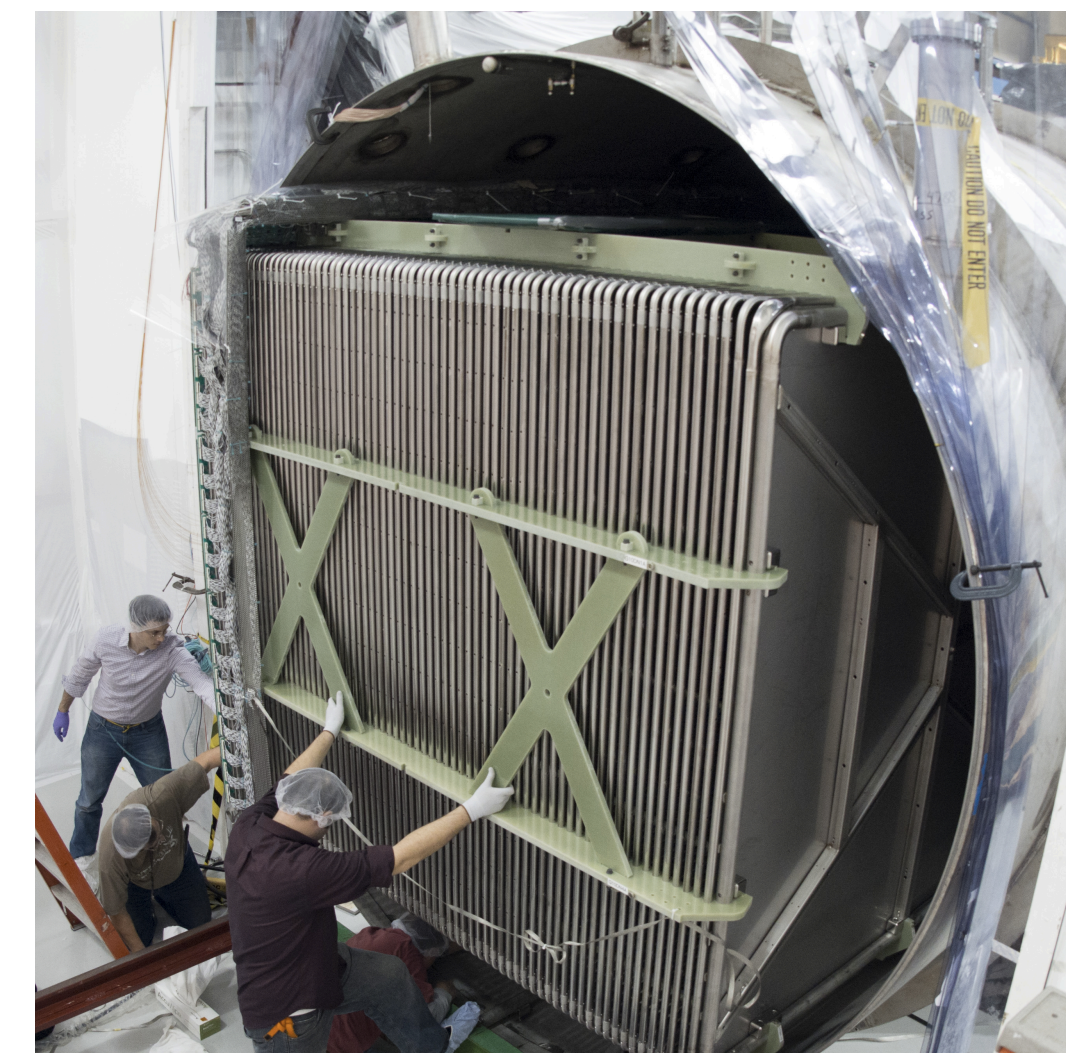
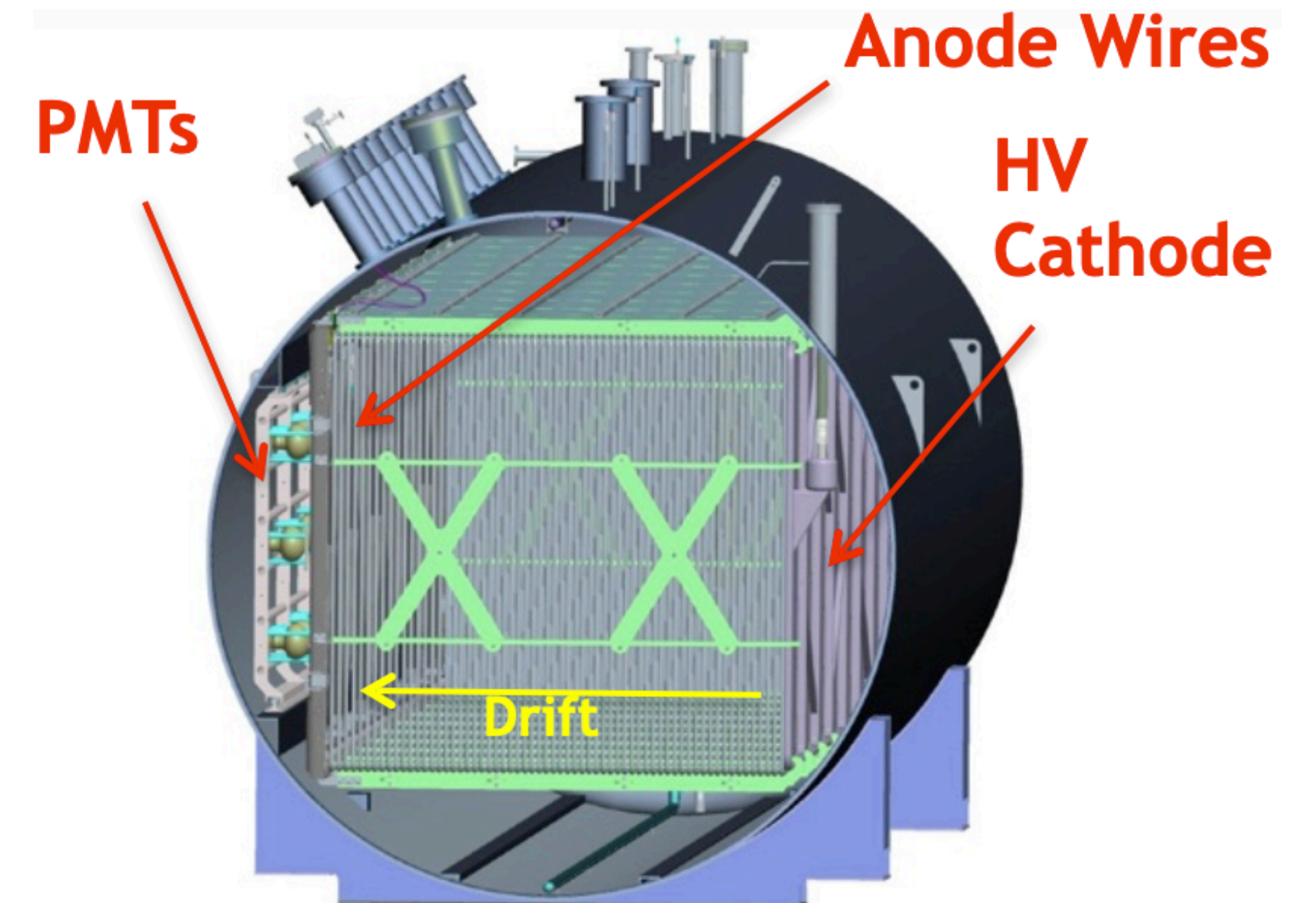
result in fine-grained 3D images,  
with calorimetry information





# MicroBooNE experiment

- LArTPC Detector
  - 85 tons of LAr active volume
  - TPC: 8192 anode sense wires in 3 planes  
PMT: 32 8-inch PMTs
  - CRT (cosmic ray tagger) is installed around TPC
  - located at BNB beamline in Fermilab, started taking data since Oct. 2015
- physics goal
  - strong understanding of the detector and highly developed event reconstruction, paving the way to future LAr detectors (SBN & DUNE)
  - neutrino interaction measurements
  - towards low-energy excess: definitively address the MiniBooNE anomaly





# This LEE search proceeds with a simultaneous side-by-side fit of four topologically distinct samples

Two **NC  $\Delta \rightarrow N\gamma$**  rich **single-photon** selections



Two high-statistics **NC  $\pi^0$  rich** **two-photon** selections

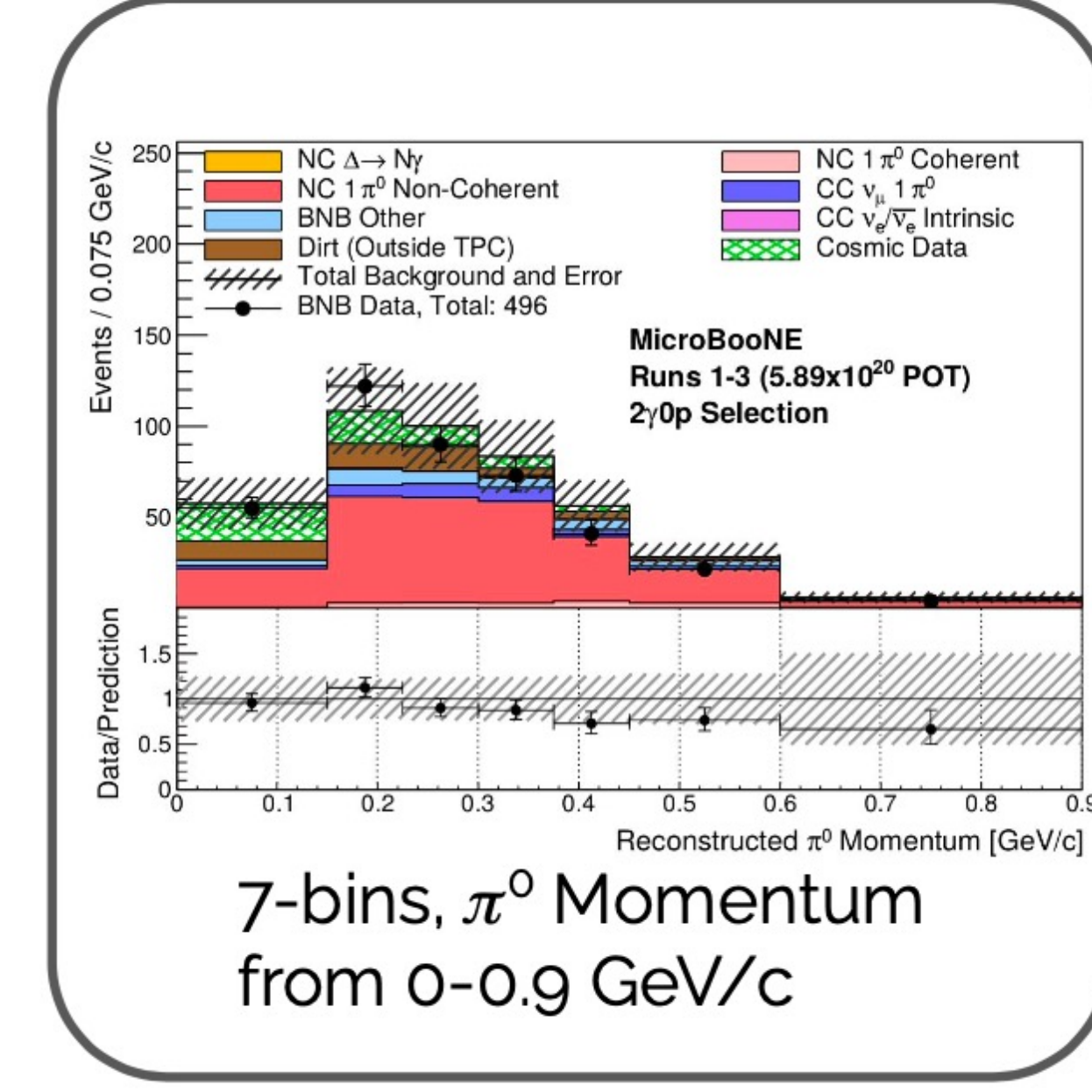
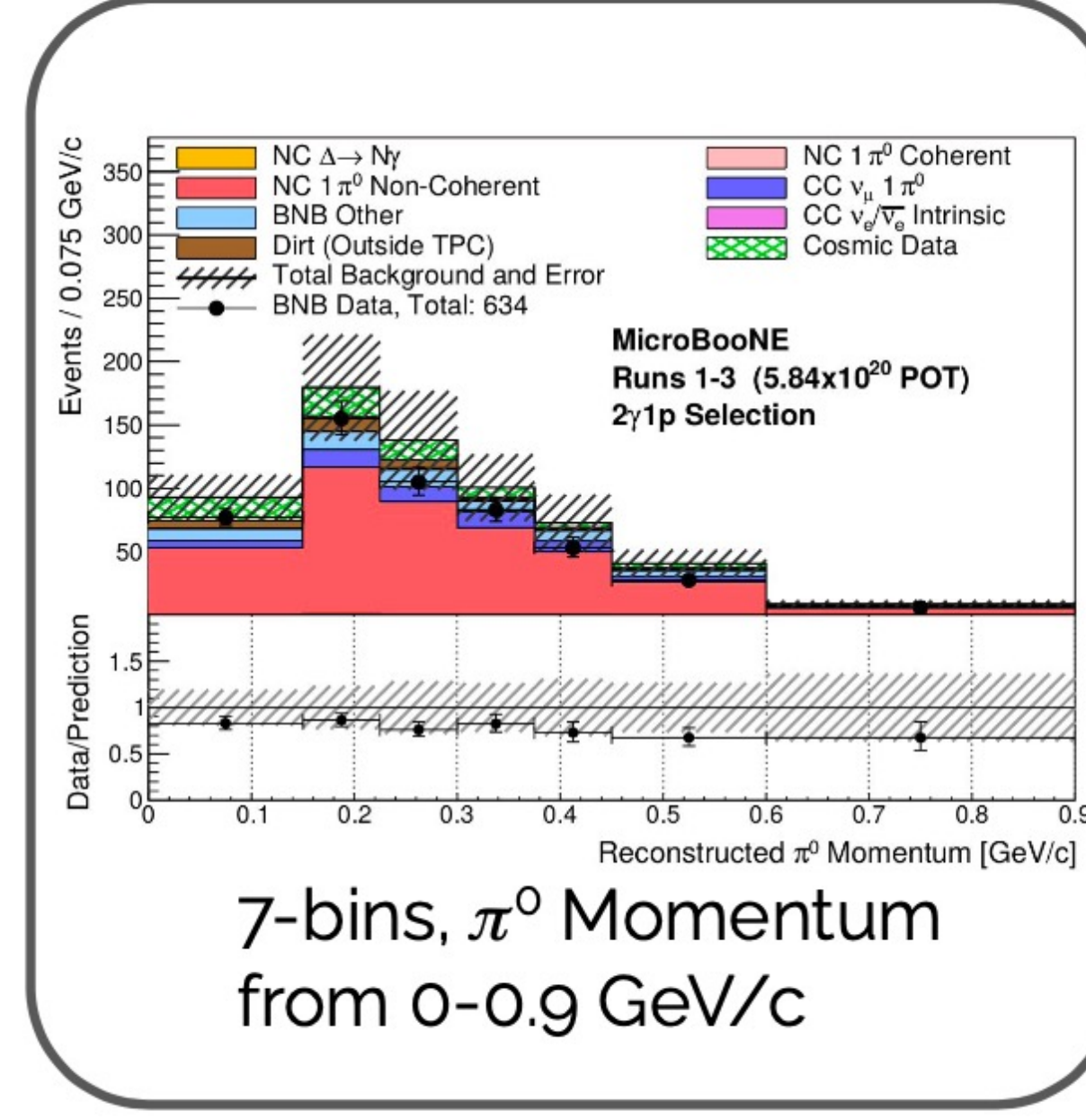
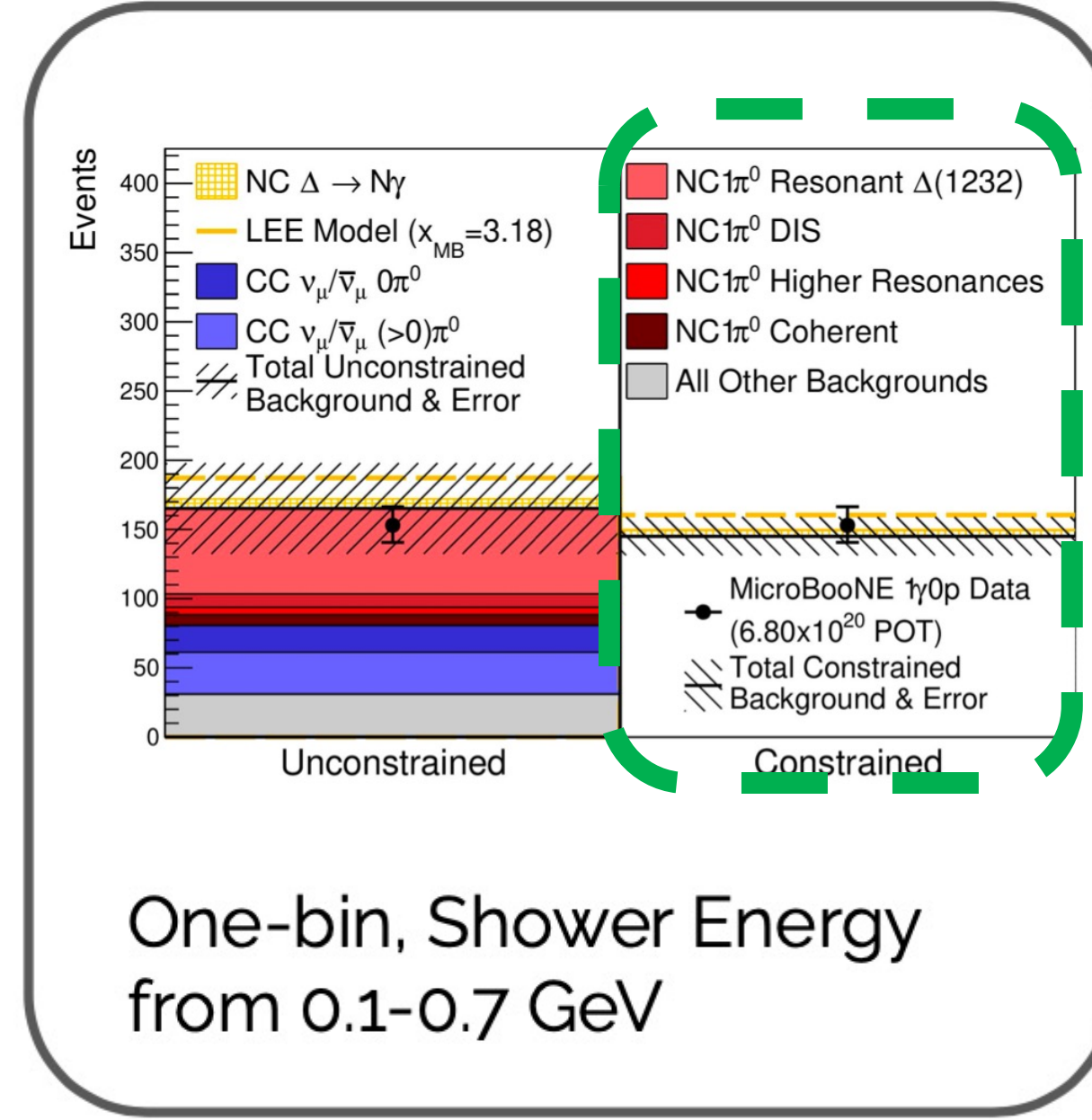
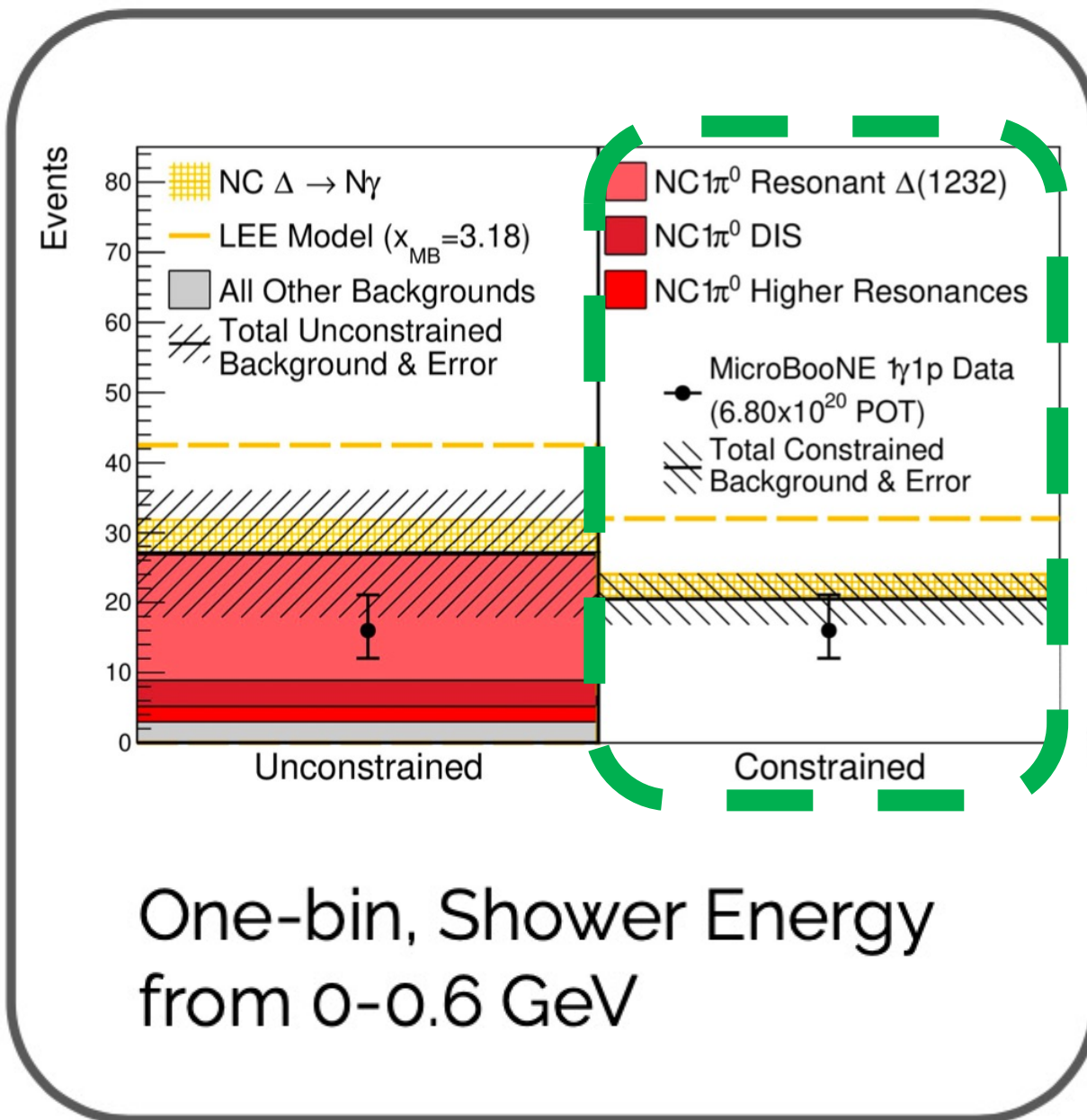
[Phys. Rev. Lett. 128, 111801](#)

**1 $\gamma$ 1p**

**1 $\gamma$ 0p**

**2 $\gamma$ 1p**

**2 $\gamma$ 0p**

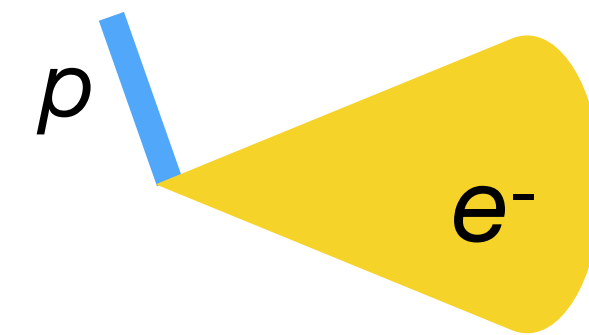




# MicroBooNE's search for an excess of electron neutrino interactions

three independent searches across multiple single electron final states

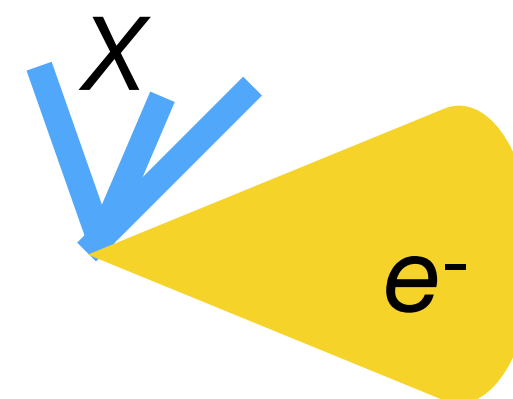
- exclusive two-body charged-current quasi-elastic (CCQE)  $\nu_e$  scattering [1e1p]



- semi-inclusive  $\nu_e$  scattering without final state pions [1eNp0π (N≥1) + 1e0p0π]



- inclusive  $\nu_e$  scattering [1eX]





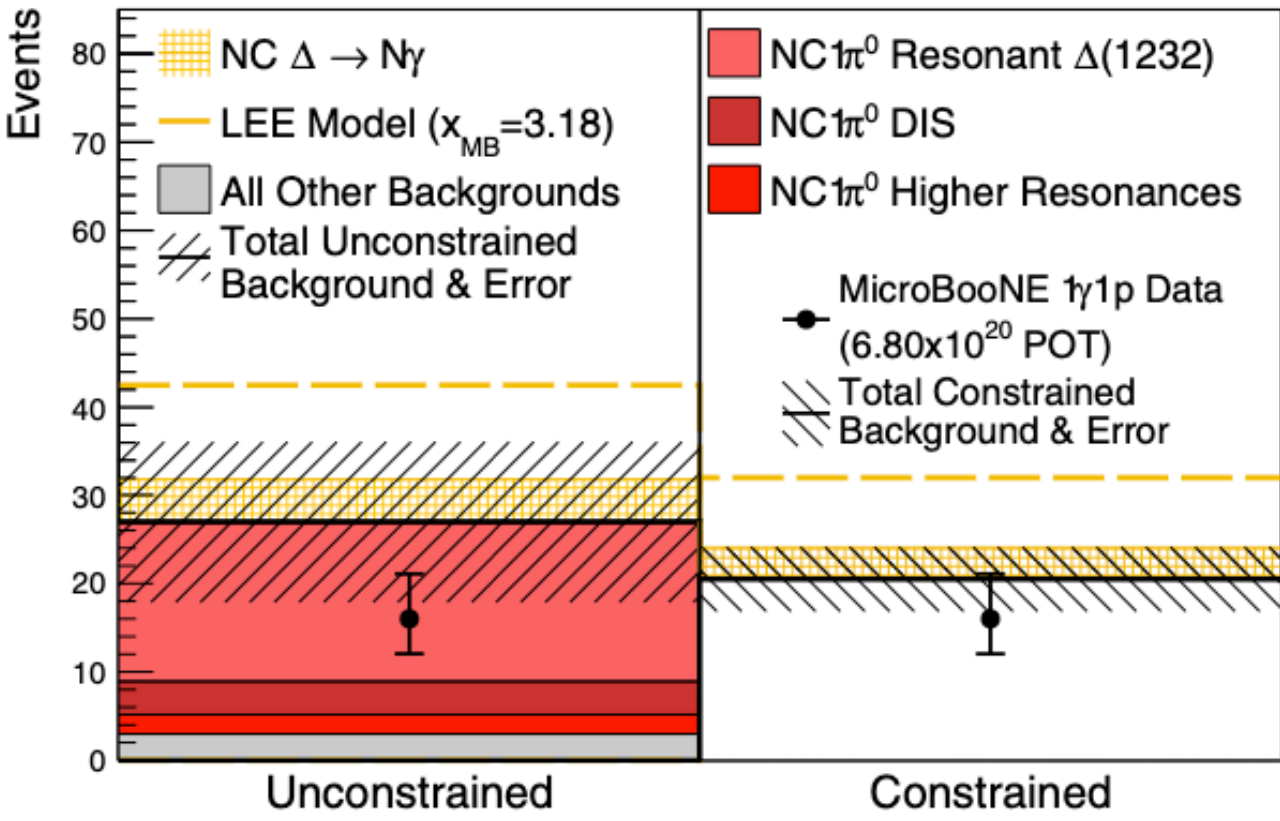
# MB excess and sterile neutrinos

- the MicroBooNE eLEE result disfavors the MB excess originating from a pure  $\nu_e$  excess
- the existence of sterile neutrinos cannot be ruled out by the MicroBooNE eLEE result, which is a generic low-energy  $\nu_e$  excess search
- the MicroBooNE eLEE results can be re-interpreted under a sterile neutrino oscillation hypothesis: a combination of short-baseline  $\nu_e$  appearance and  $\nu_e$  disappearance
- 3+1 oscillation searches using the selections in the MicroBooNE eLEE searches are performed

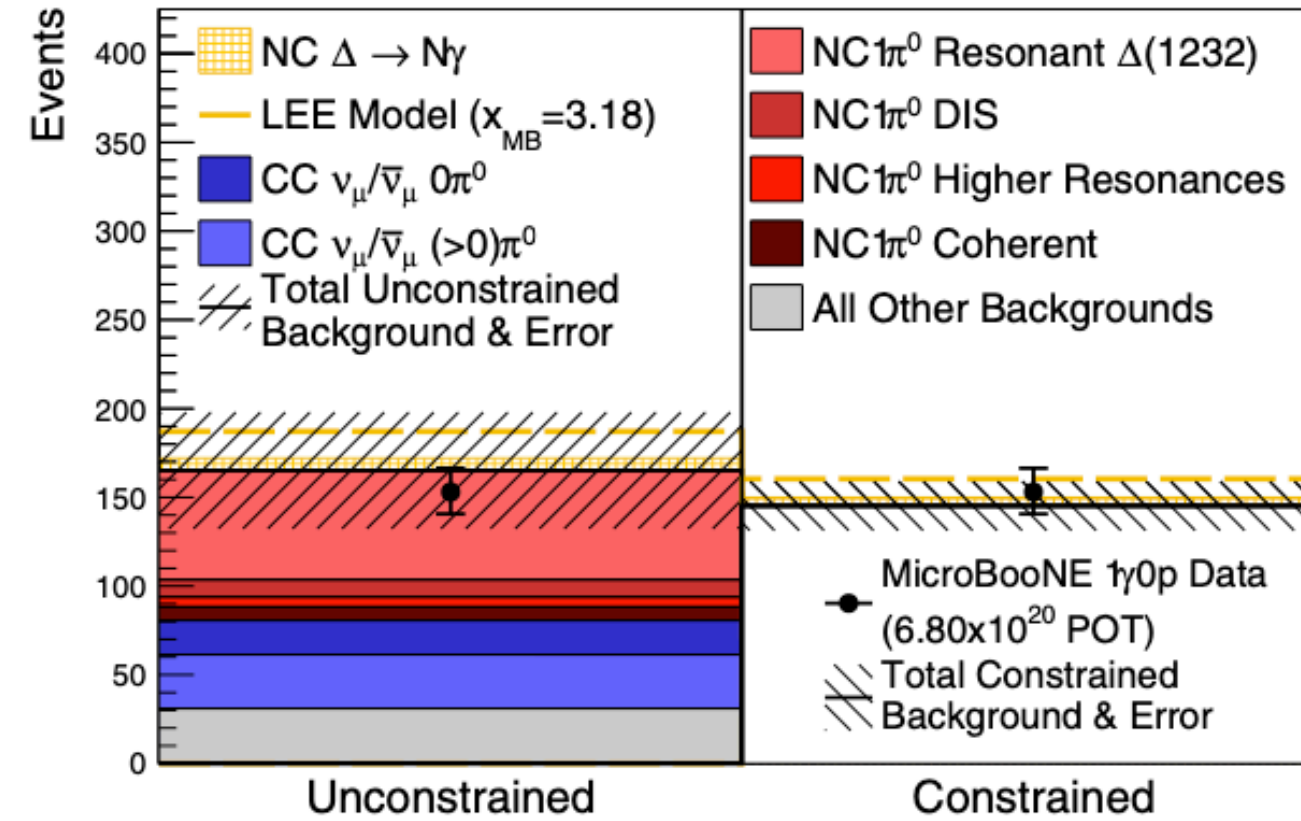


# First LEE results 2021

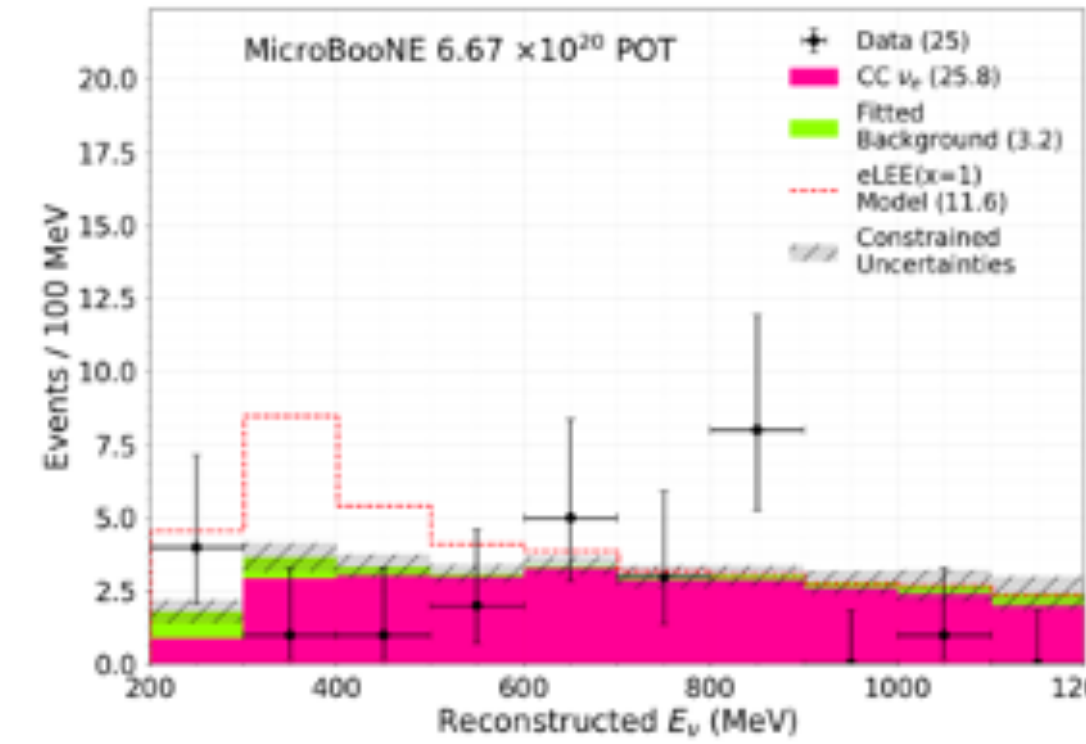
1 $\gamma$ 1p



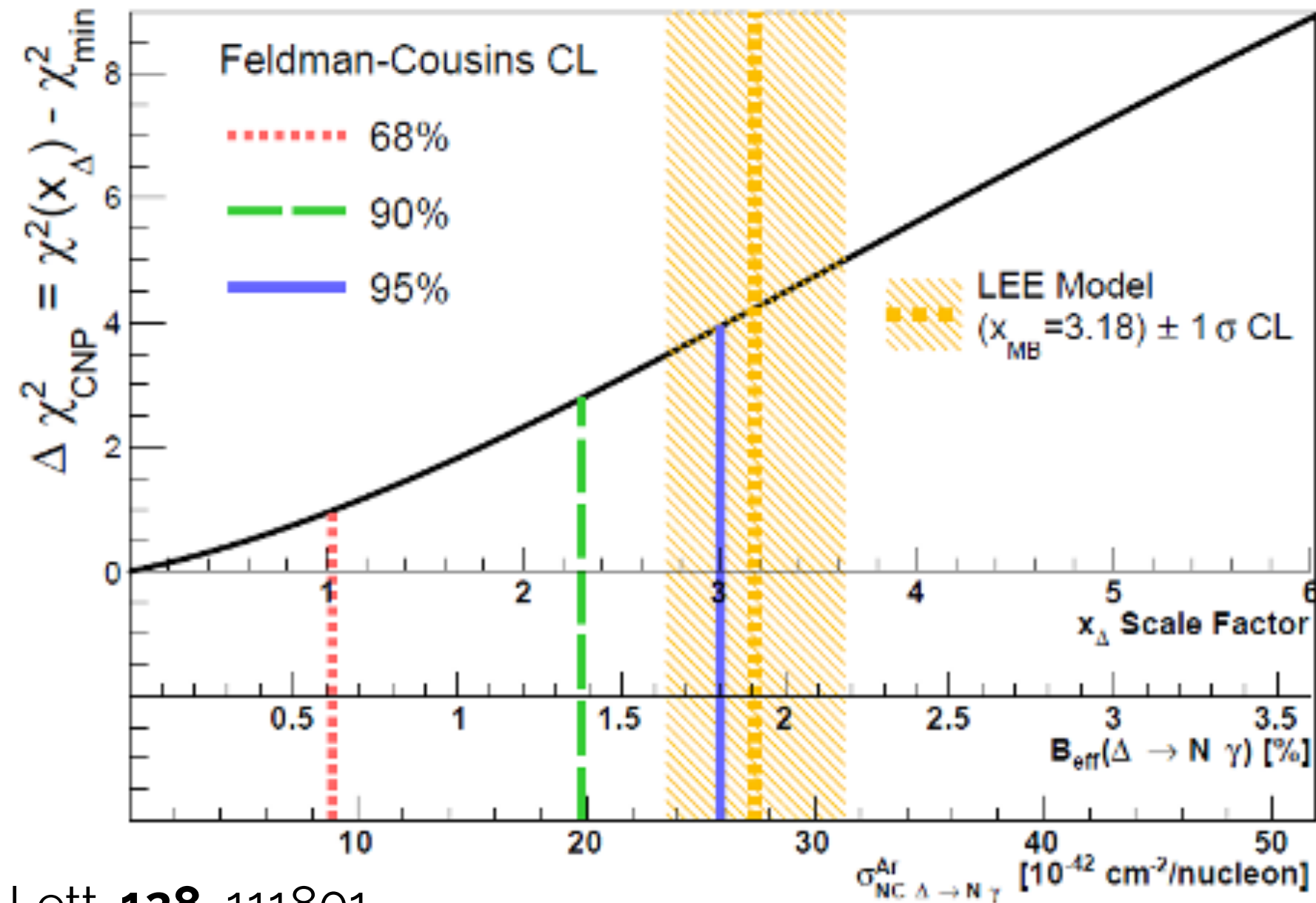
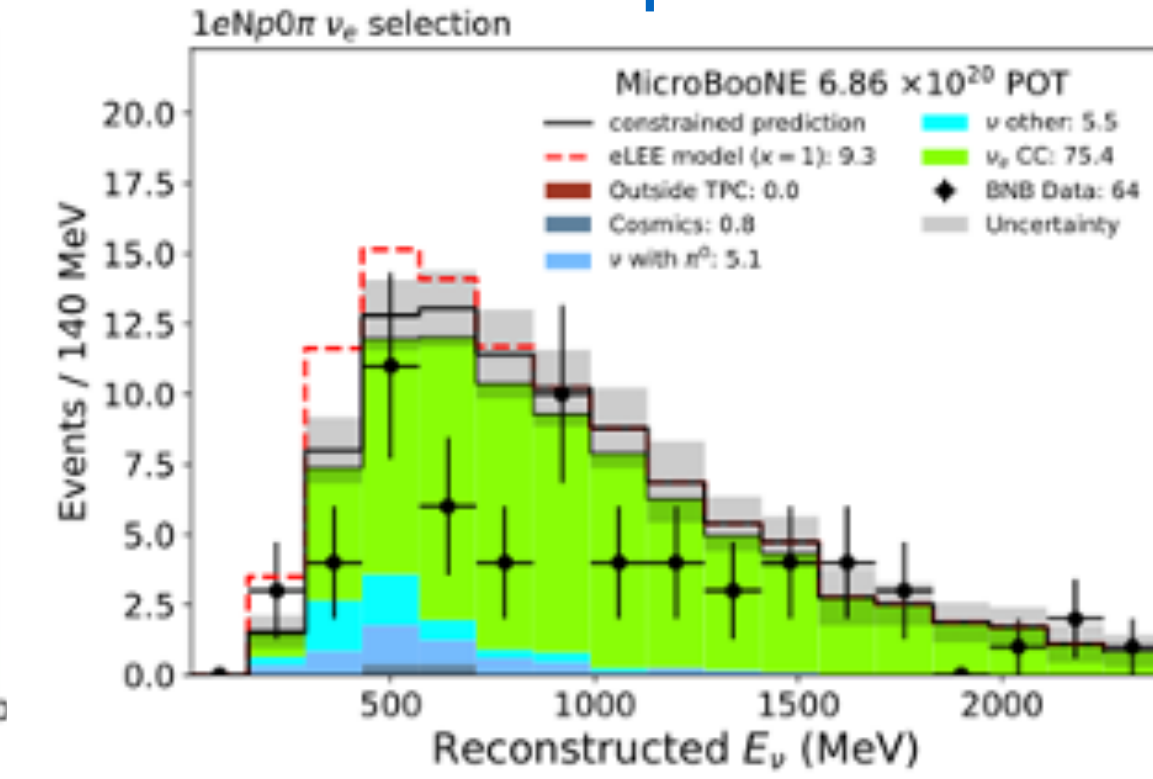
1 $\gamma$ 0p



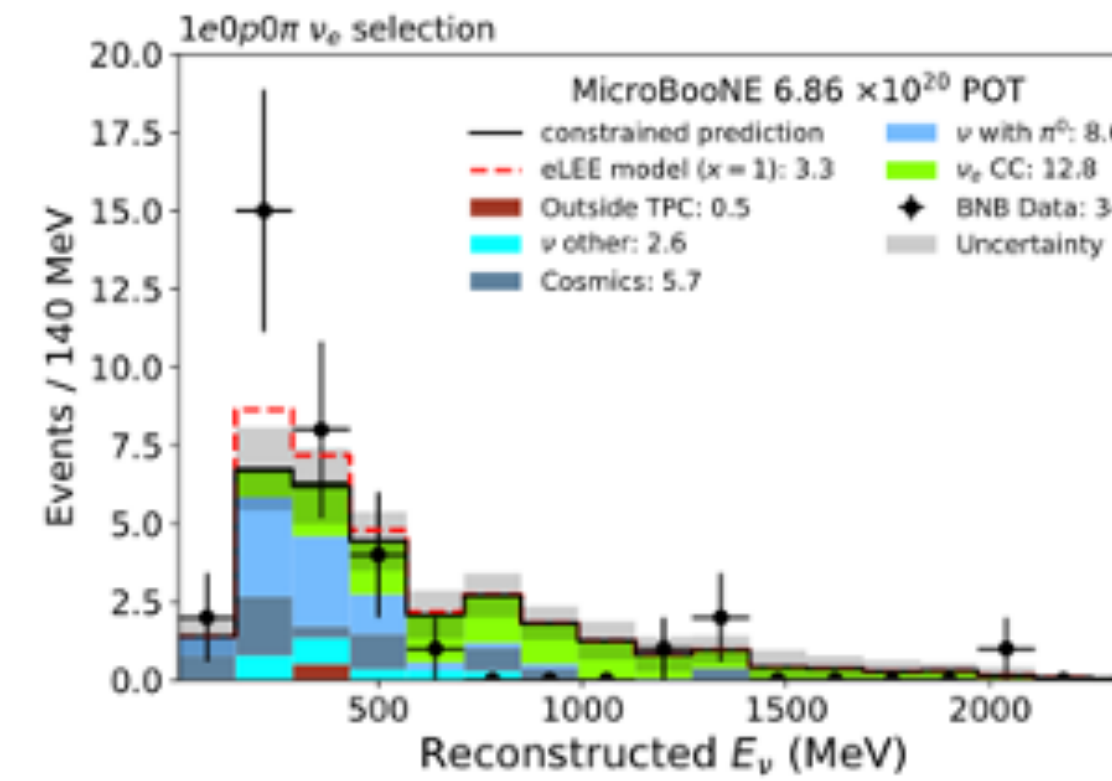
1e1p



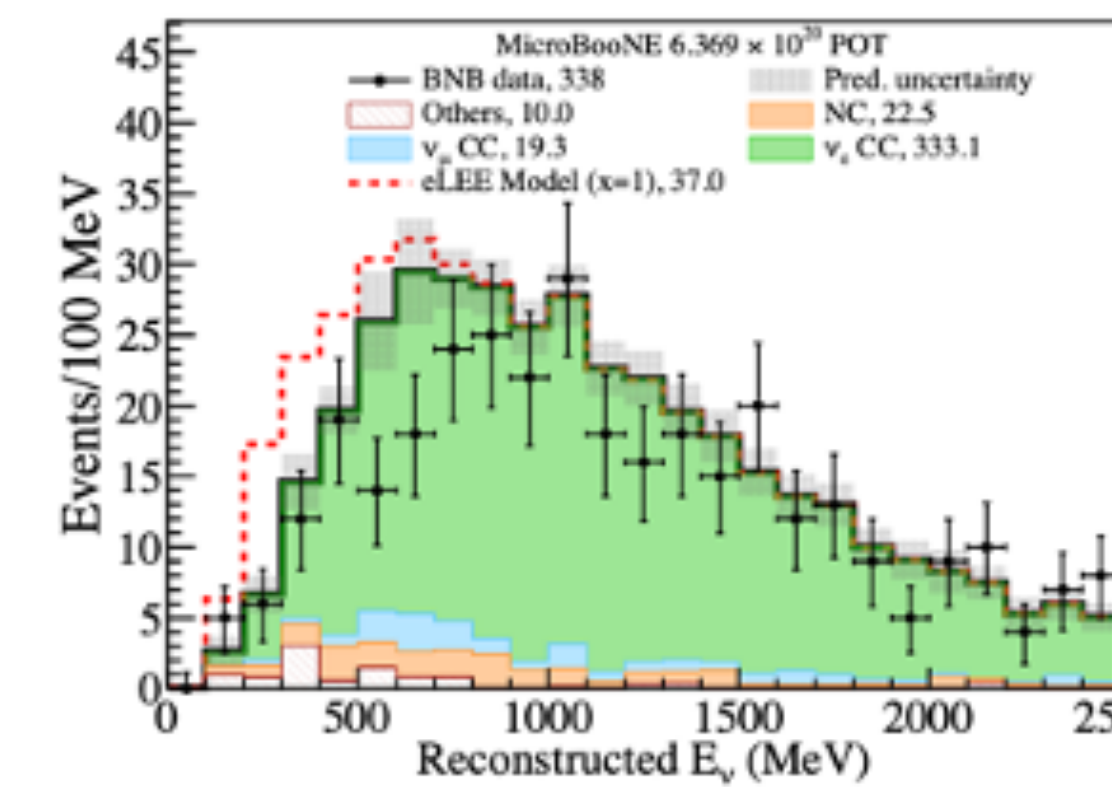
1eNp0π



1e0p0π



1eX

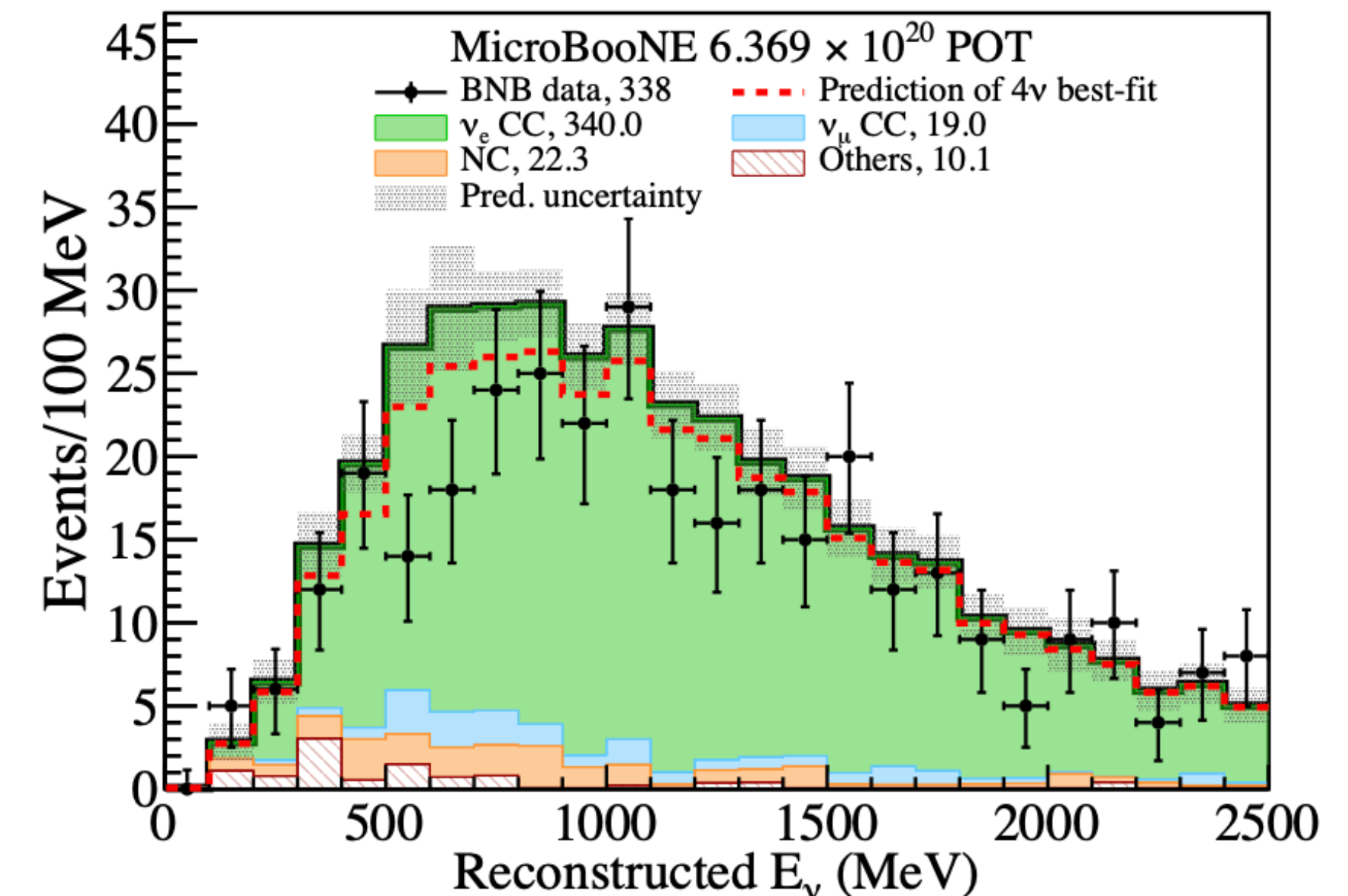
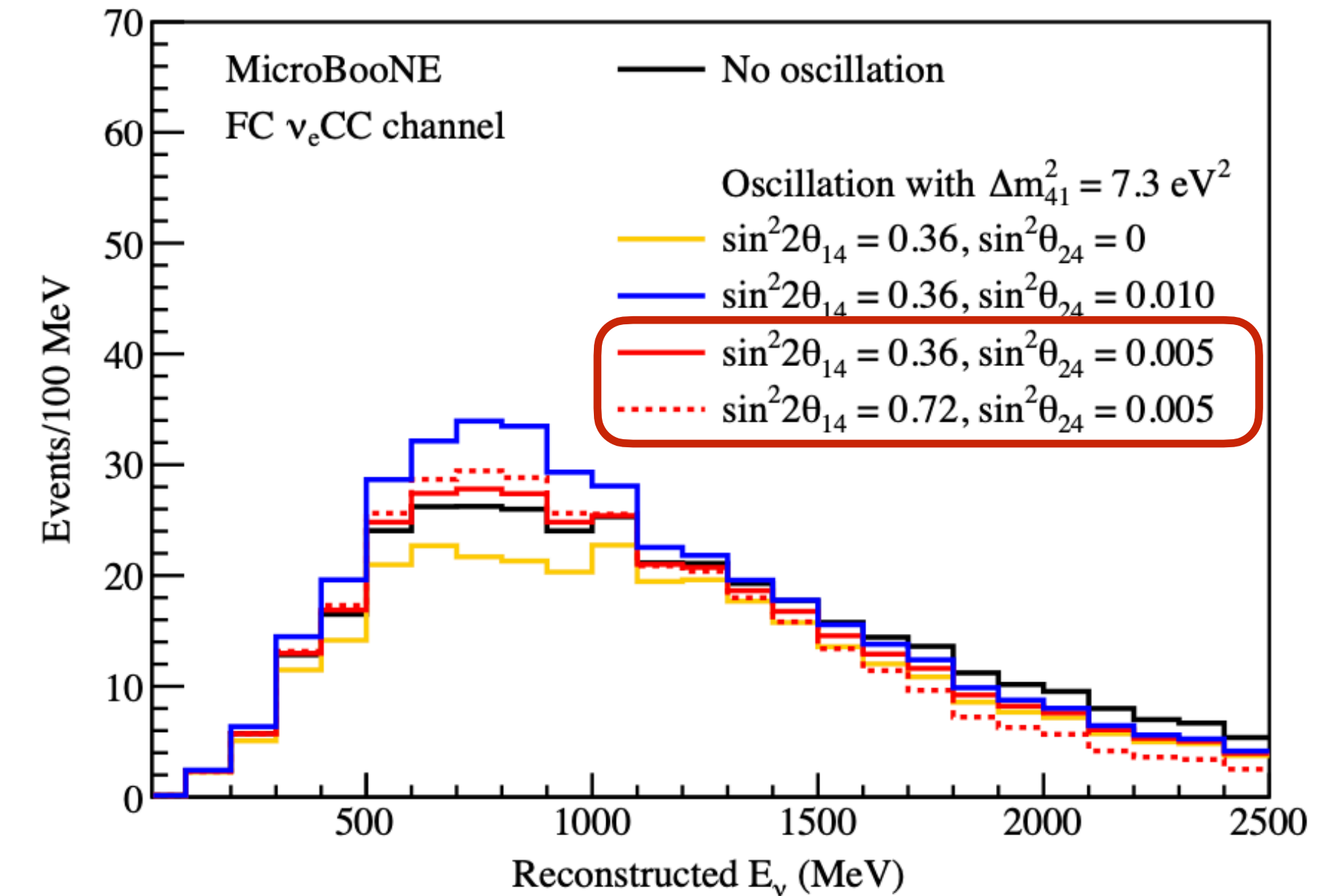




# 3+1 neutrino oscillation analysis

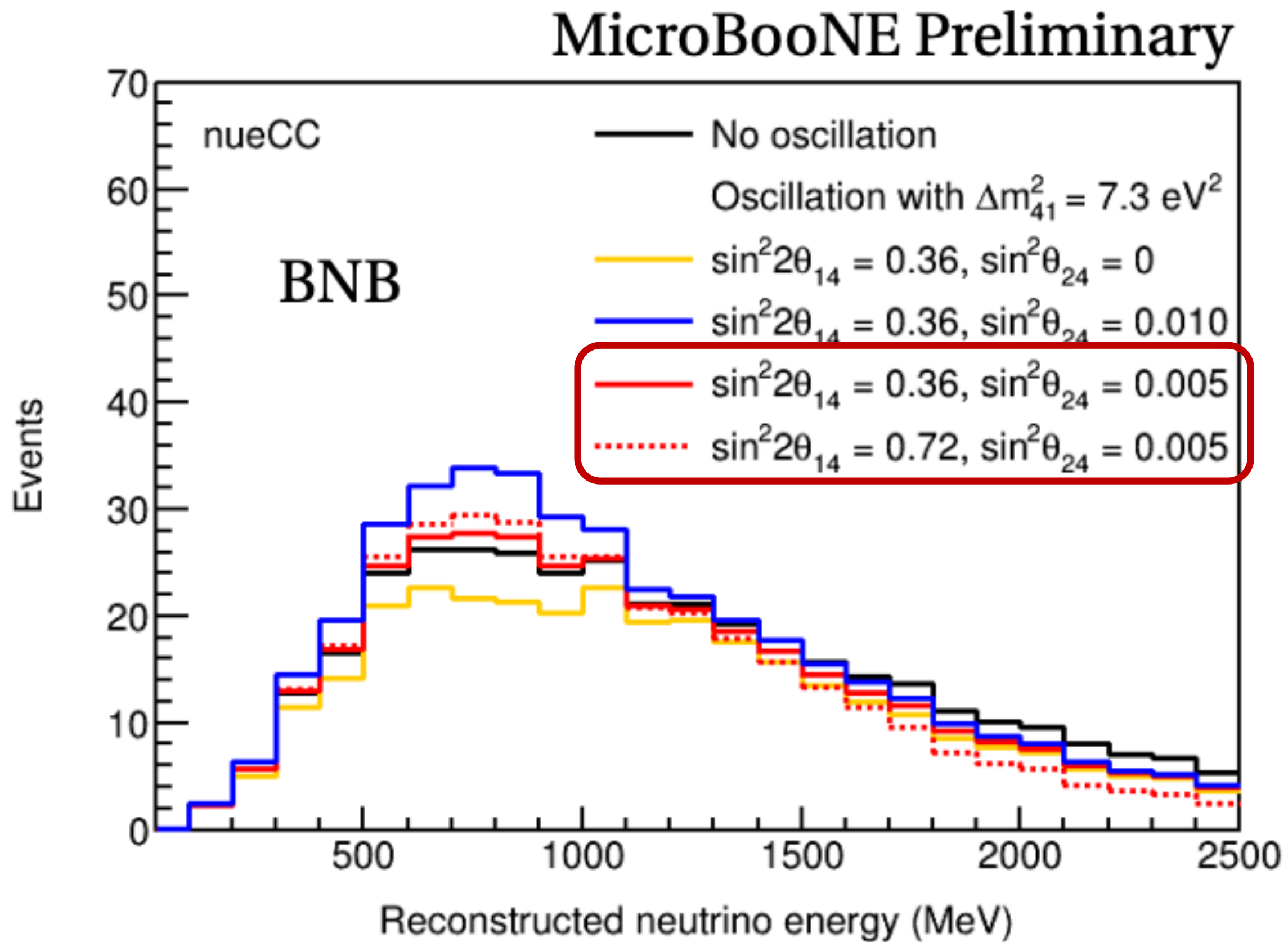
Phys. Rev. Lett. 130, 011801 (2023)

- eLEE results are re-interpreted under a sterile neutrino oscillation hypothesis: a combination of short-baseline  $\nu_e$  appearance,  $\nu_e$  disappearance, and  $\nu_\mu$  disappearance
- $\nu_e$  disappearance can cancel the appearance of  $\nu_e$  events:  
*degeneracy of oscillation parameters*
- considering full 3+1 oscillation, BNB Run1-3 data was found to be **consistent with the  $3\nu$  hypothesis within  $1\sigma$**  following the Feldman-Cousins approach





# Cancellation of $\nu_e$ appearance and $\nu_e$ disappearance -- degeneracy of oscillation parameters



Different degeneracy points:  
degeneracy mitigation utilizing both

$\nu_e$  disappearance     $\nu_e$  appearance

$$N_{\nu_e} = N_{\text{intrinsic } \nu_e} \cdot P_{\nu_e \rightarrow \nu_e} + N_{\text{intrinsic } \nu_\mu} \cdot P_{\nu_\mu \rightarrow \nu_e}$$

$$= N_{\text{intrinsic } \nu_e} \cdot \left[ 1 + \left( R_{\nu_\mu/\nu_e} \cdot \sin^2 \theta_{24} - 1 \right) \cdot \sin^2 2\theta_{14} \cdot \sin^2 \Delta_{41} \right]$$

- **Degeneracy** when  $\sin^2 \theta_{24}$  approaches  $R_{\nu_e/\nu_\mu}$  which is the ratio of intrinsic  $\nu_e$  and  $\nu_\mu$  in the neutrino flux
- **Sensitivity/exclusion limits gets much worse around the degeneracy point**

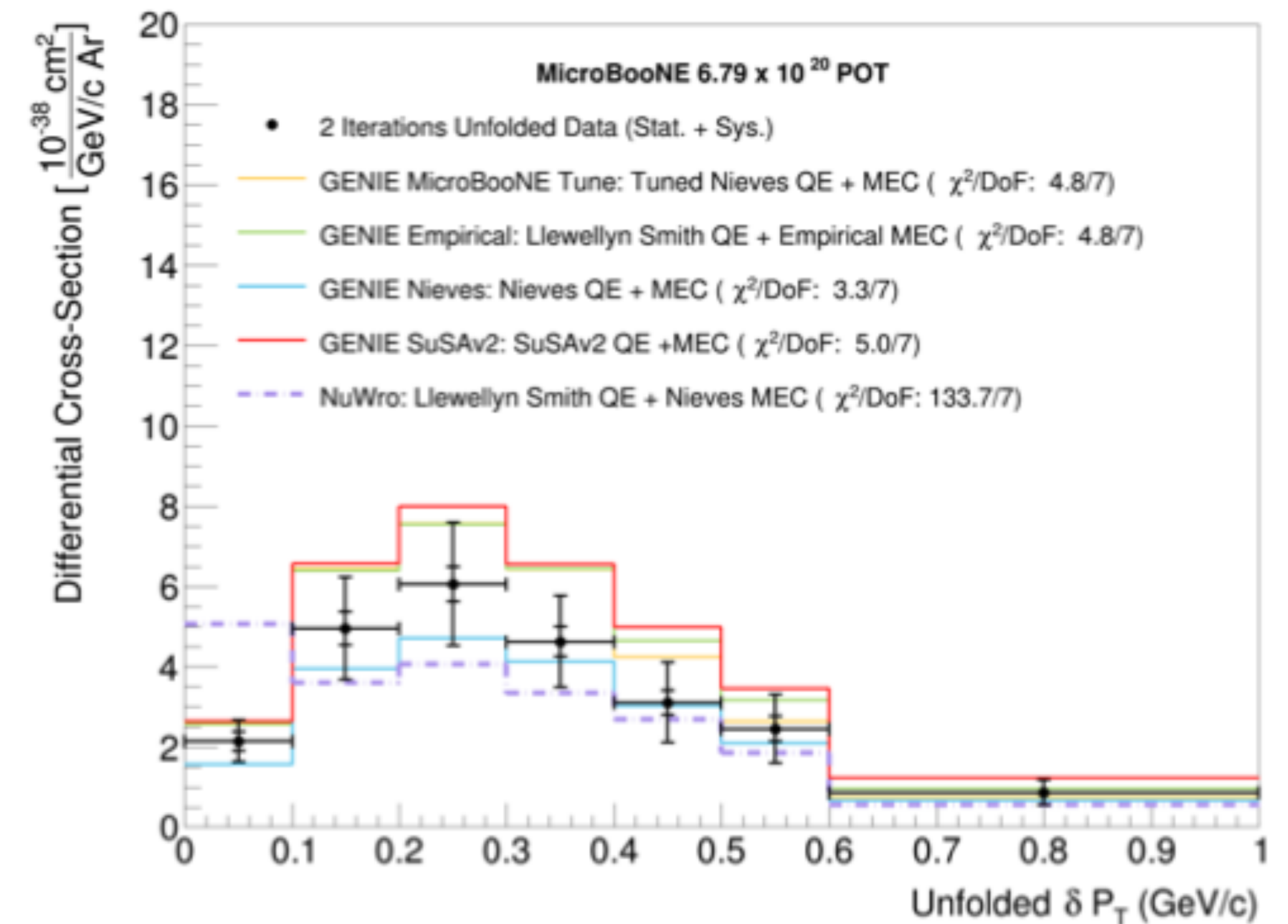
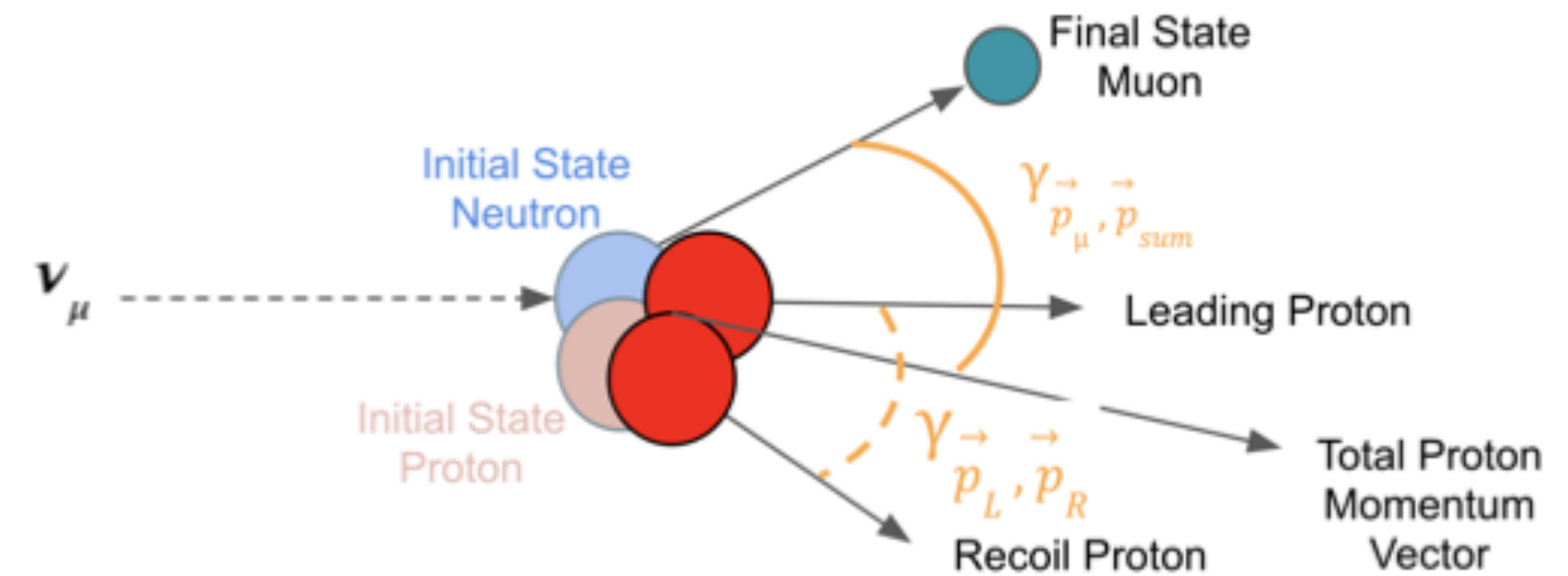
	$R_{\nu_e/\nu_\mu}$ (degeneracy $\sin^2 \theta_{24}$ value)
MicroBooNE w. BNB	~0.005 (average)
MicroBooNE w. NuMI	~0.04 (average)



# Differential cross section of $\nu_\mu$ CC 2p

arXiv:2211.03734

- first time differential cross section measurement in this topology
  - sensitive to the Meson Exchange Current (MEC) interactions
- results w.r.t. transverse momentum strongly disfavor NuWro's treatment of correlated P-N pairs (back-to-back





# CCQE-like $\nu_\mu$ CC with transverse kinematic imbalance (TKI)

arXiv:2301.03706

- first -Ar differential Xs on TKI variables
- sensitive to details of proton FSI modeling and the initial-state Fermi motion
- extension to double differential Xs  $\{\delta\alpha_T, \delta P_T\}$  for the first time
- probe region with greatest model discrimination power

