

Recent Results from MicroBooNE

NuFact 2024

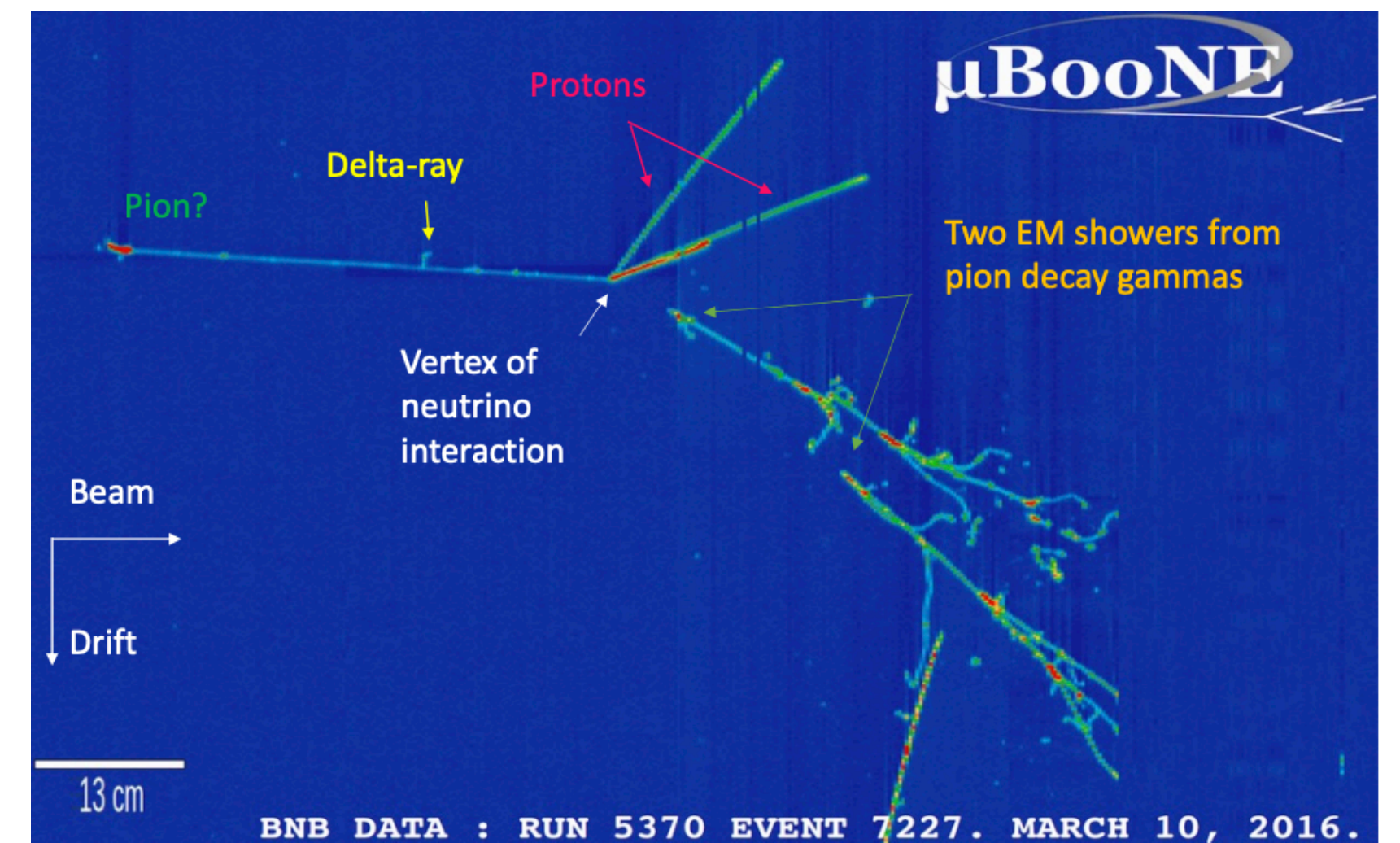
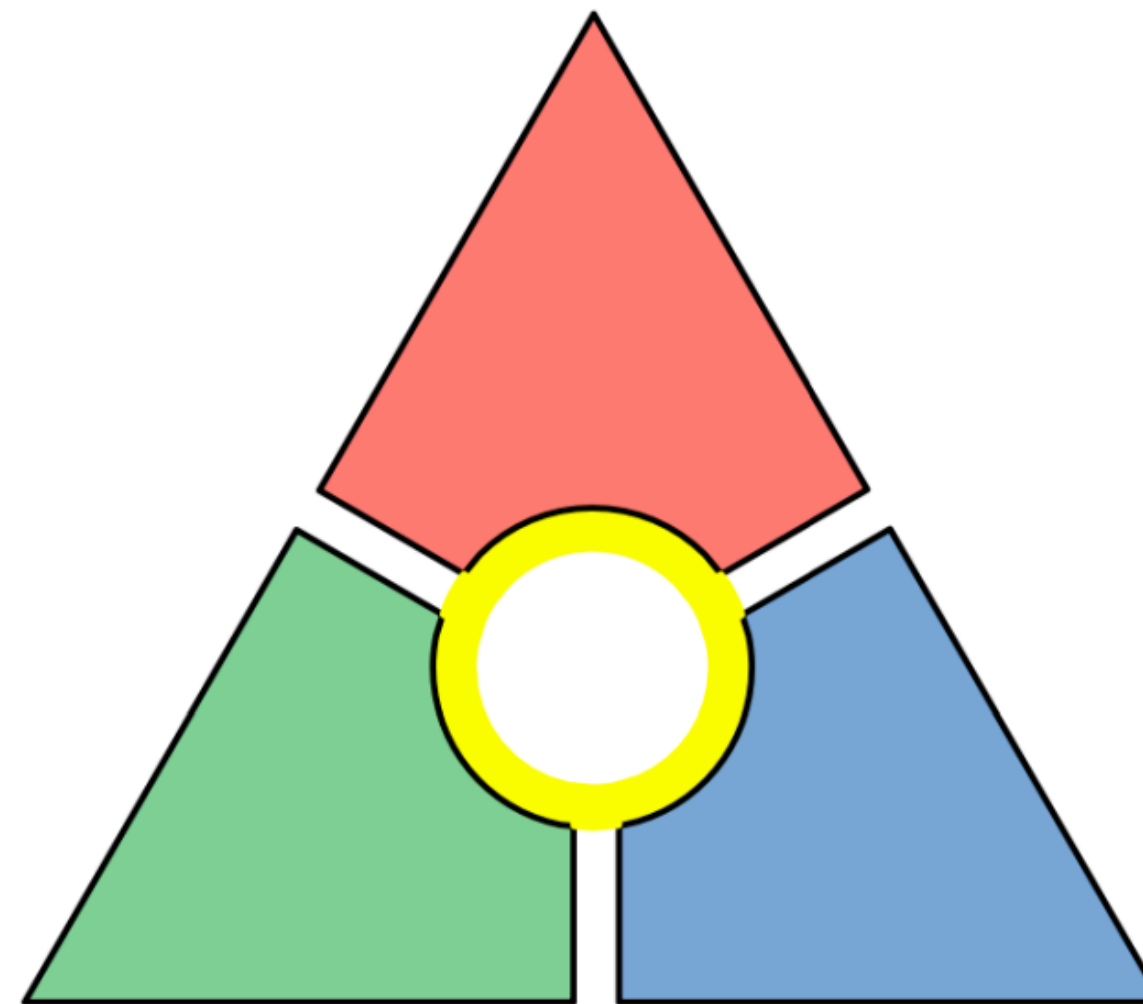
Nitish Nayak

(For the MicroBooNE Collaboration)

Sept 17th, 2024

MicroBooNE Science Goals

- Investigate MiniBooNE Low Energy Excess (LEE)
- Search for BSM Physics



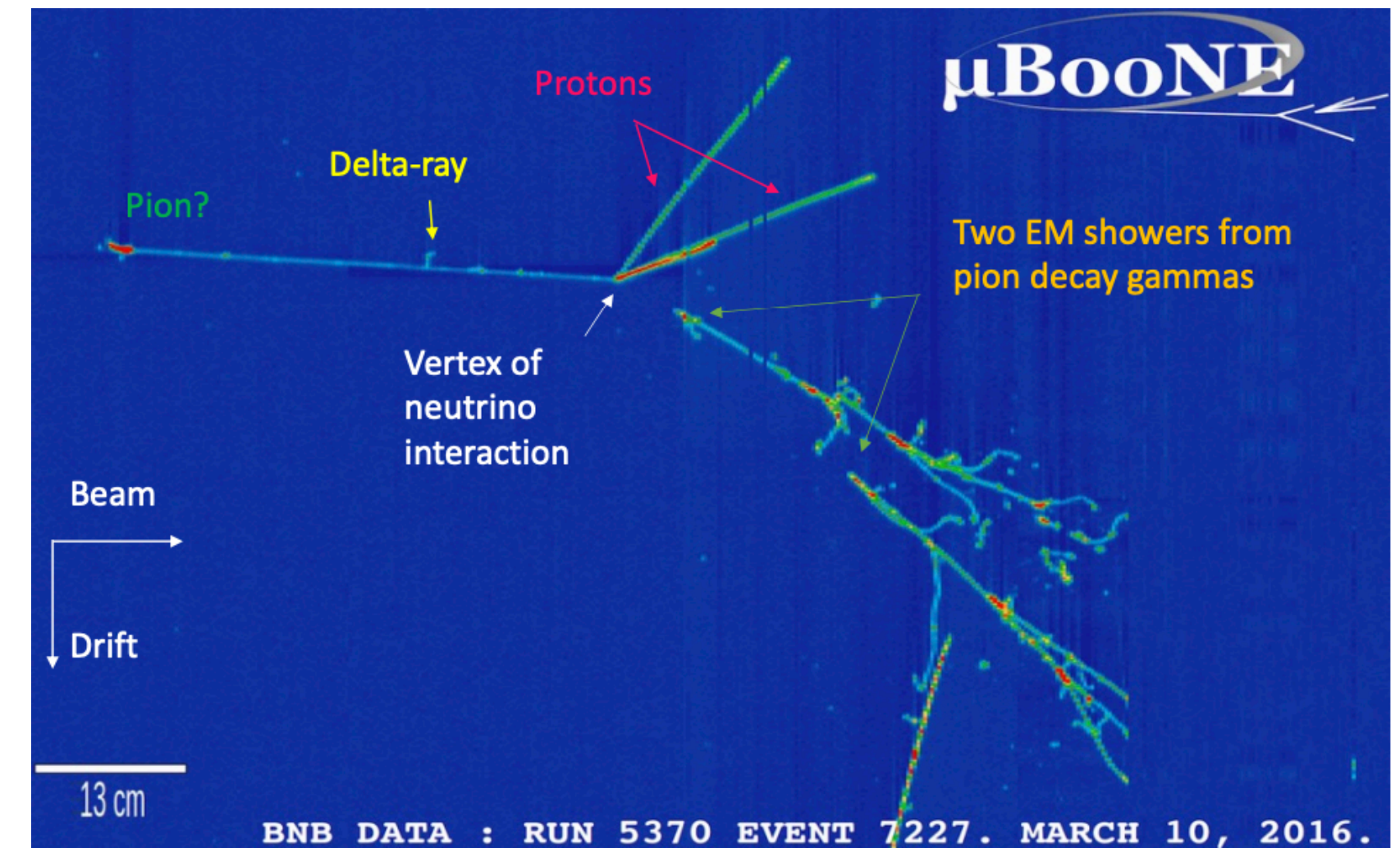
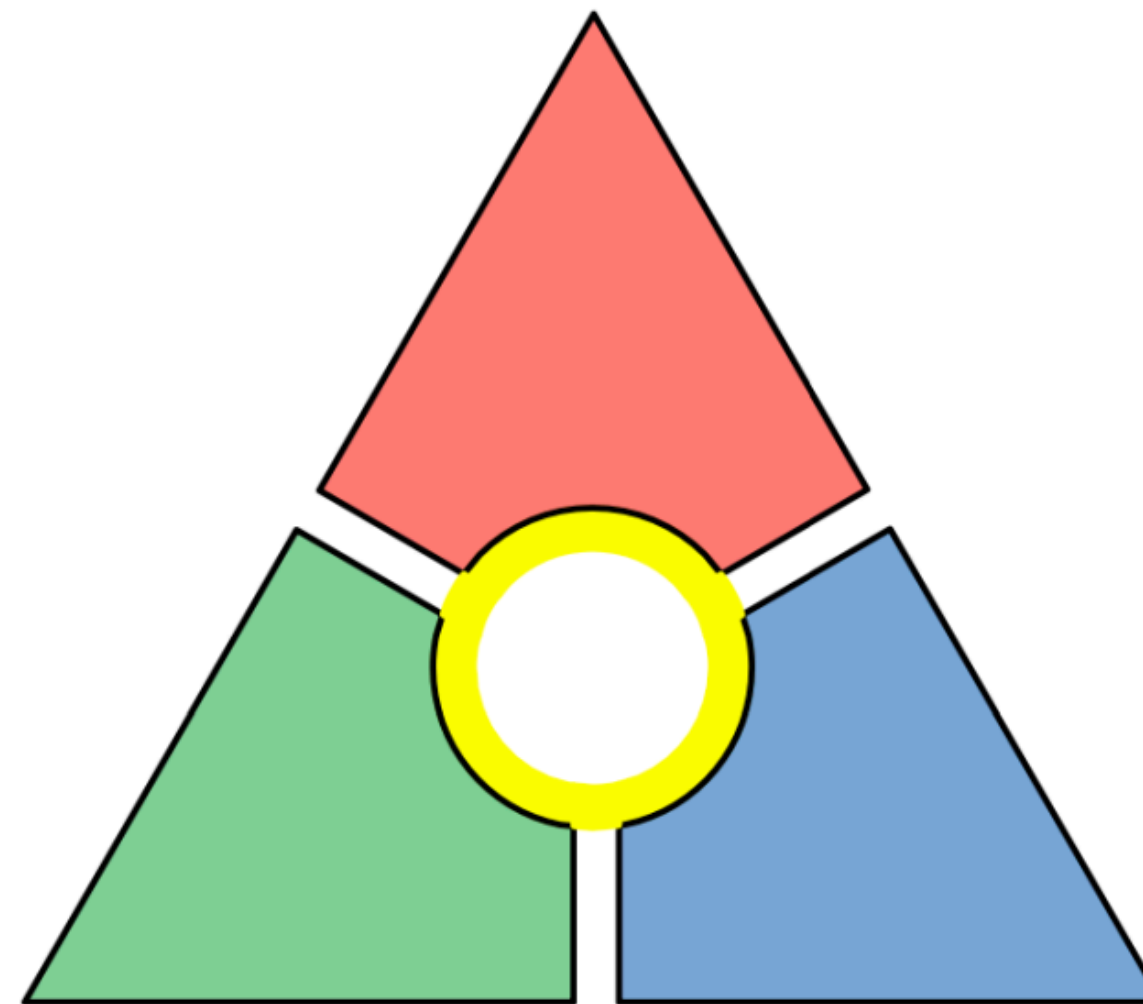
- Advance LArTPC capabilities for next generation neutrino experiments (SBN program, DUNE)

- Illuminate ν -Ar scattering physics across many topologies

MicroBooNE Science Goals

New Results! ★

- Investigate MiniBooNE Low Energy Excess (LEE) ★
- Search for BSM Physics



- Advance LArTPC capabilities for next generation neutrino experiments (SBN program, DUNE) ★

- Illuminate ν -Ar scattering physics across many topologies ★

MicroBooNE @ NuFact 2024

Parallel Talks

- MicroBooNE's BSM Program - Keng Lin (Monday)
- Anomalous γ and e^+e^- Searches - Erin Yandel (Monday)
- ν_e Low Energy Excess Search - Fan Gao (Thursday)

- Inclusive and Pionless Measurements - Dan Barrow (Thursday)
- Pion Production Measurements - Patrick Green (Thursday)

- MeV-Scale Radon Measurements - Will Foreman (Wednesday)

Posters

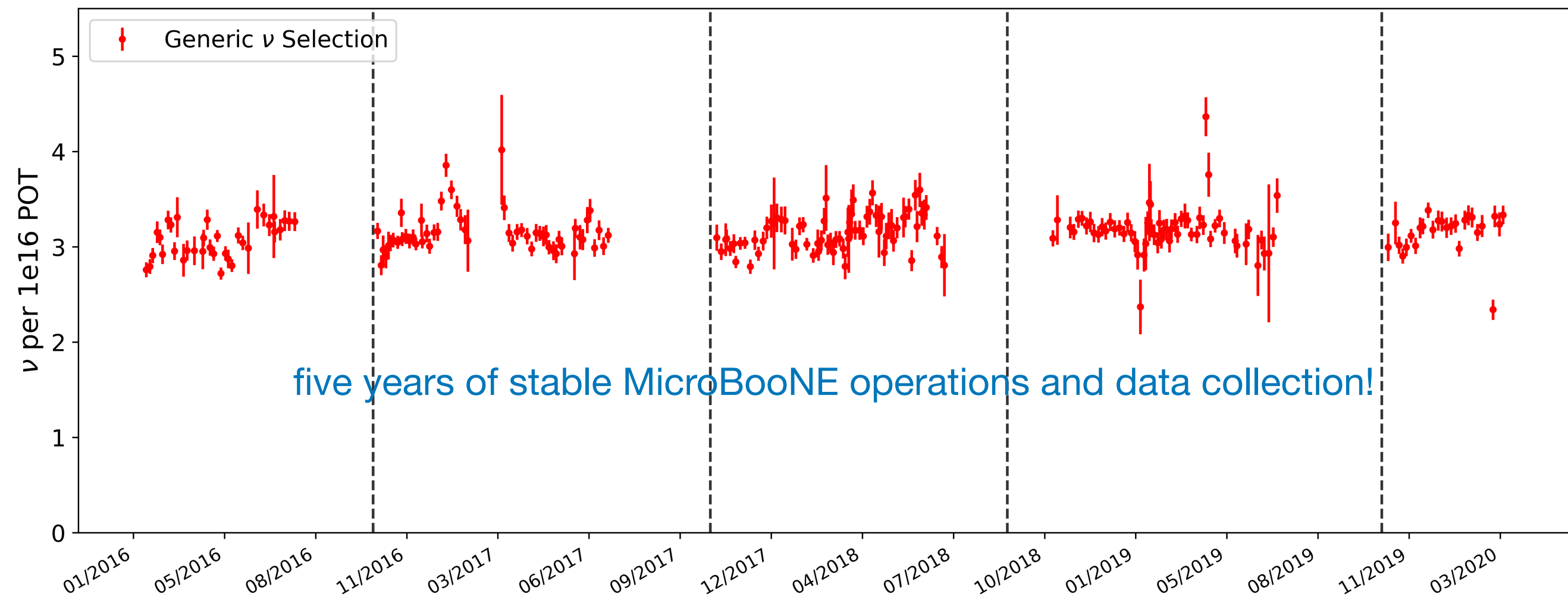
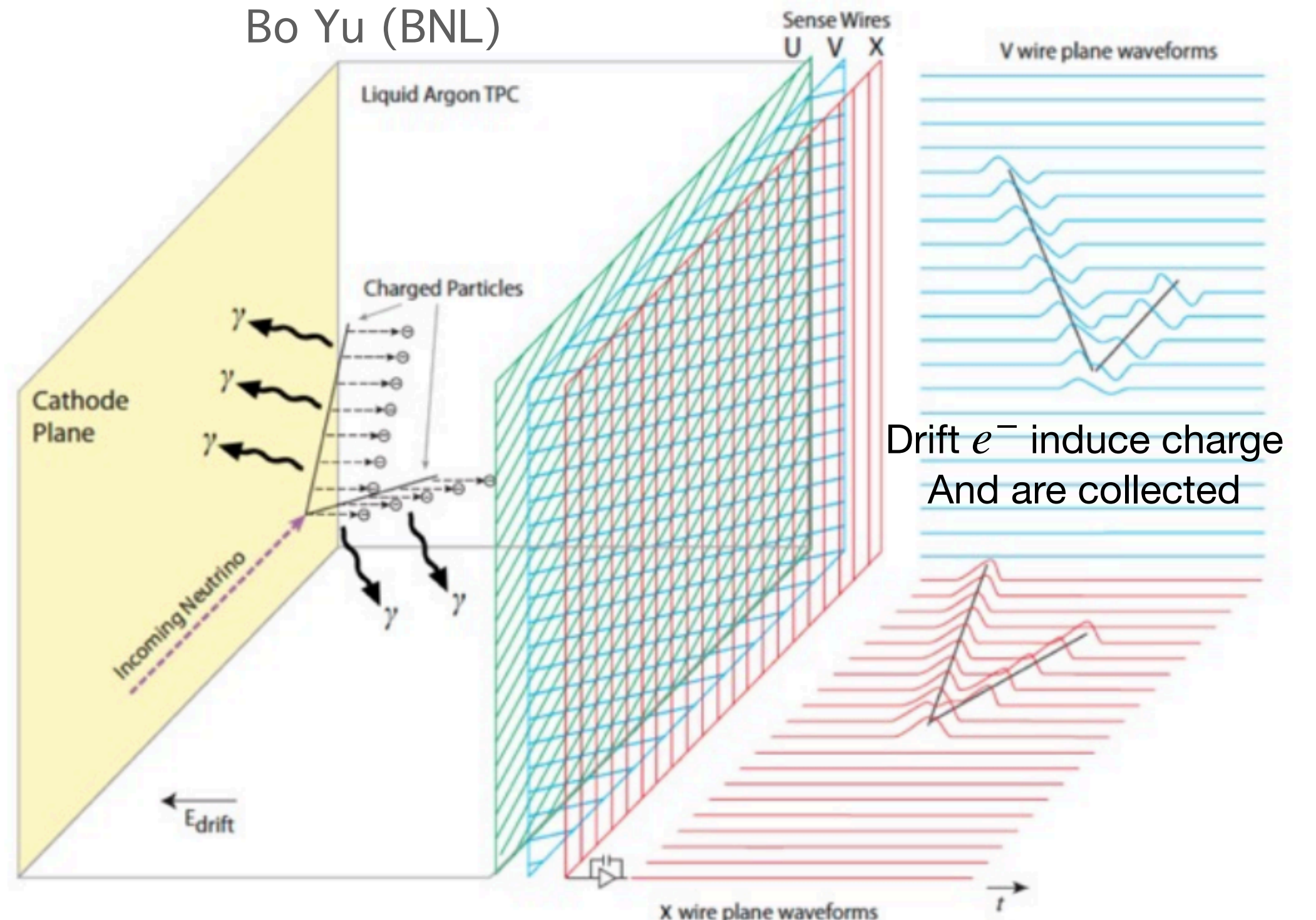
- NC $\Delta \rightarrow 1\gamma$ - Lee Hagaman

- ν_μ CC Inclusive - London Cooper-Troendle
- ν_μ CC2p - Dan Barrow
- ν_μ CC0 π - Panos Englezos
- ν_μ CC0p/Np - Ben Bogart
- Rare Mesons - Jairo Rodriguez
- Charged Pions - Philip Detje

- MeV-Scale Physics - Diego Andrade

 <- Lookout for this throughout the talk!

The Experiment



MicroBooNE Papers

2017 2018 2019 2020 2021 2022 2023 2024

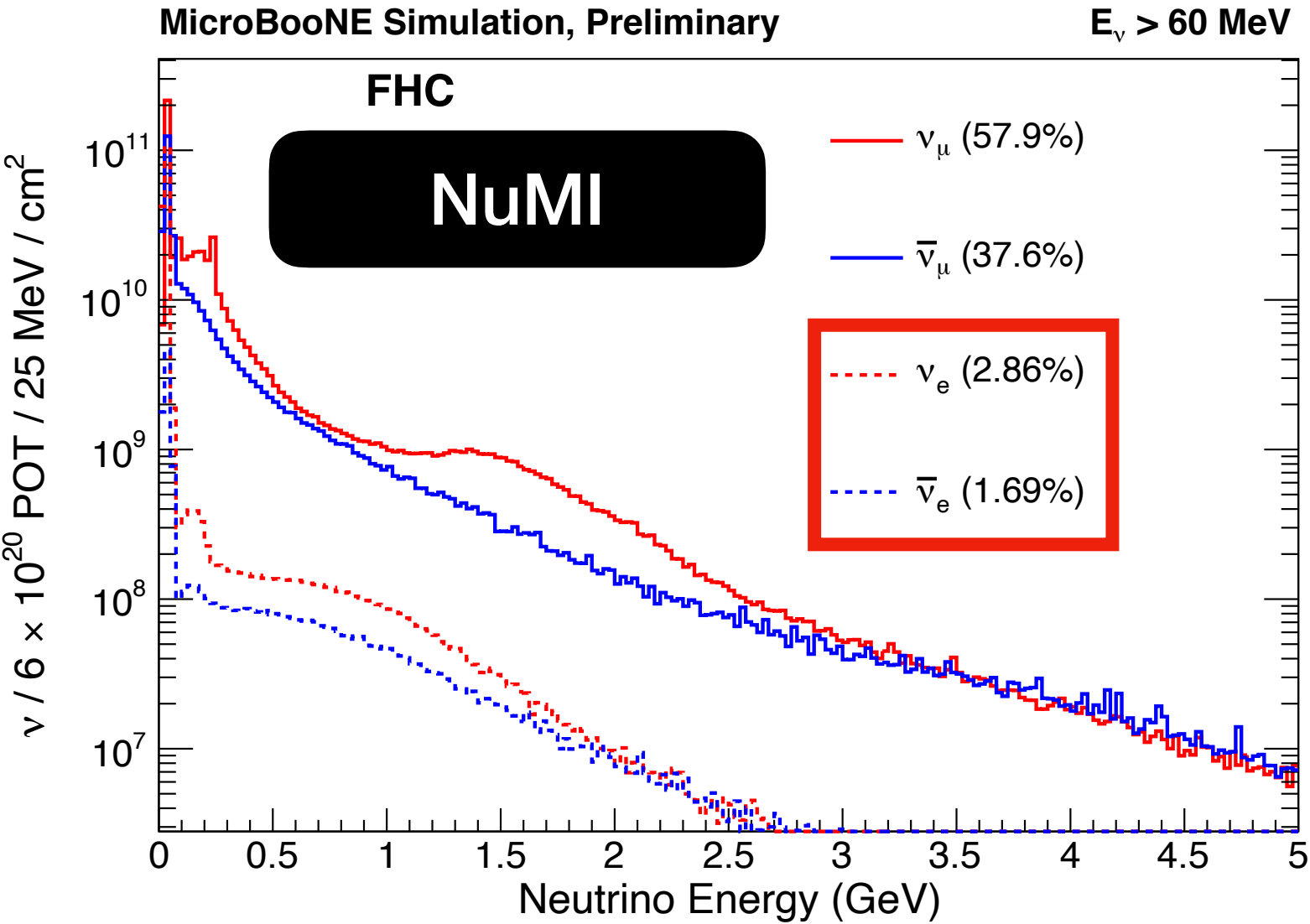
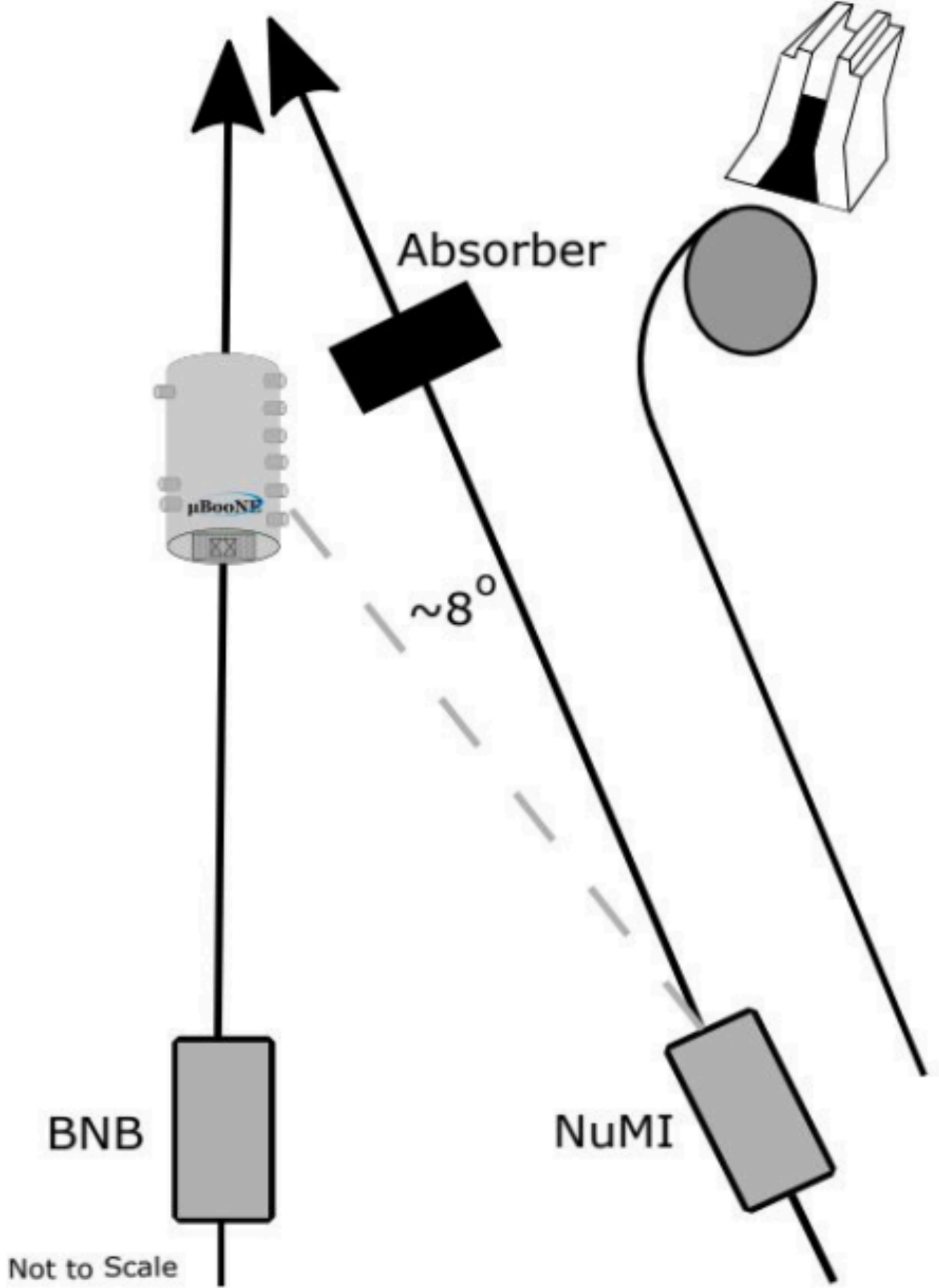
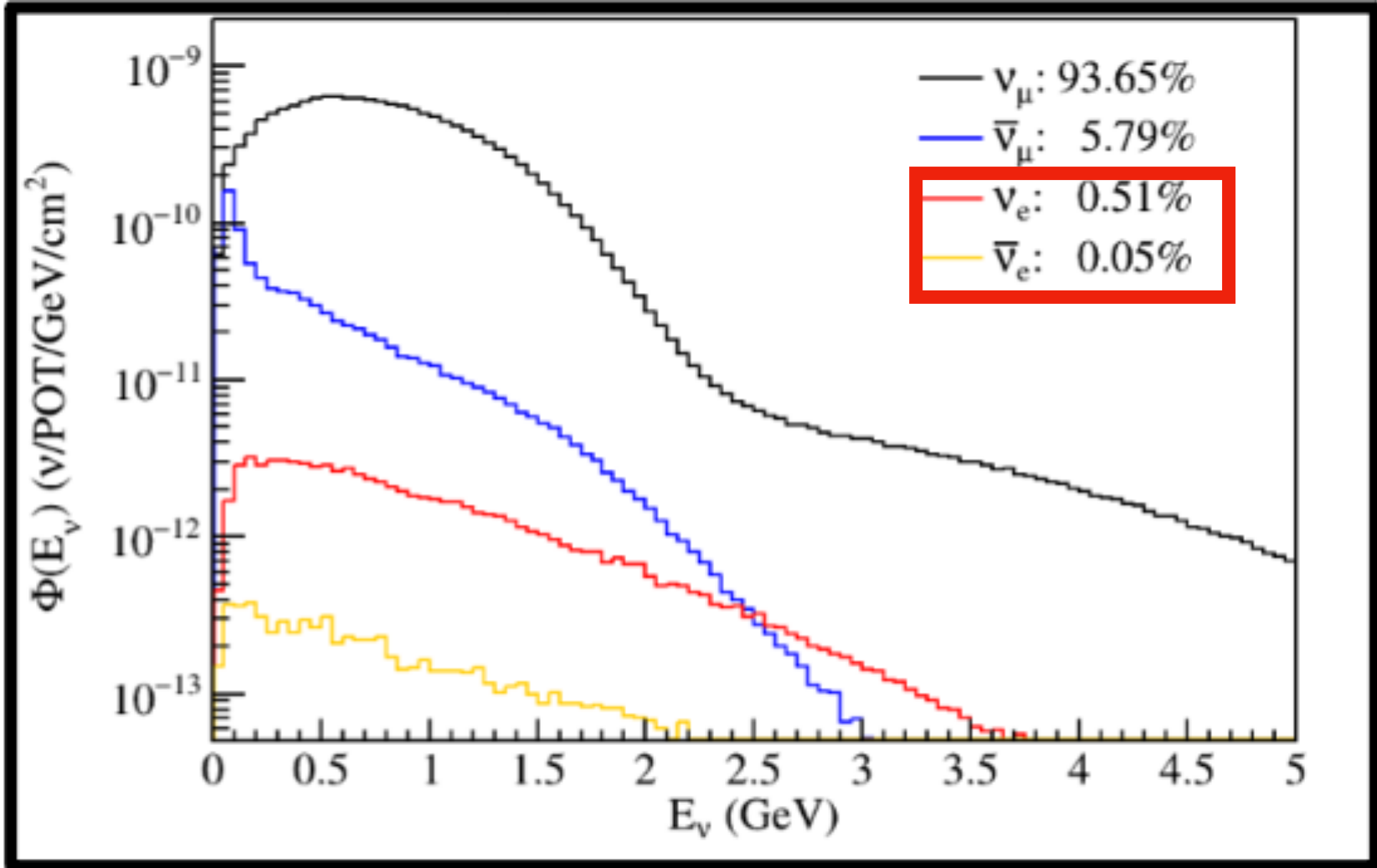
69 papers and counting!

- Demonstration of neutron identification in neutrino interactions in the MicroBooNE liquid argon time projection chamber
- Improving hadron energy estimation of charged-current interaction events with recurrent neural networks in MicroBooNE
- First double-differential cross section measurement of neutral-current π^0 production in neutrino-argon scattering in the MicroBooNE detector
- Measurement of the differential cross section for neutral pion production in charged-current muon neutrino interactions on argon with the MicroBooNE detector
- Measurement of double-differential cross sections for mesonless charged-current muon neutrino interactions on argon with final-state protons using the MicroBooNE detector
- First simultaneous measurement of differential muon-neutrino charged-current cross sections on argon for final states with and without protons using MicroBooNE data
- First search for dark-current processes using the MicroBooNE detector
- Search for heavy neutral leptons in electron-positron and neutral-pion final states with the MicroBooNE detector
- Measurement of nuclear effects in neutrino-argon interactions using generalised kinetic imbalance variables with the MicroBooNE detector
- First demonstration for a LATPC-based search for intranuclear neutron-antineutron transitions and annihilation $n-\bar{n}$ in argon using the MicroBooNE detector
- Measurement of triple-differential inclusive muon-neutrino charged-current cross section on argon with the MicroBooNE detector
- Measurement of antineutron daughter decay rates and energy spectra in liquid argon using the MicroBooNE detector
- First measurement of η production in neutrino interactions on argon with MicroBooNE
- First demonstration of O(1 ns) timing resolution in the MicroBooNE liquid argon time projection chamber
- Multi-differential cross section measurements of muon-neutrino-argon quasi-elastic-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 Λ baryon production in muon antineutrino interactions in the MicroBooNE detector
- First measurement of energy-dependent inclusive 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 ν_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 π^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 LATPC 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 ν_e interactions without pions in the final state with the MicroBooNE experiment
- Search for an anomalous excess of charged-current quasi-elastic ν_e interactions with the MicroBooNE experiment using deep-learning-based reconstruction
- New beam-driven CCNE lines for MicroBooNE
- Search for an anomalous excess of inclusive charged-current ν_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
- High-performance Genetic Neutrino Detection in a LATPC near the Earth's Surface with the MicroBooNE Detector
- Wire-Cell 3D pattern recognition techniques for neutrino event reconstruction in large LATPCs
- Electromagnetic shower reconstruction and energy validation with Michel electrons and π^0 samples for the deep-learning-based analyses in MicroBooNE
- 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 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 heavy neutral leptons decaying into muon-pion 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
- Vertex-Finding and Reconstruction Techniques for Neutrino Event Reconstruction in Large LATPCs
- 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
- Design and Construction of the MicroBooNE Cosmic Ray Tagger System
- 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 Q(100) MeV Electromagnetic Activity from Neutral Pion to Gamma Gamma Decays in the MicroBooNE LATPC
- 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 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 LAr TPCs II: Data/Simulation Comparison and Performance in MicroBooNE
- Localization Electron Signal Processing in Single Phase LAr TPCs 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
- Mitigation of Cosmic Ray Reconstruction Efficiencies in 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

Neutrino Beams @ MicroBooNE

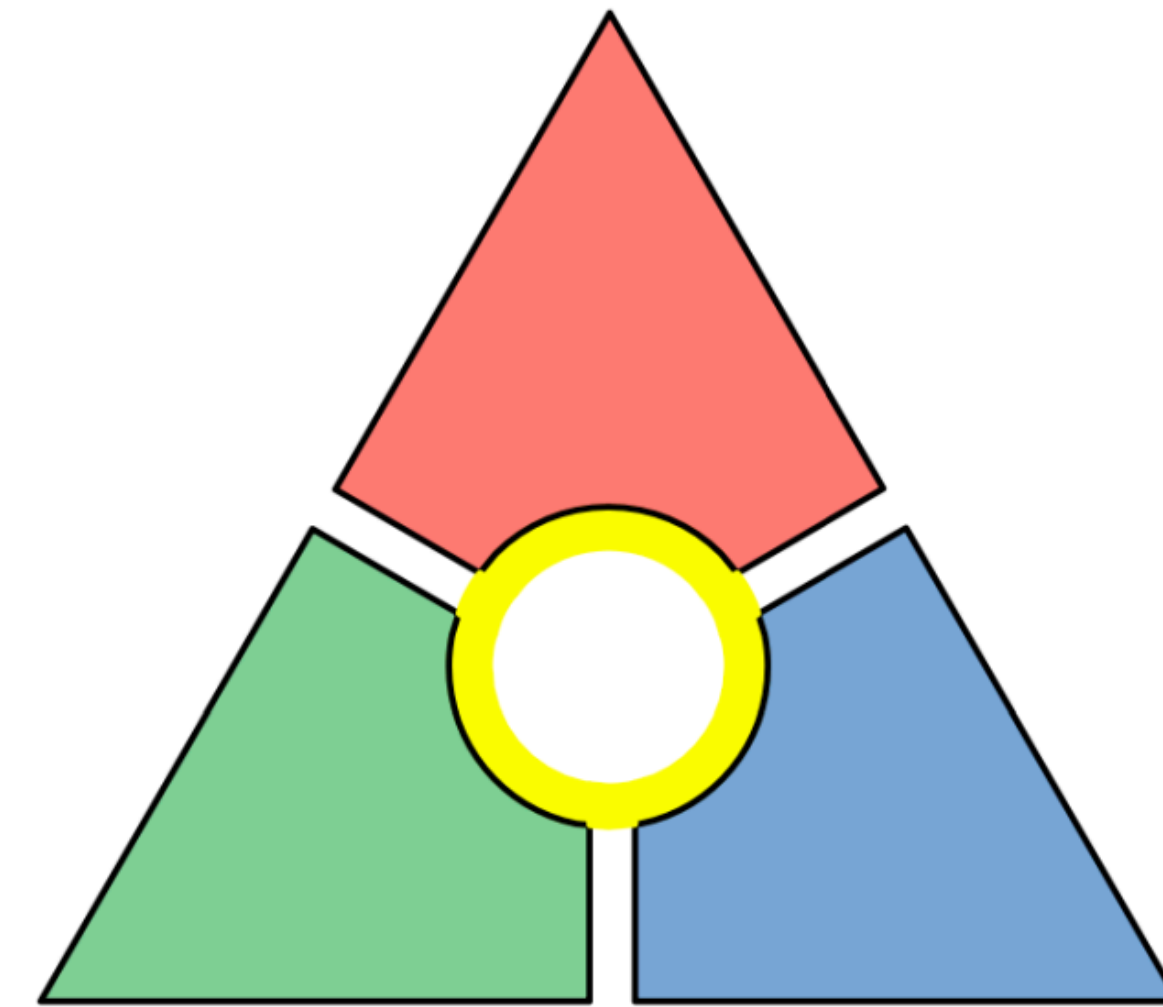
- MicroBooNE’s placement enables “one detector, two beams” concept
- $\mathcal{O}(500k)$ interactions across both beams
 - BNB is on-axis
 - NuMI spans 8° (target) \rightarrow 120° (absorber) and has significantly more $\nu_e / \bar{\nu}_e$

BNB



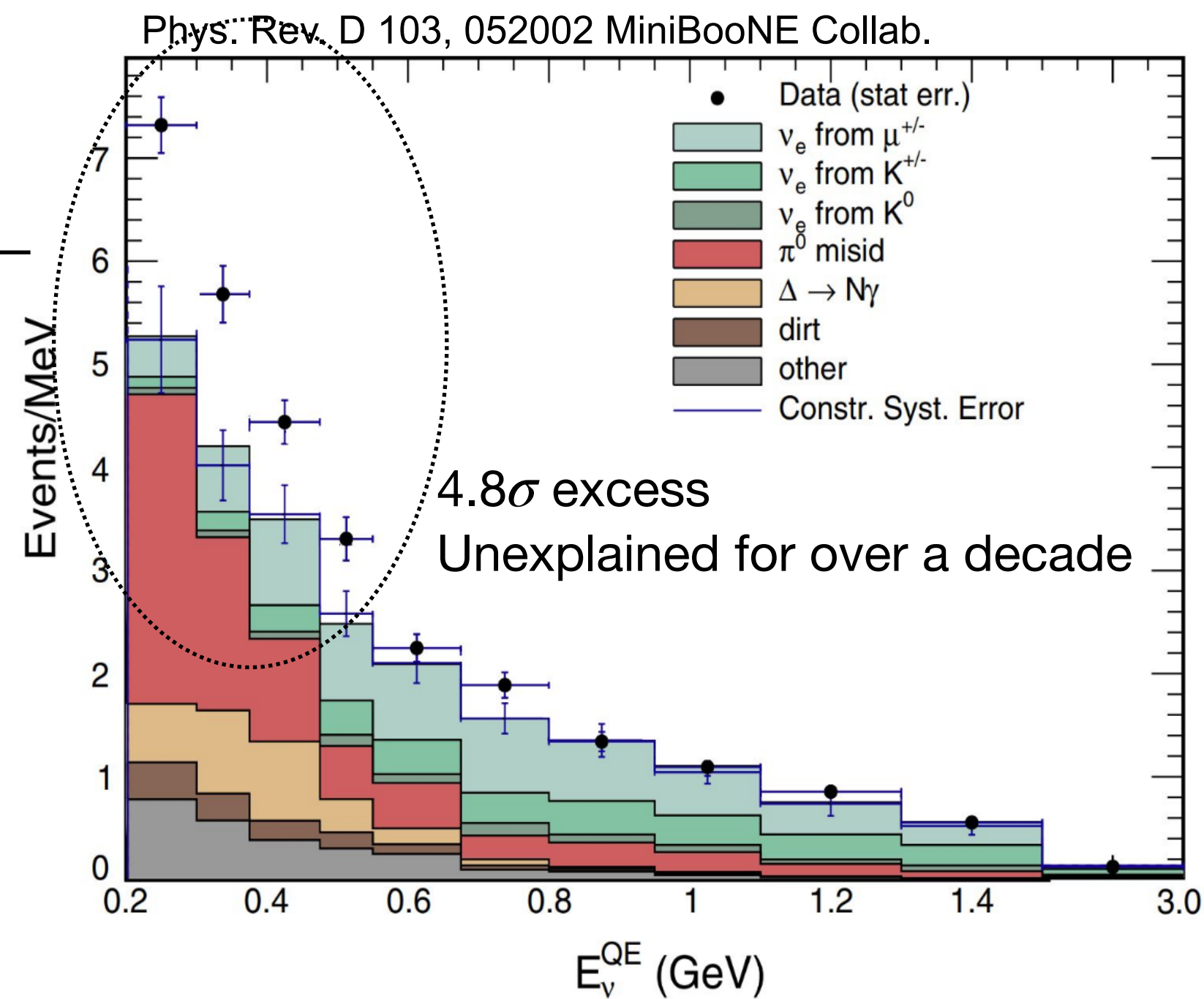
MicroBooNE Science Goals

Enhancing our previous BSM searches

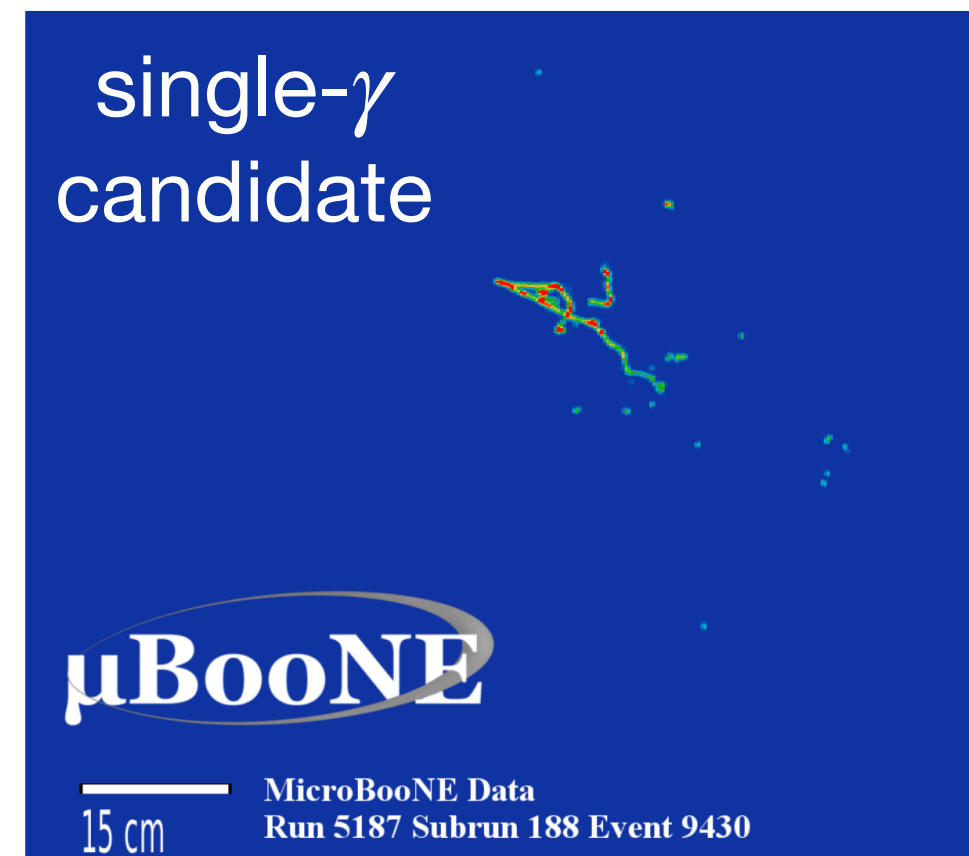


Low Energy Excess Search

e^+e^- ?



single- γ ?

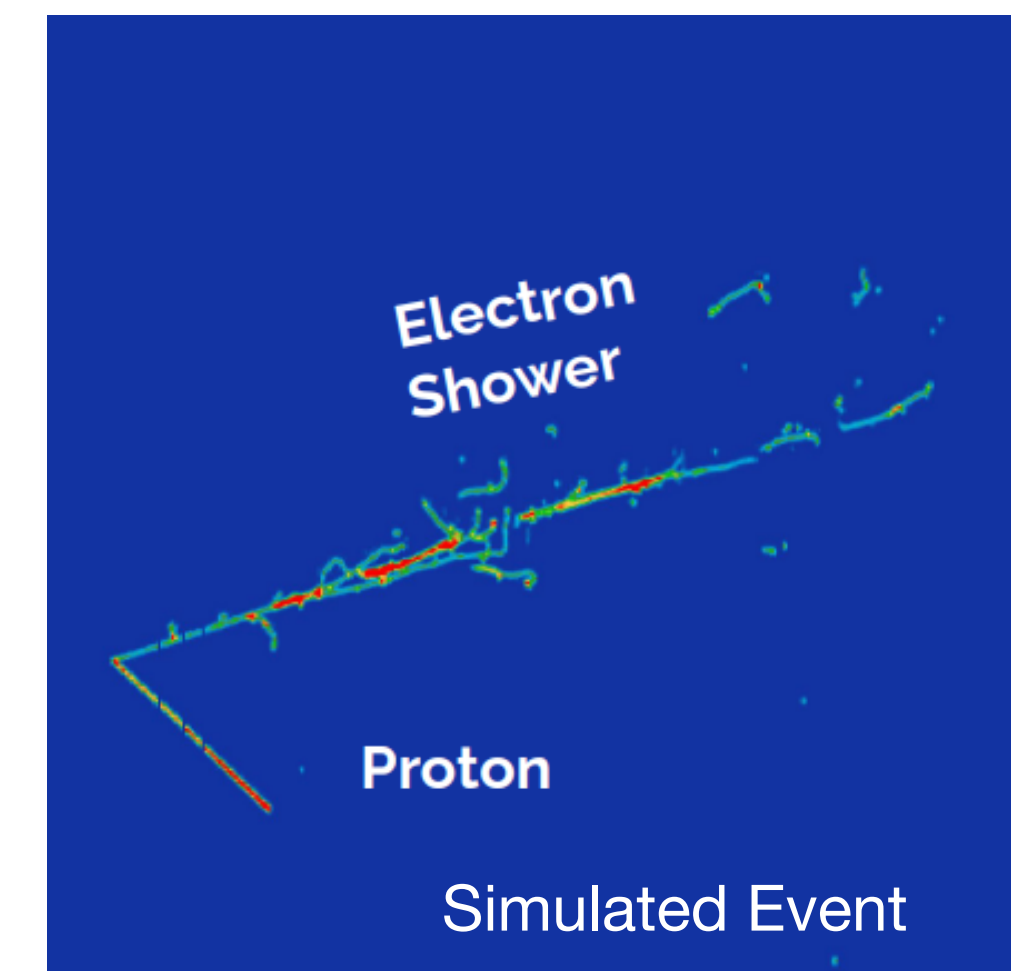


PRL 128 (2022) 111801

◆ First generation analyses

ν_e ?

ν_s ?



PRL 128 (2022) 24, 241801

PRL 130 (2023) 1, 01180

- Famous MiniBooNE/LSND anomaly that is consistent with well-motivated BSM models!
 - Sterile neutrinos, Dark neutrinos, enhancements to SM 1γ production etc
- MicroBooNE has much better e/γ separation capabilities
- Can shed light on the sources of this anomaly - ongoing/updated analyses targeting all topologies

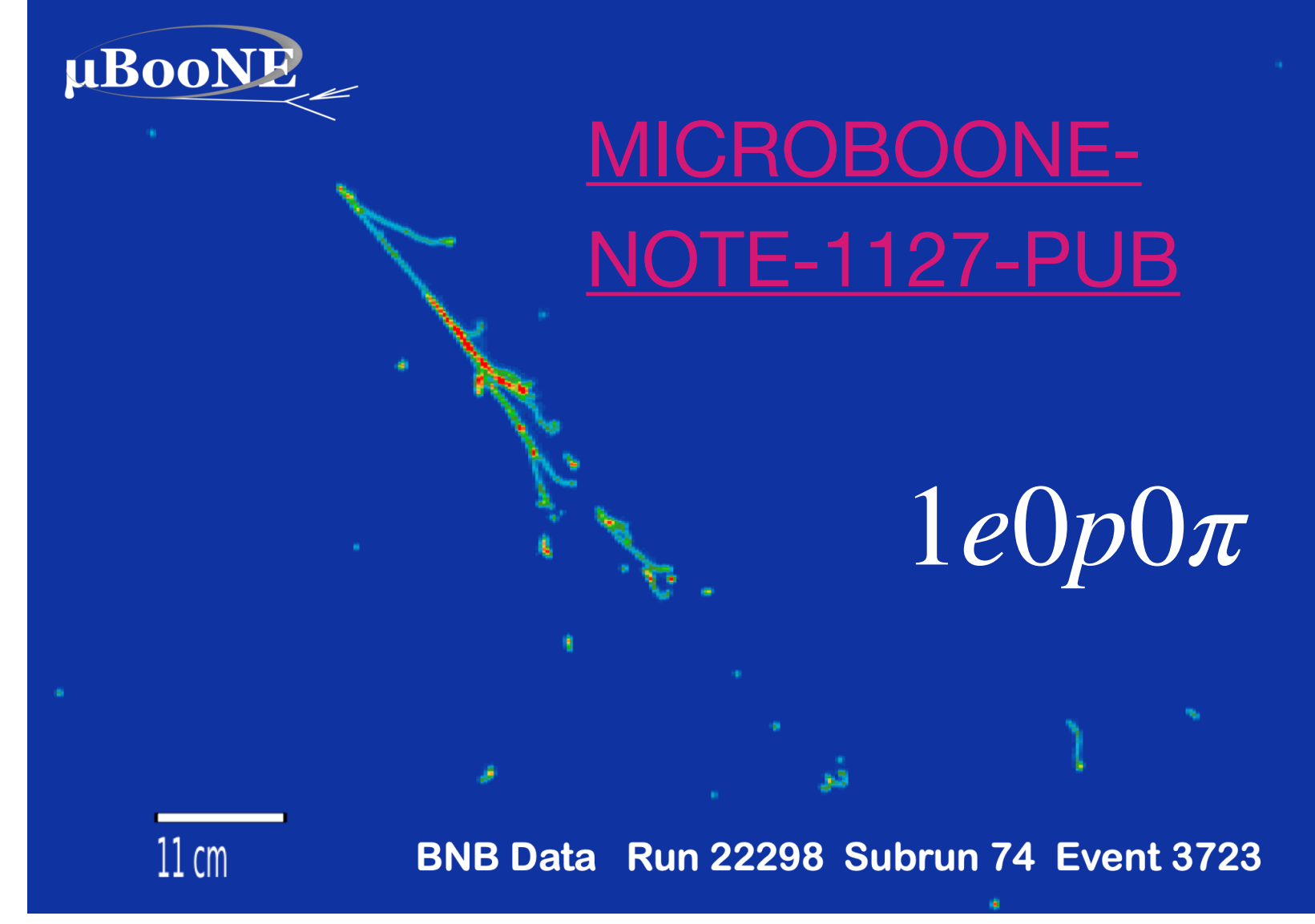
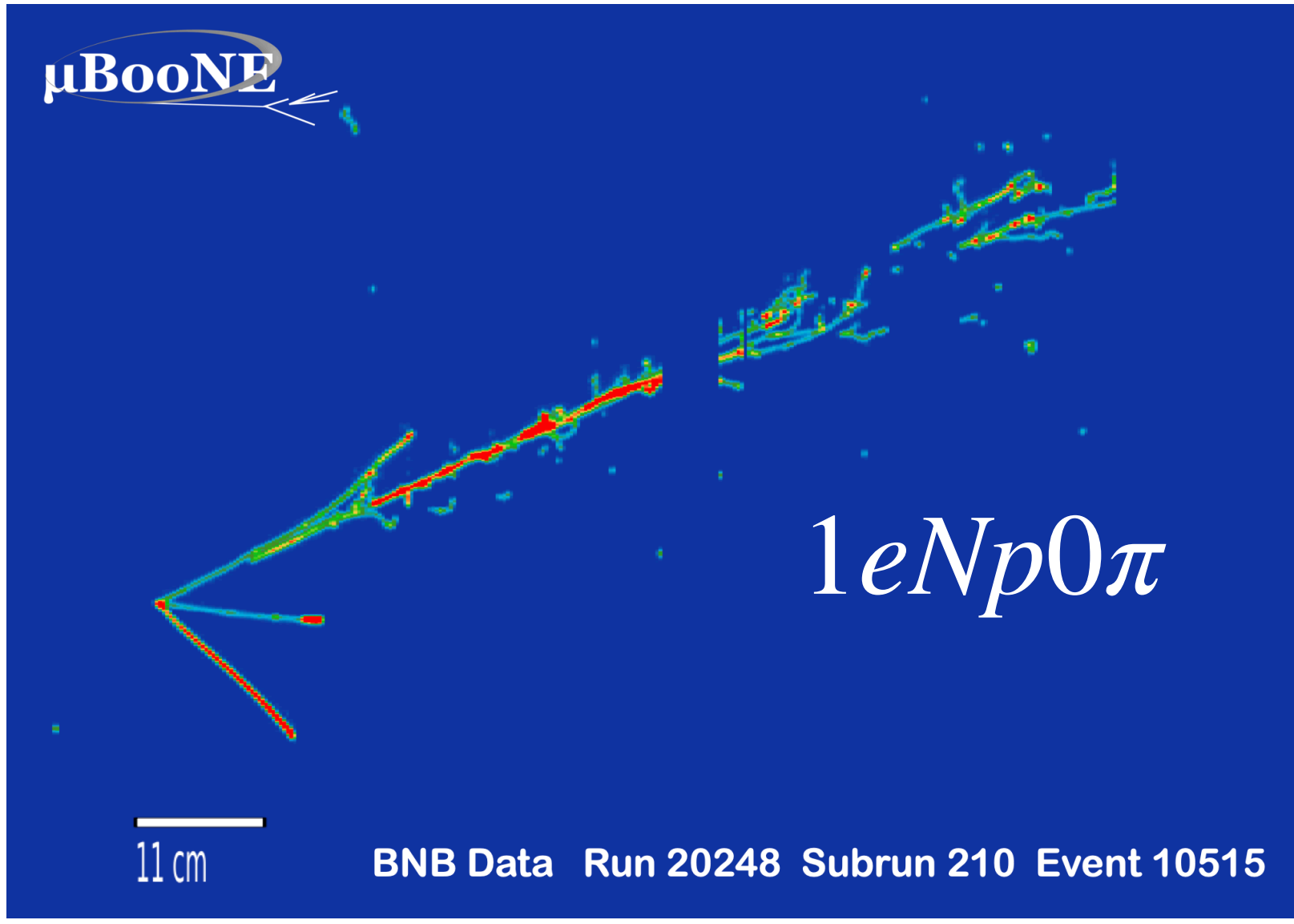
LEE Search (ν_e -like)

BNB

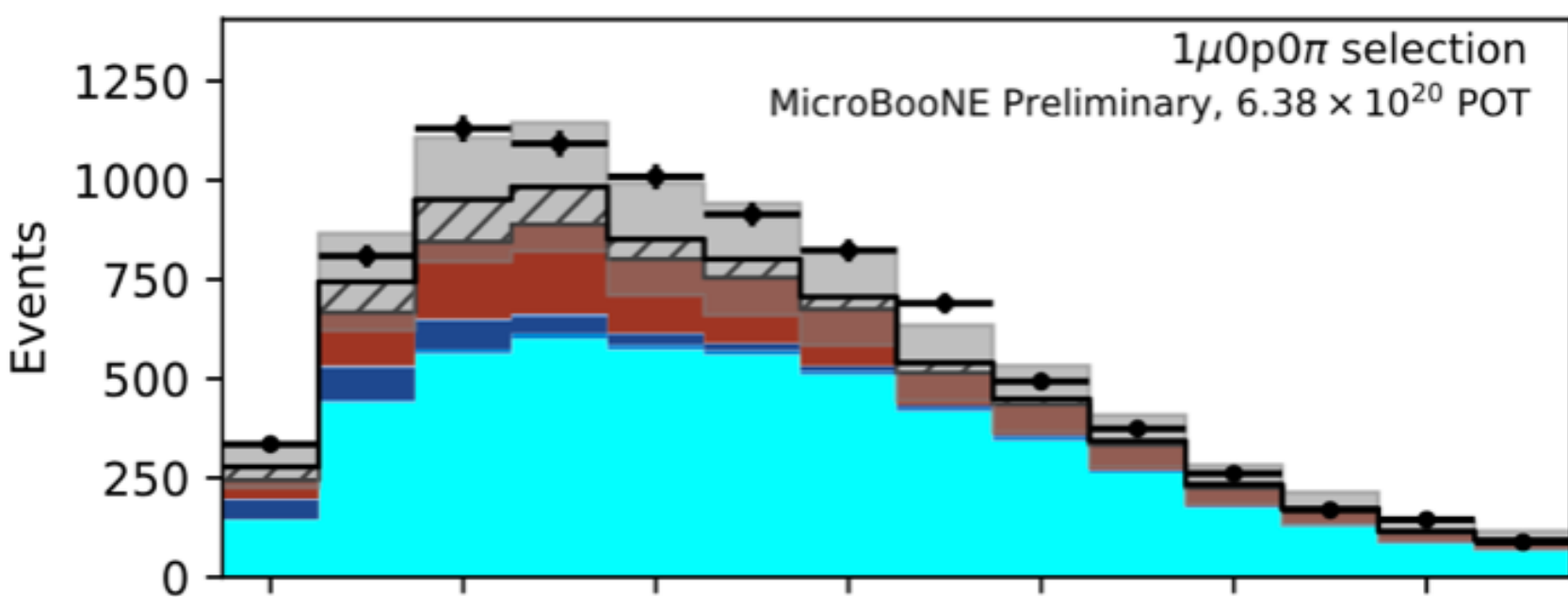
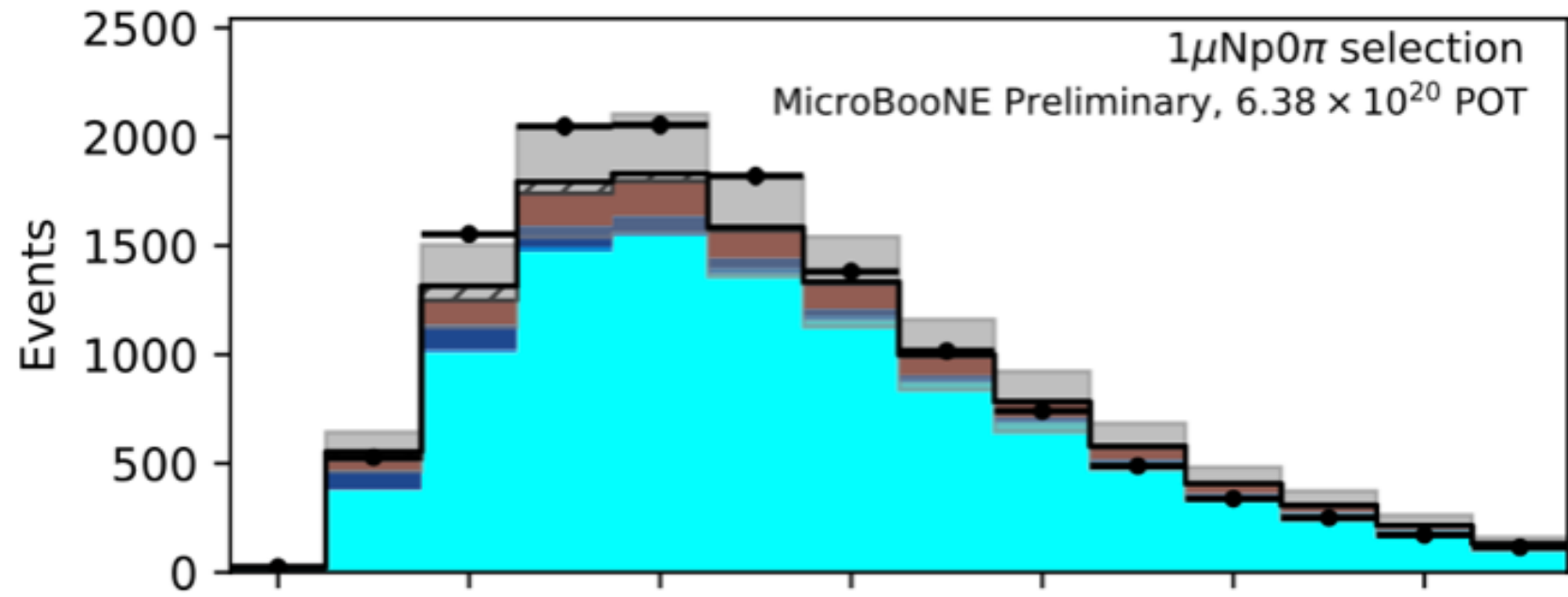
New Results! 

 - ν_e Low Energy Excess Search - Fan Gao

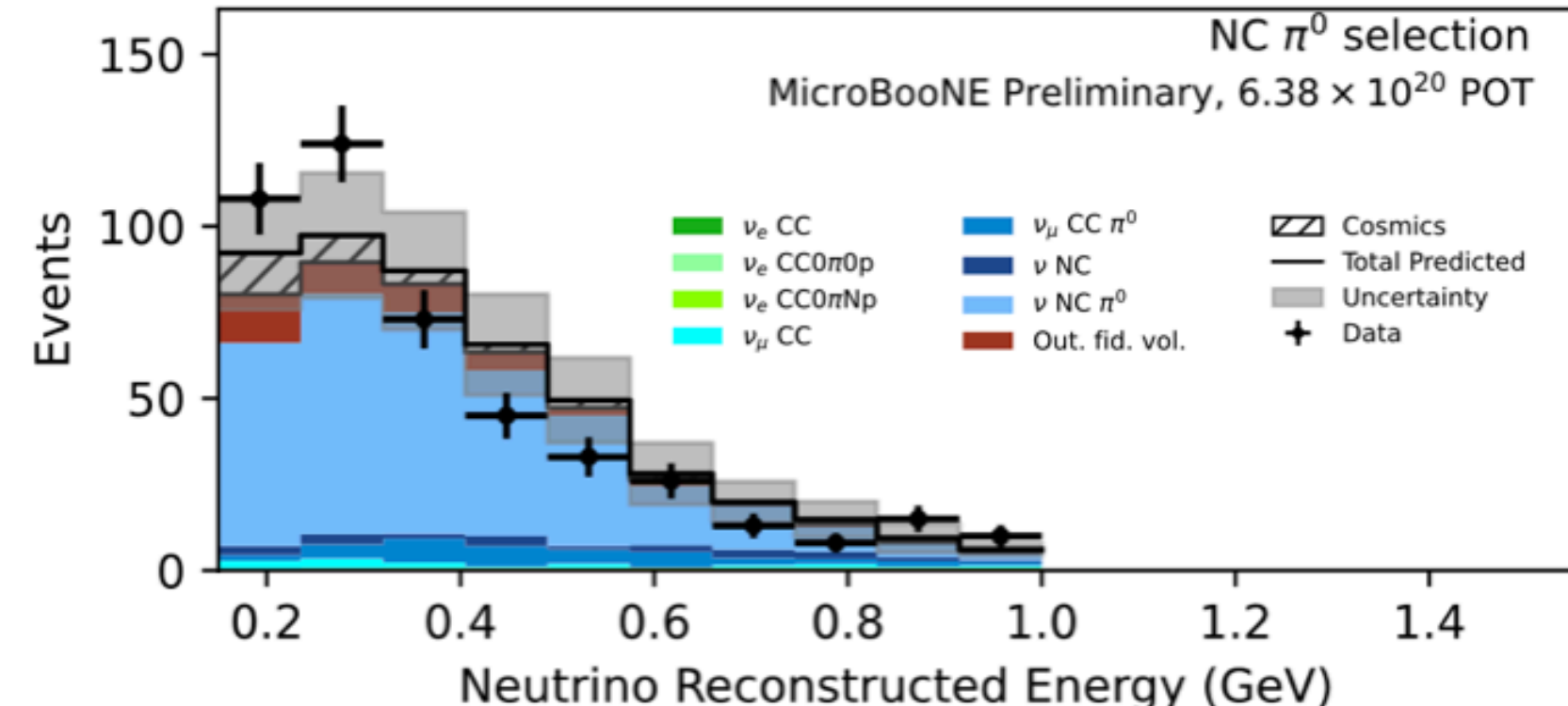
- 1st Round - saw no evidence of ν_e - like excess
- Since then, updates to [PRD 105 \(2022\) 11, 112004](#)
 - Same topology as MiniBooNE LEE ($\nu_e CC0\pi$)
- First analysis to use full MicroBooNE dataset!
 - $6.8 \times 10^{20} \rightarrow 11.1 \times 10^{20}$ POT
- New background constraint from $\nu_\mu CC$ and $NC\pi^0$ rich sidebands



match hadronic final states of ν_e signal channel



constrain dominant π^0 background



LEE Search (ν_e -like)

BNB

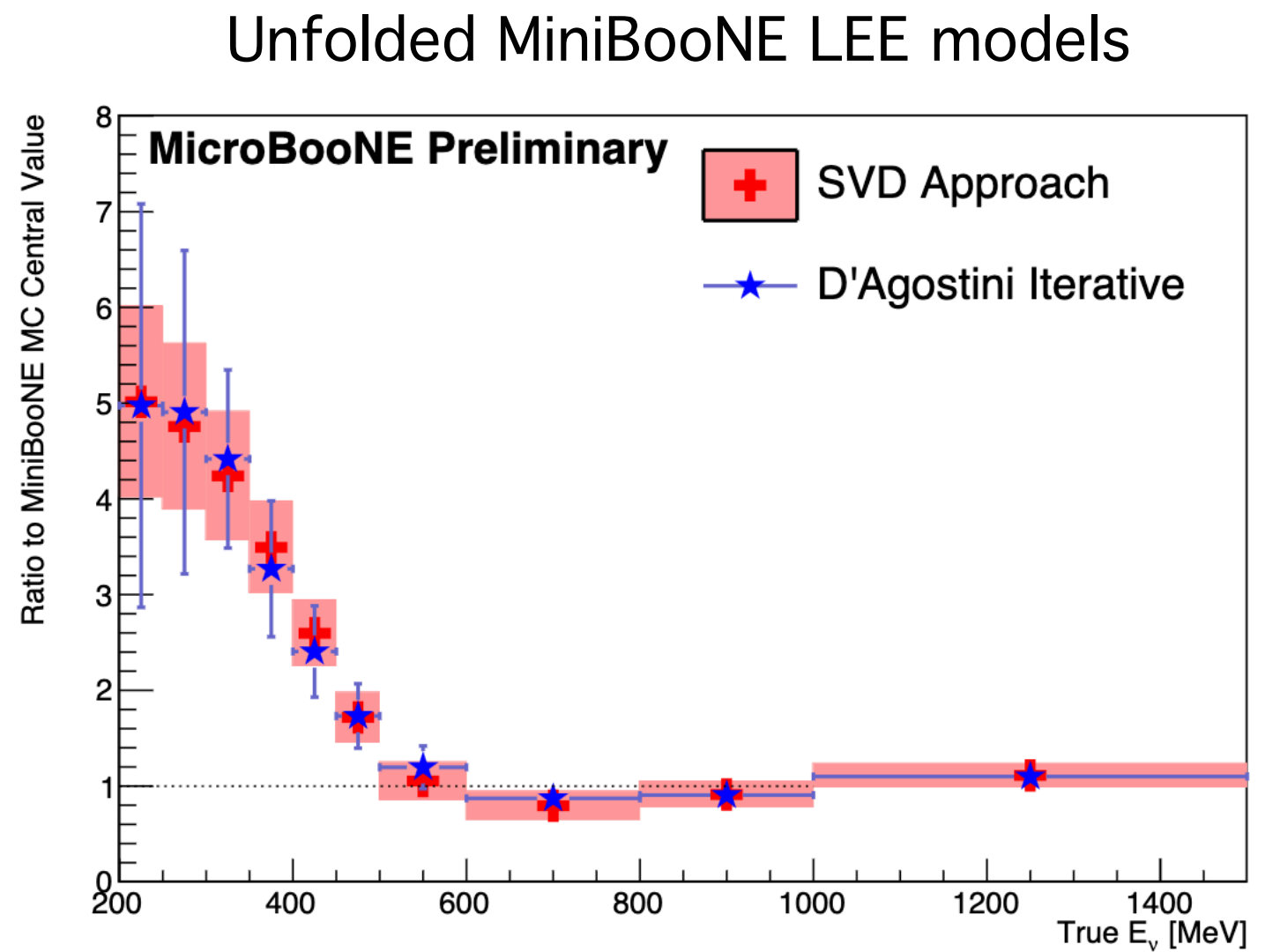
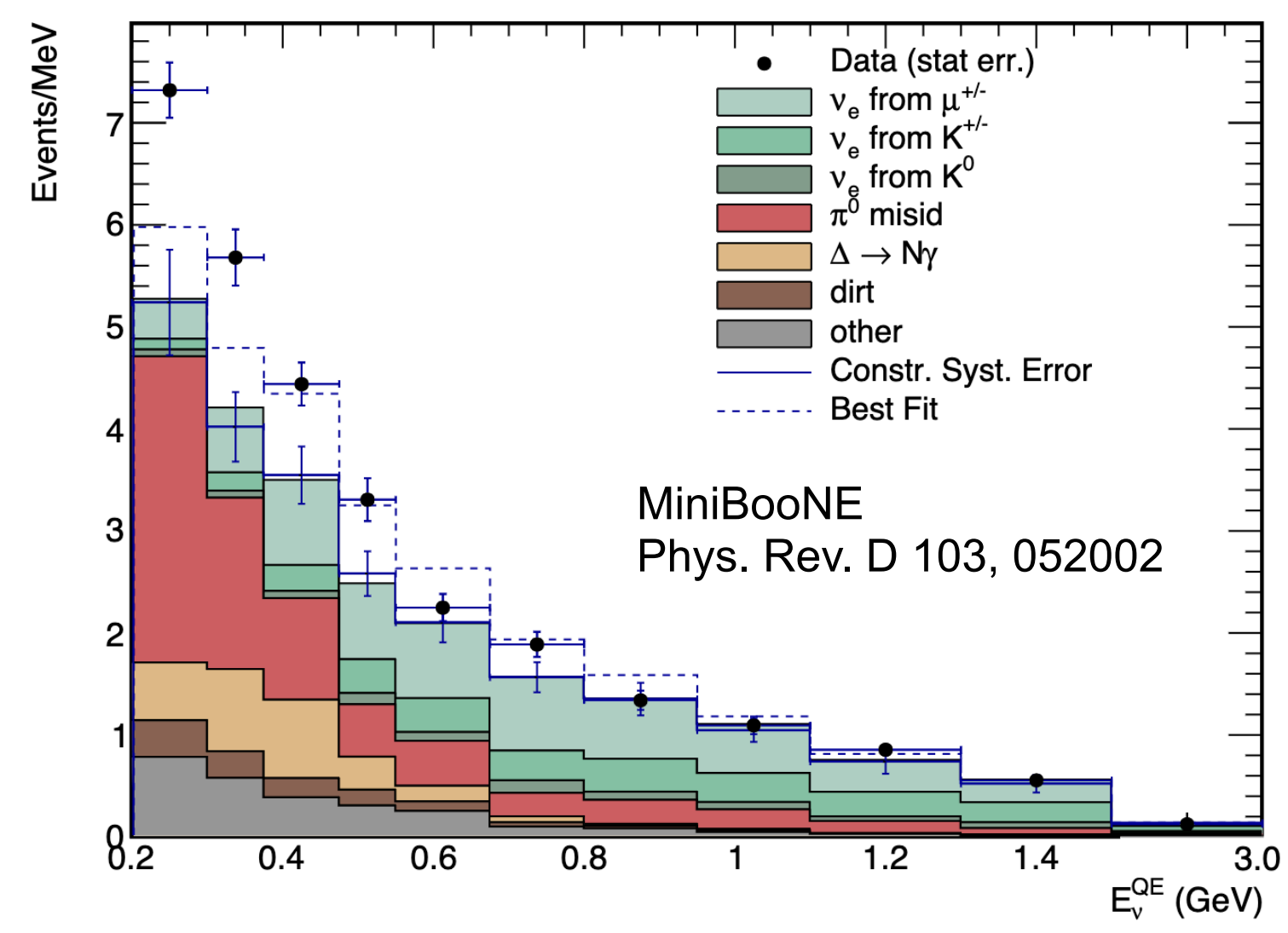
Previously :

- MiniBooNE-like excess based on enhancement in true E_ν

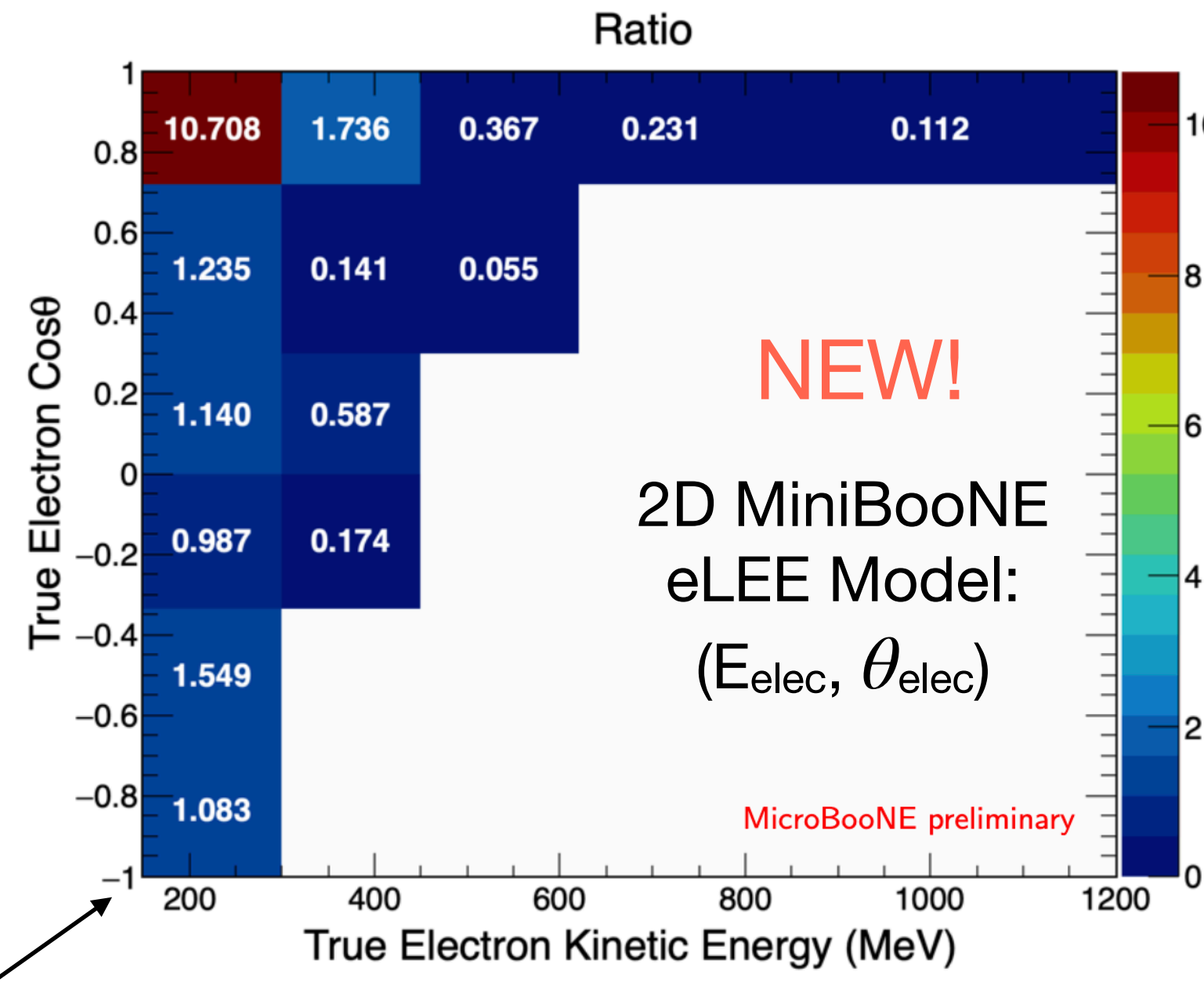
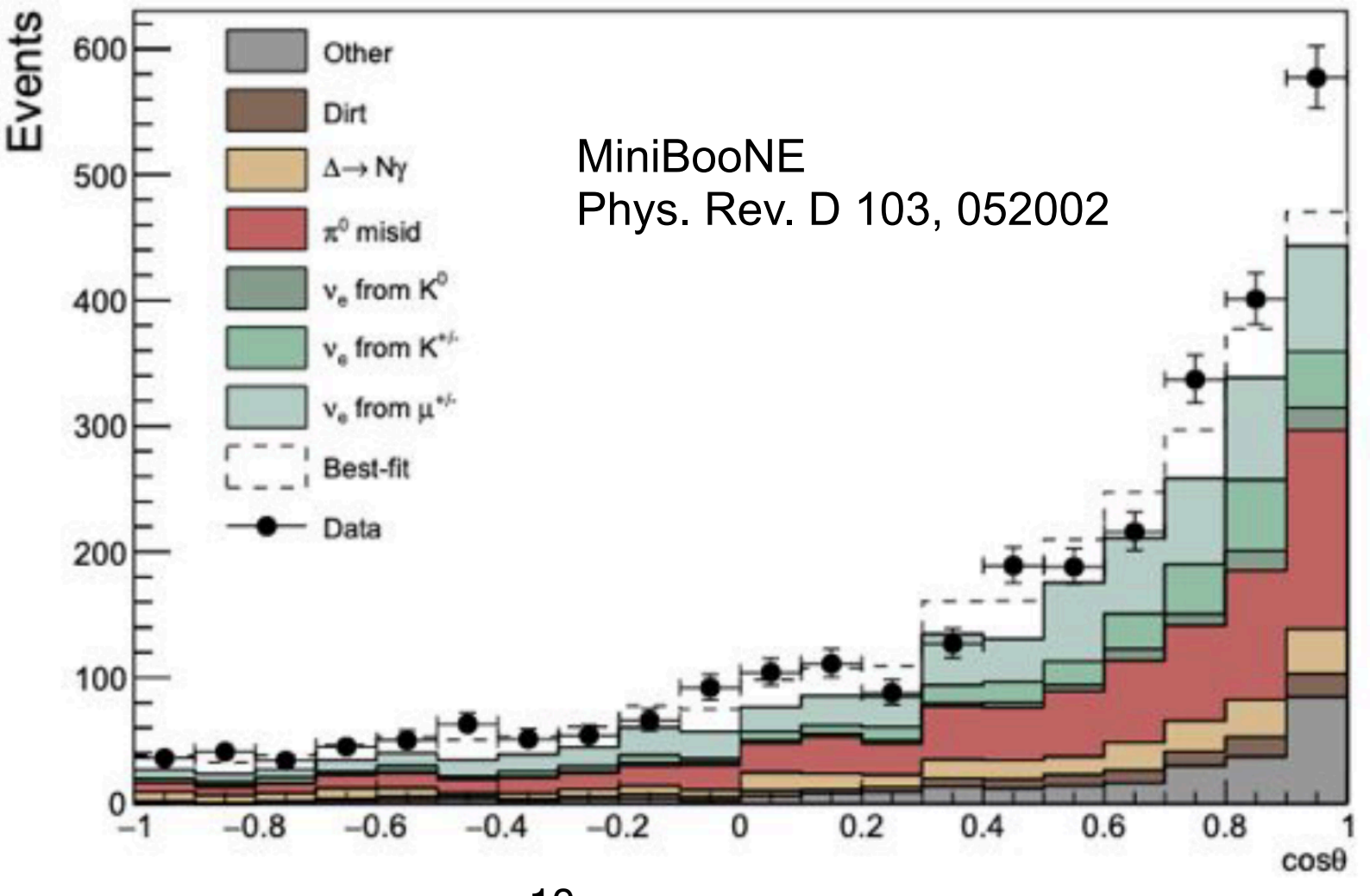
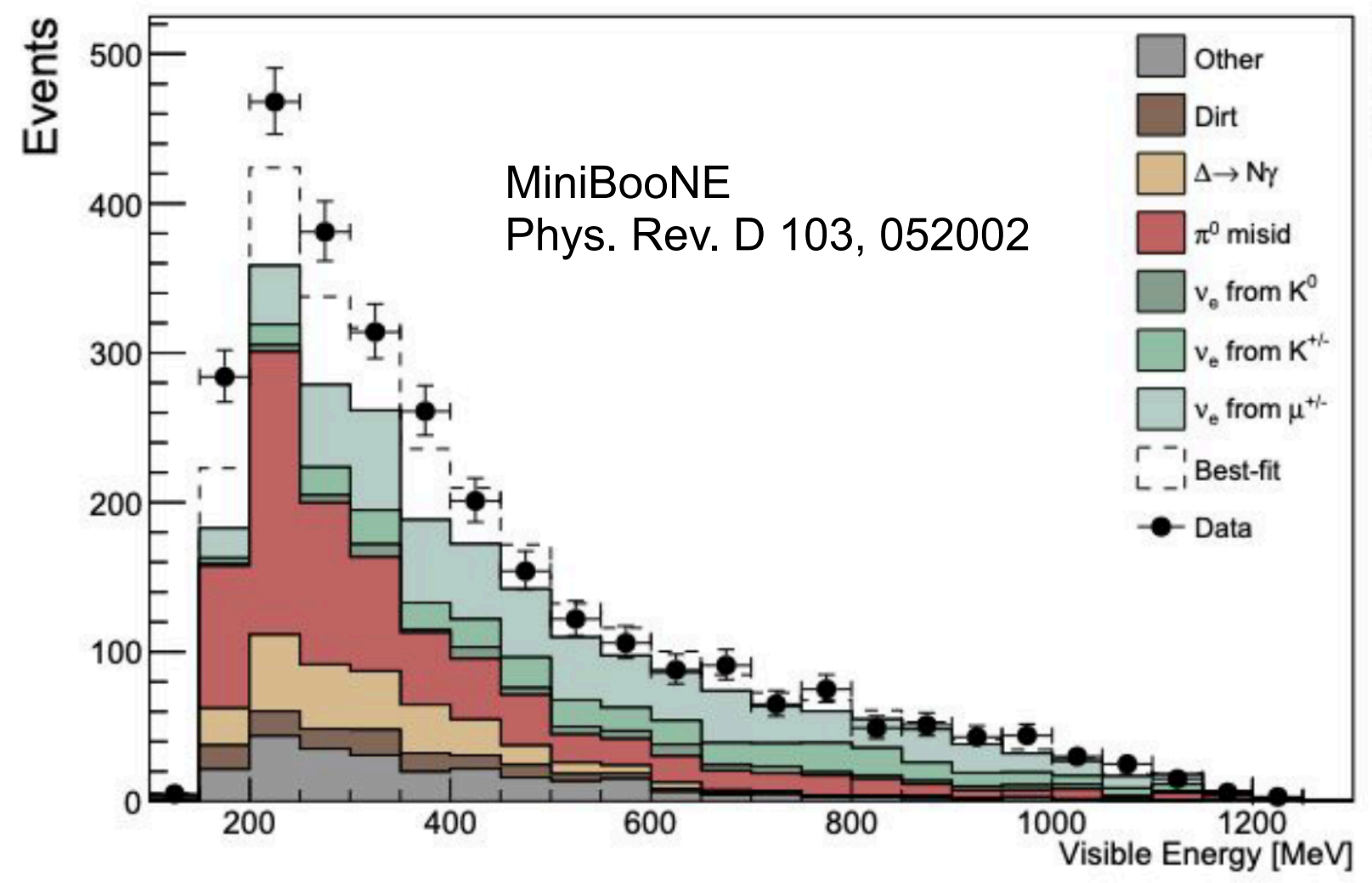
Update to include :

- Enhancement in true E_e , $\cos\theta_e$ (shower kinematics) as well

MiniBooNE LEE hypothesis for ν_e -like is more comprehensive

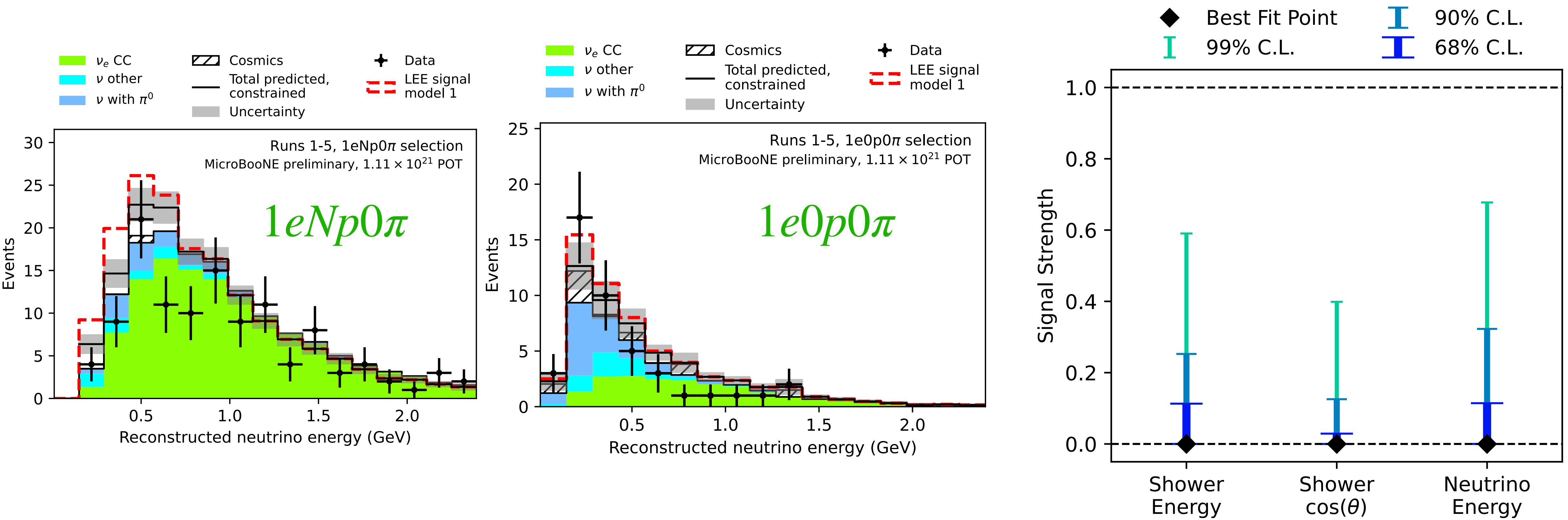


Shower energy Shower angle



LEE Search (ν_e -like)

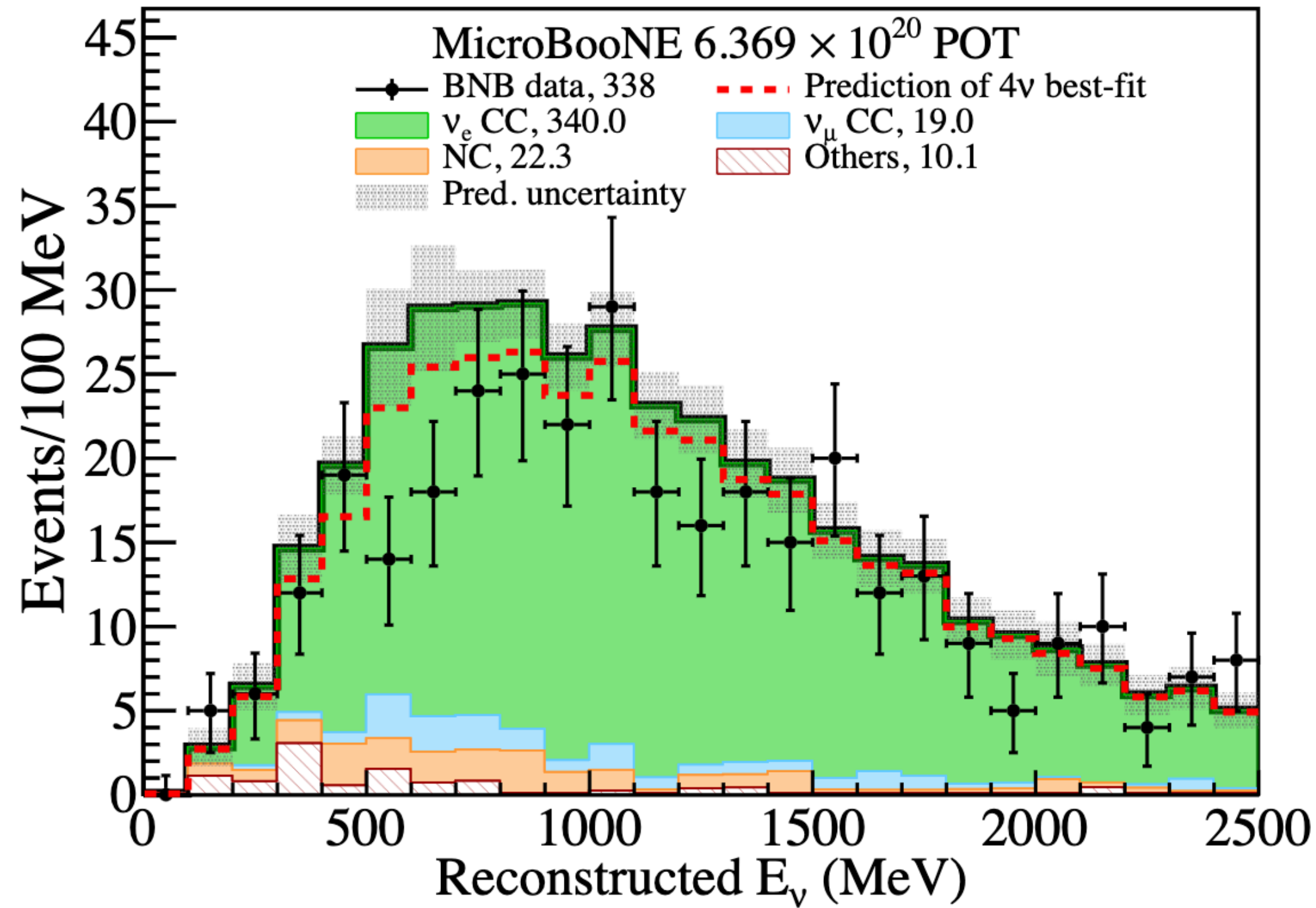
BNB



- With $\sim 65\%$ more stats and new sideband constraints \Rightarrow able to provide strong limits on the MiniBooNE LEE-like models
- Inconsistent with ν_e -like excess at $> 99\%$ CL!
- Consistent results across all kinematic observables

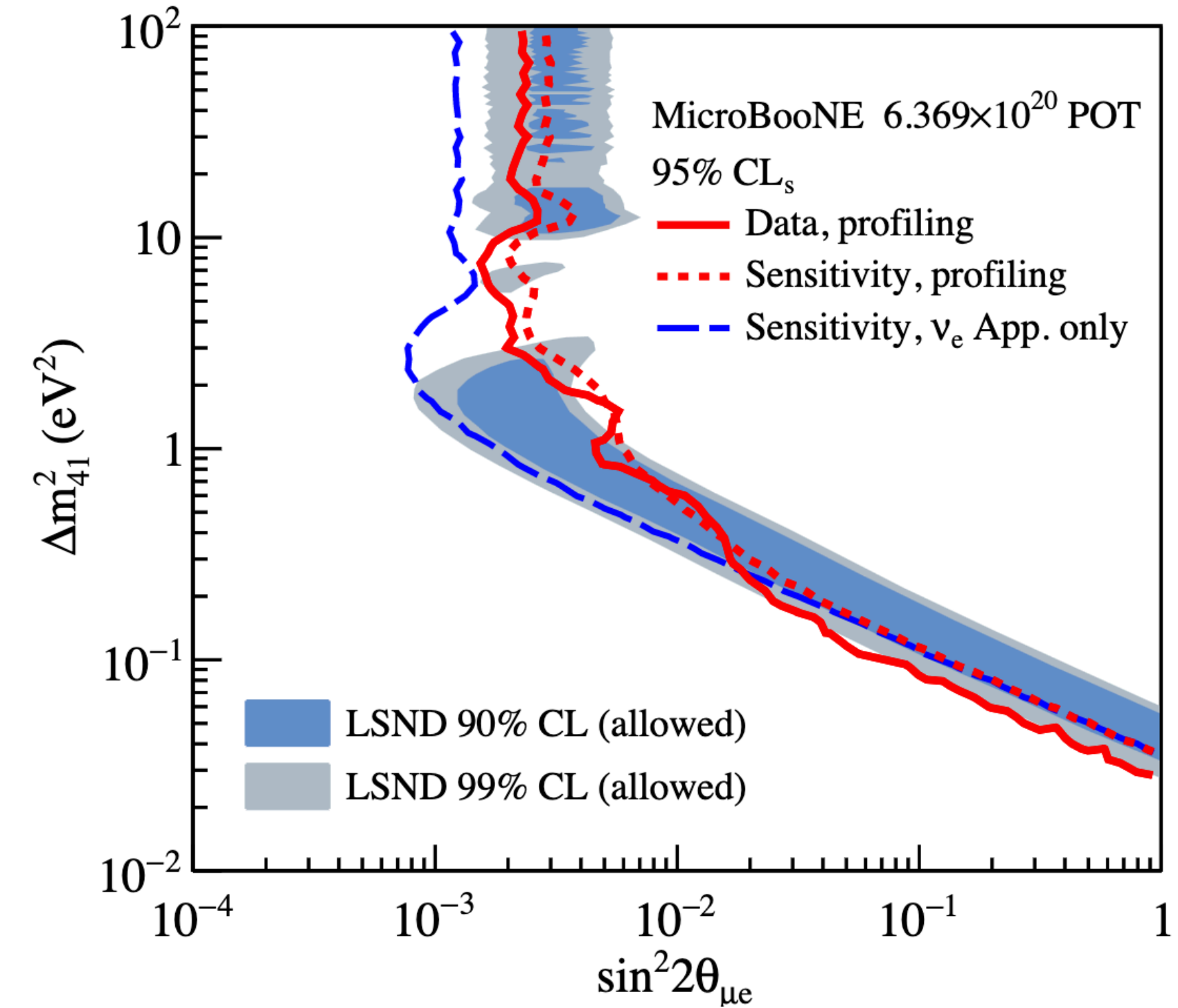
3+1 ν_s Oscillations

BNB + NuMI



$$\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$$

$$\nu_e \rightarrow \nu_s$$

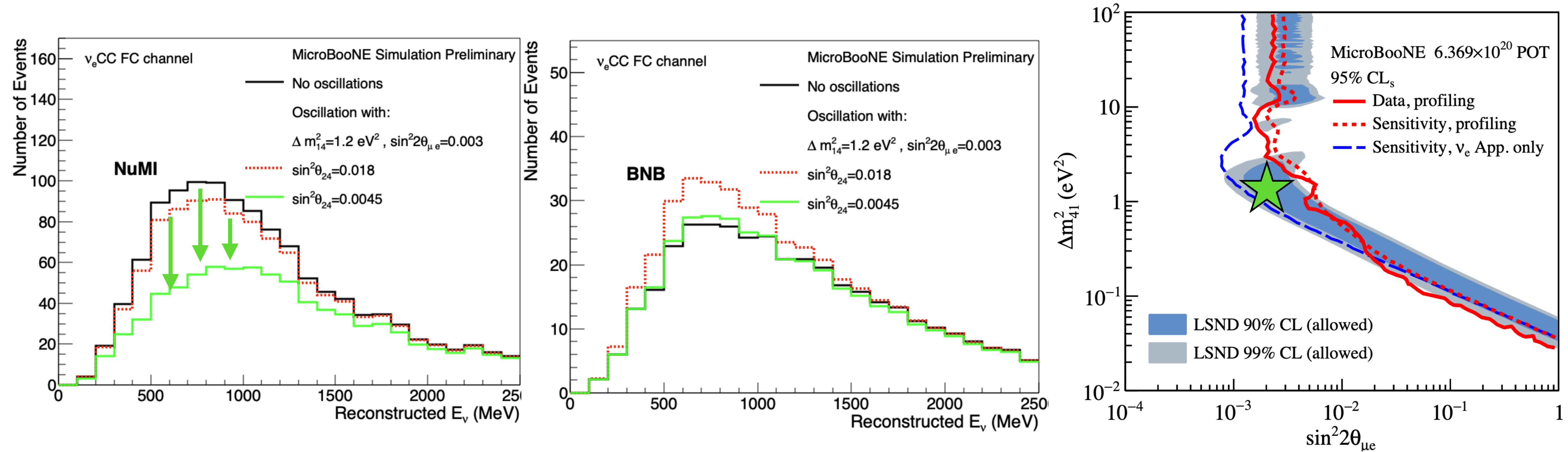


PRL 130 (2023) 1, 01180

- Previously, 3+1 ν_s search based on BNB-only ν_e analysis (inclusive $\nu_e CC$)
- Able to reject some LSND allowed regions at 95% CL
- However, sensitivity limited by cancellation effect of ν_e -appearance and ν_e disappearance @ BNB

3+1 ν_s Oscillations

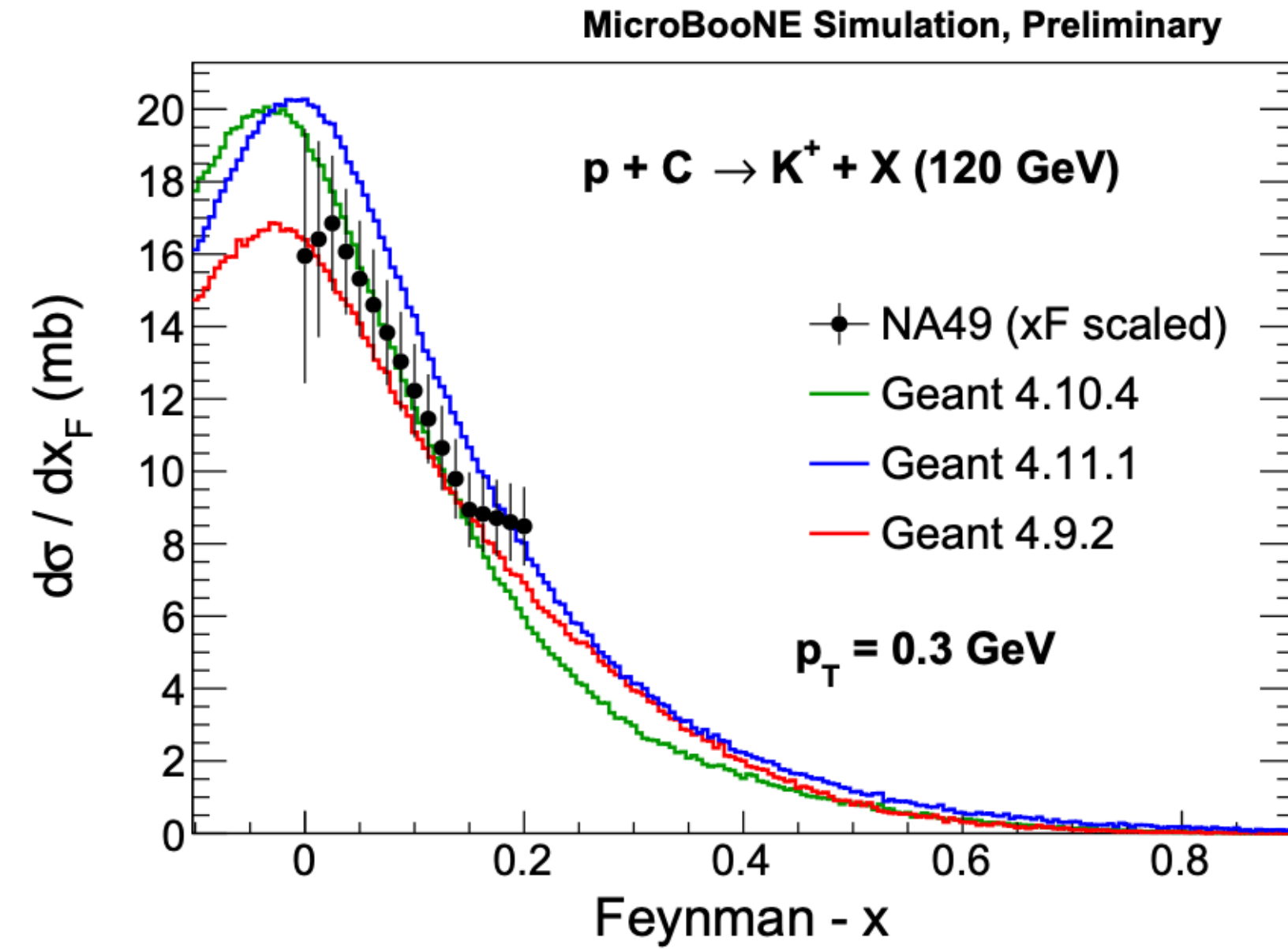
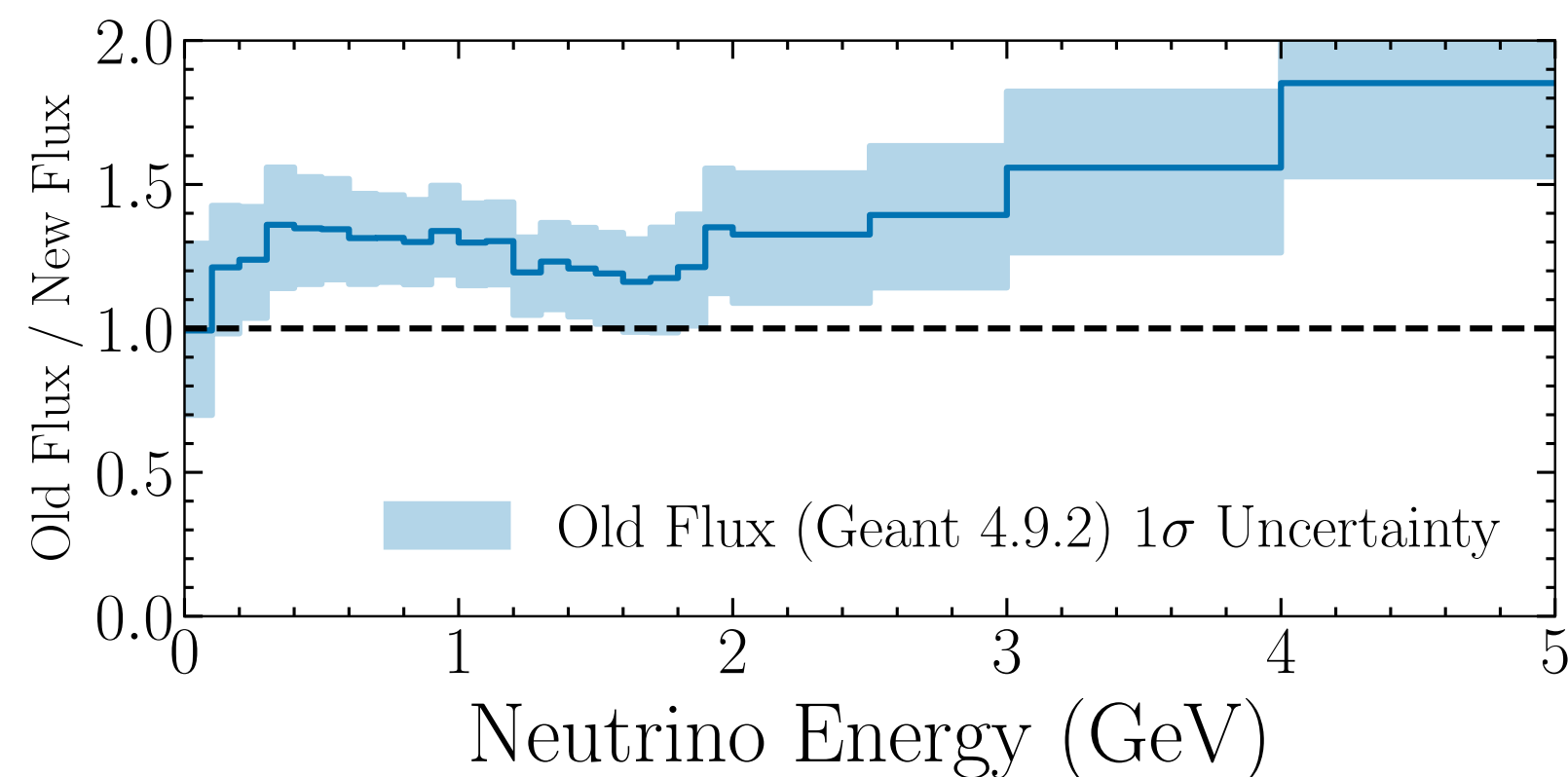
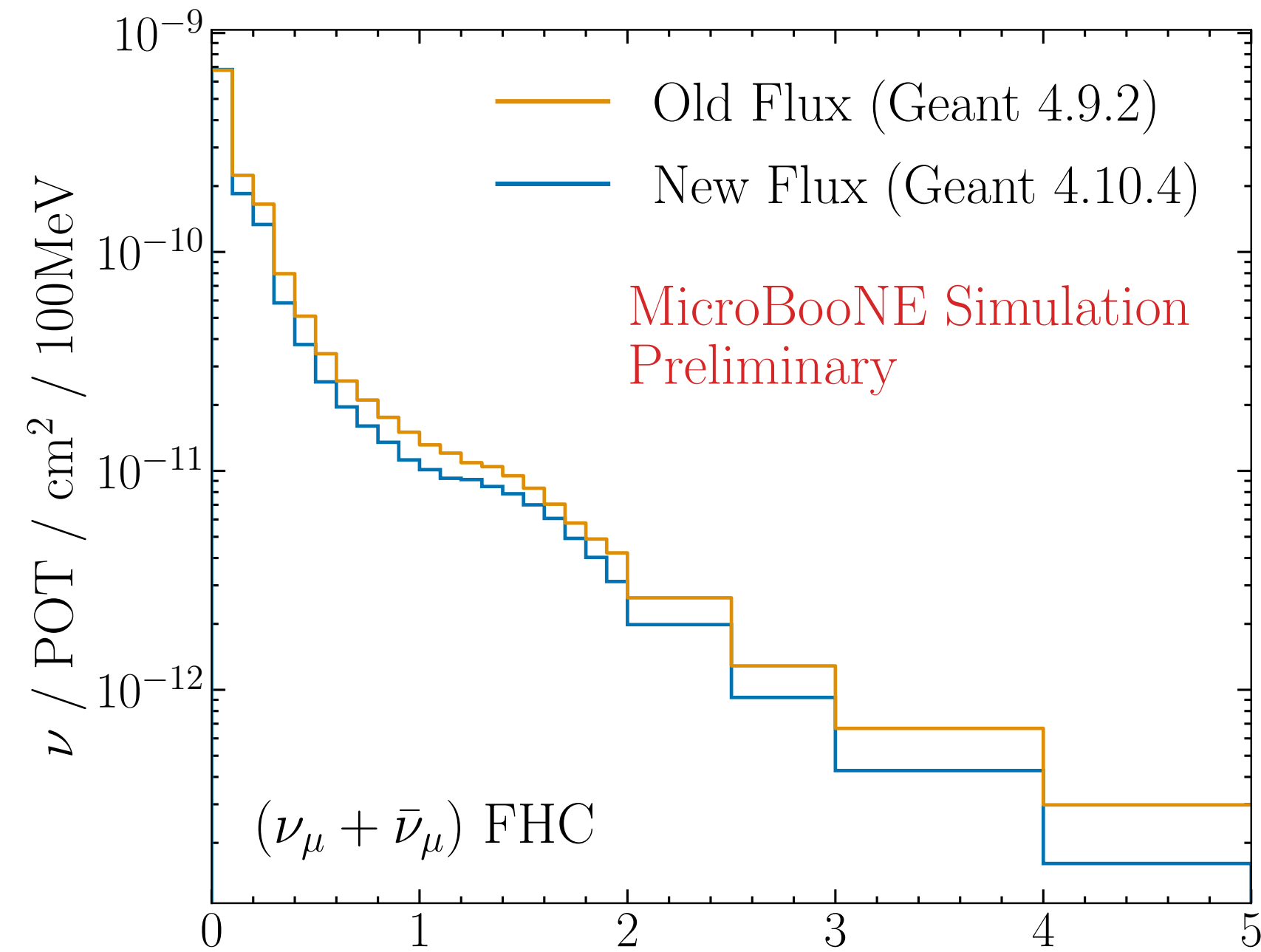
BNB + NuMI



- This appearance-disappearance degeneracy can be broken by using NuMI sample
- Different baseline, different intrinsic ν_e contribution in flux ($\sim 4\%$ vs 0.5% in BNB \Rightarrow disappearance effect dominates relative to BNB)
- Pioneering “one detector, two beams concept”

Updating the NuMI simulation

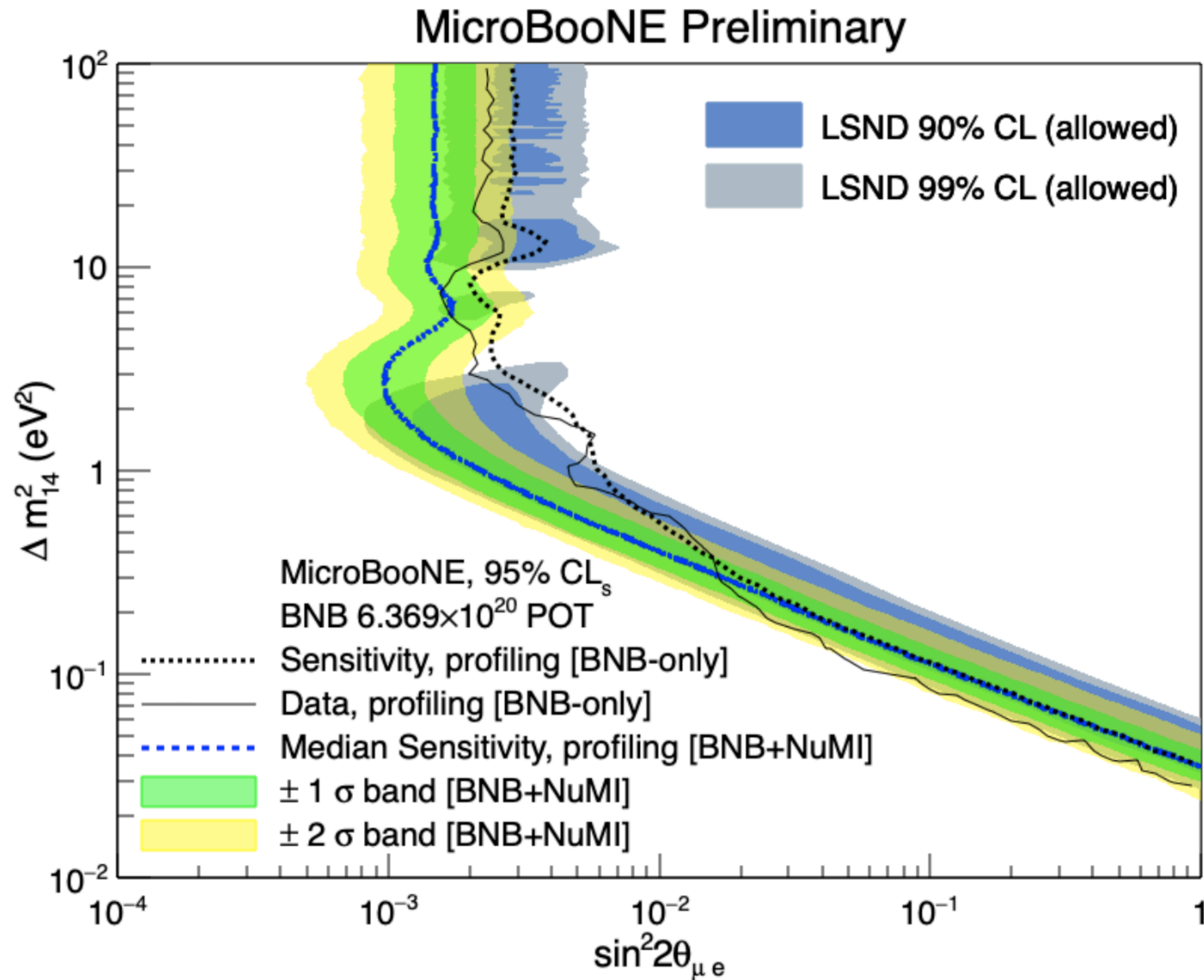
• More details at [MICROBOONE-NOTE-1129-PUB](#)



- NuMI sits at $\sim 8^\circ$ (highly off-axis!) \Rightarrow very little phase space coverage for external hadron production data
- We have overhauled our NuMI simulation
 - Beamline geometry updates
 - Updated to a modern G4 version (4.10) for a better base model
 - Constraints from NA49 and others similar to NOvA, MINERvA
 - Conservative treatment of uncertainties outside data coverage

3+1 ν_s Oscillations

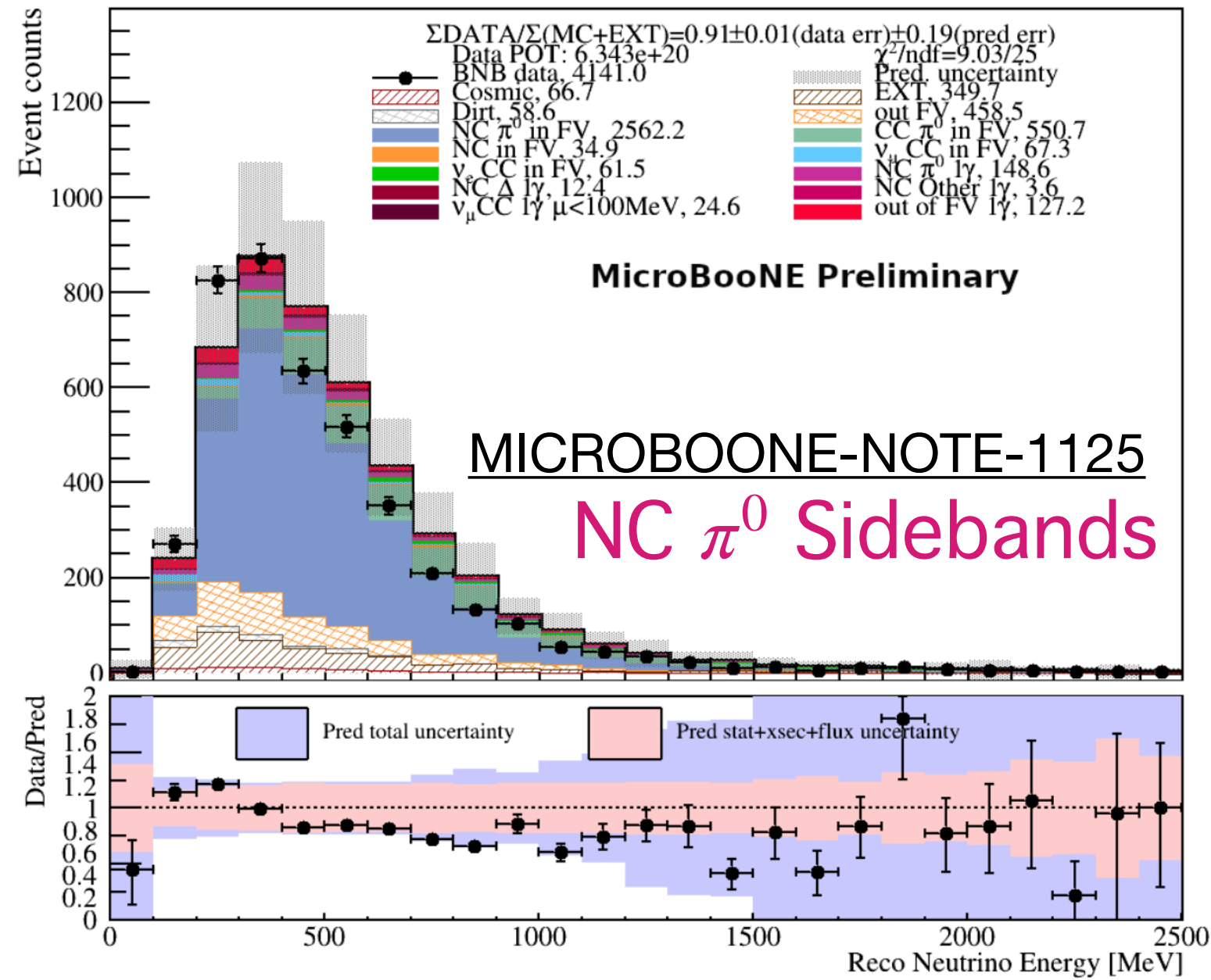
BNB + NuMI



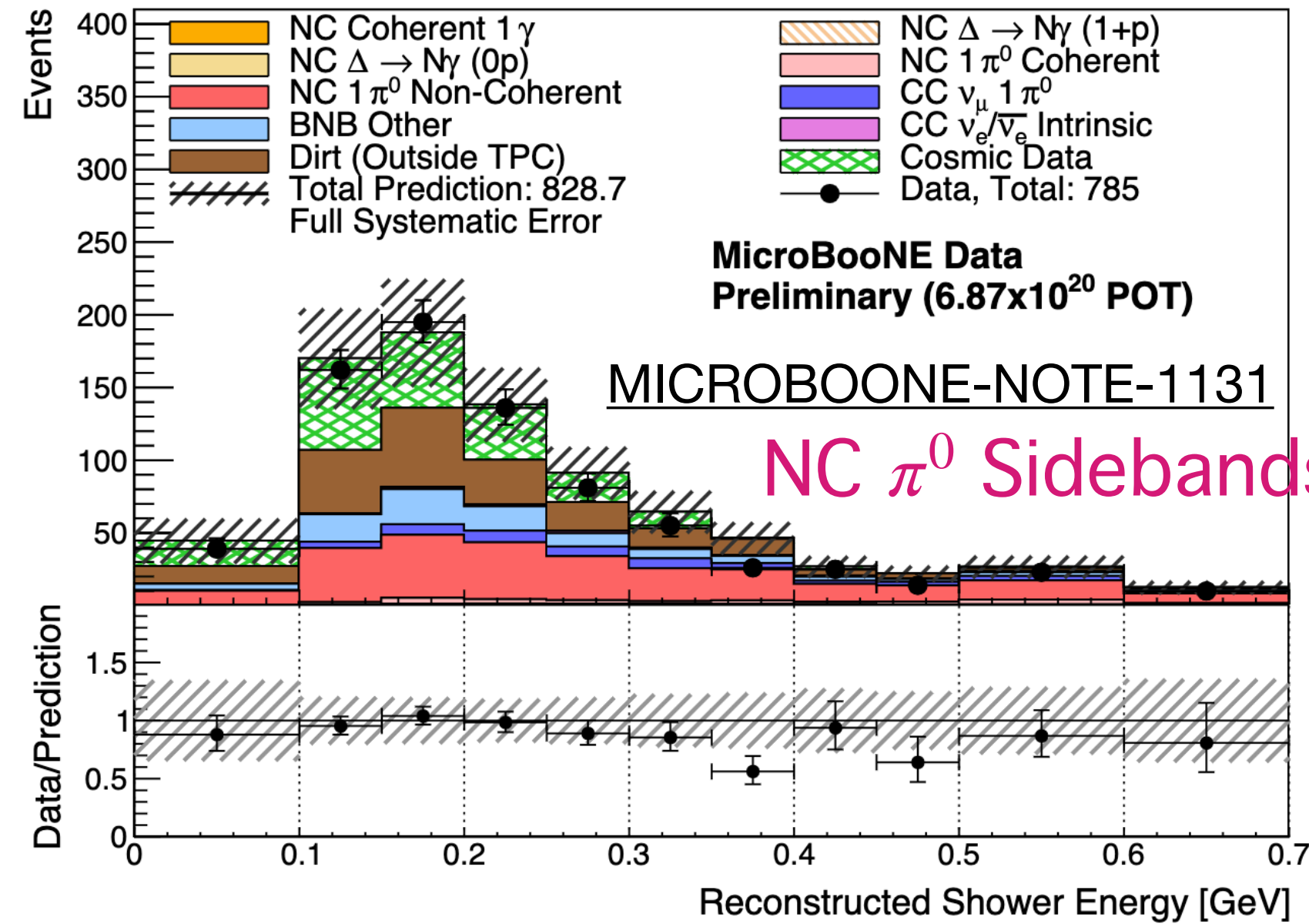
- Allows for significant increase in sensitivity when including both beams!
- Stay tuned for upcoming results!
- More details in [MICROBOONE-NOTE-1132-PUB](#)

LEE Search (single- γ)

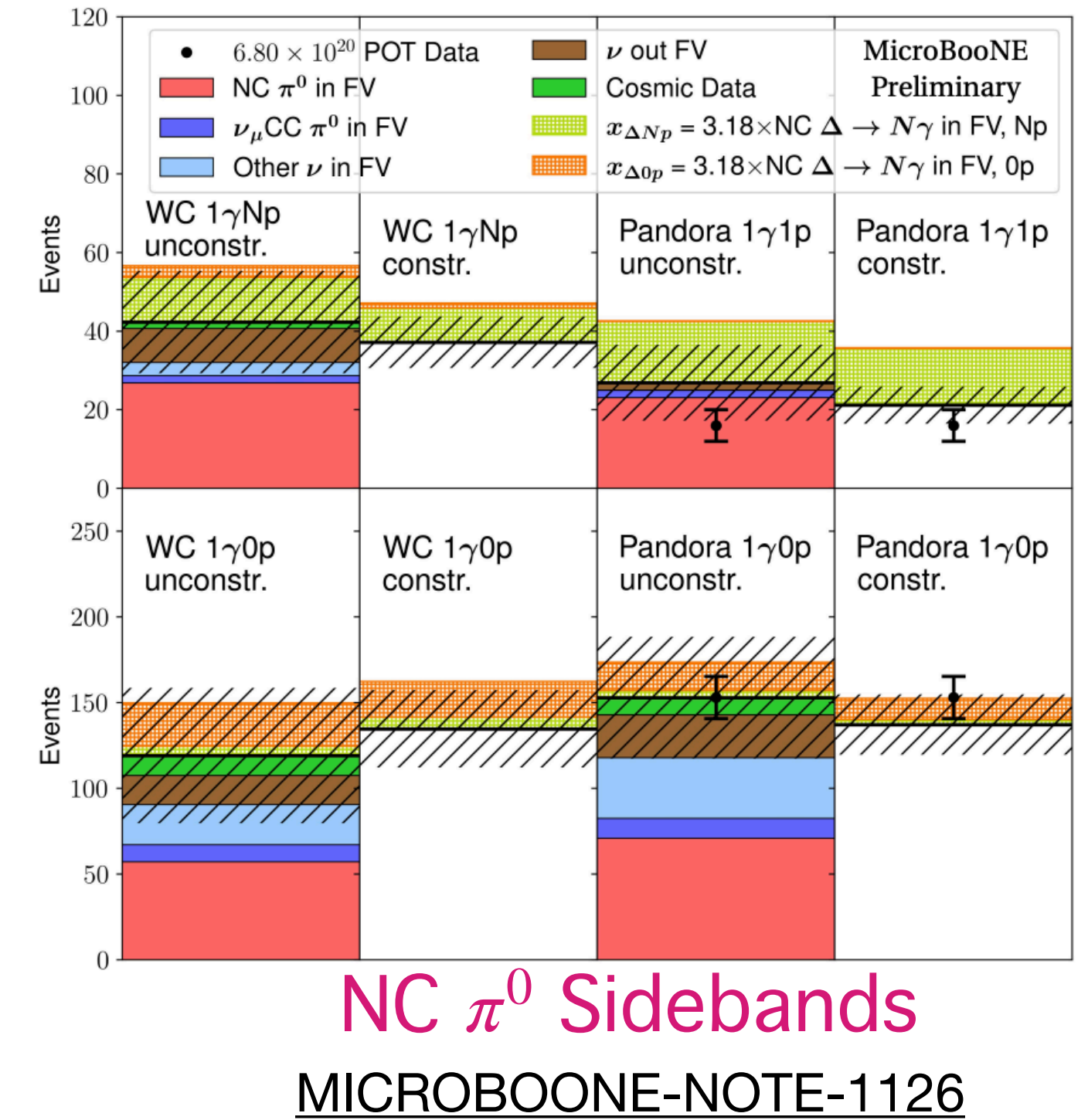
Inclusive single- γ



Enhancement in NC Coherent



Enhancement in NC $\Delta \rightarrow 1\gamma$



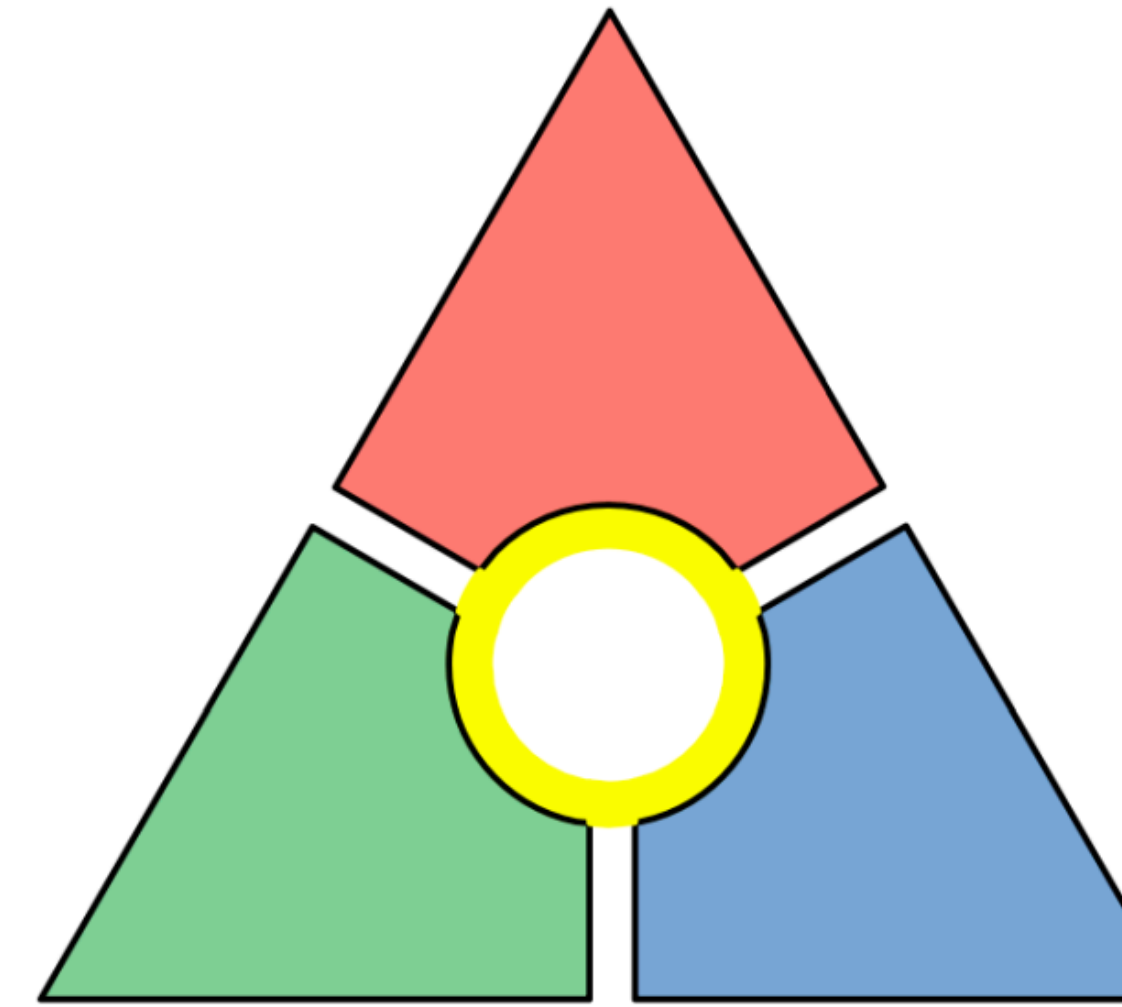
- Previously, saw no evidence of enhancement to NC $\Delta \rightarrow 1\gamma$
 - Disfavor sole MiniBooNE explanation at 95% CL

🤔 - Anomalous γ and e^+e^- Searches - [Erin Yandel](#)
 🤔 - NC $\Delta \rightarrow 1\gamma$ - [Lee Hagaman](#)

- Now, casting a wider net with new and updated analyses - both generic (inclusive) and specific enhancements
- Stay tuned for results!

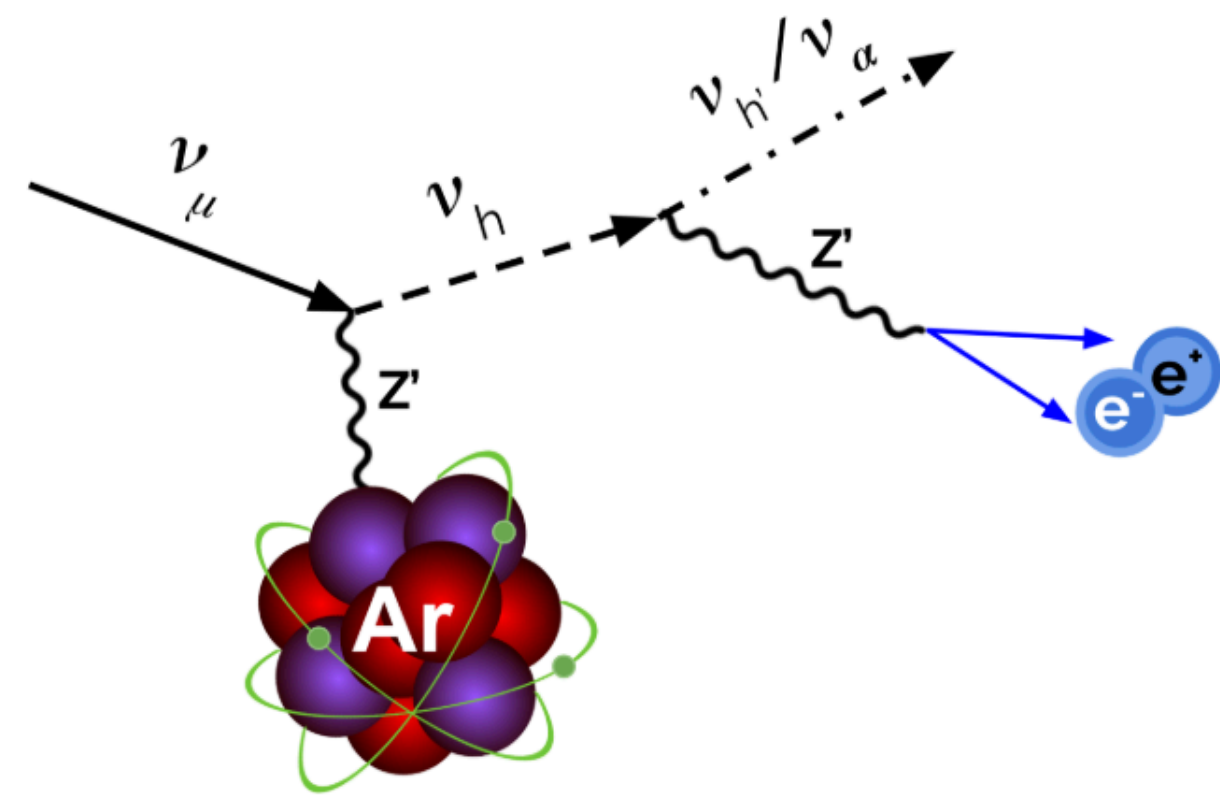
MicroBooNE Science Goals

Extending our BSM program

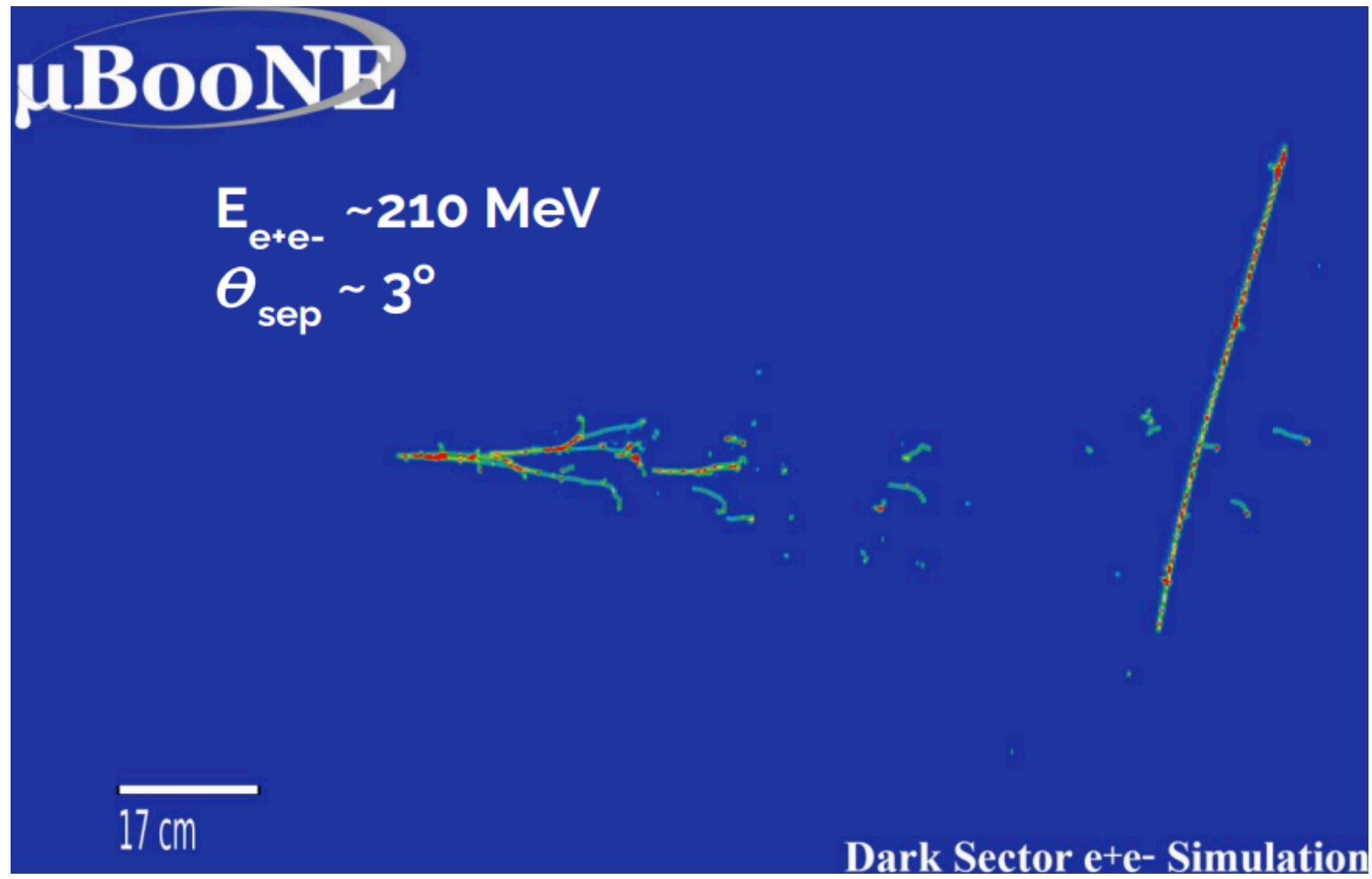


LEE Search (BSM e^+e^-)

BNB

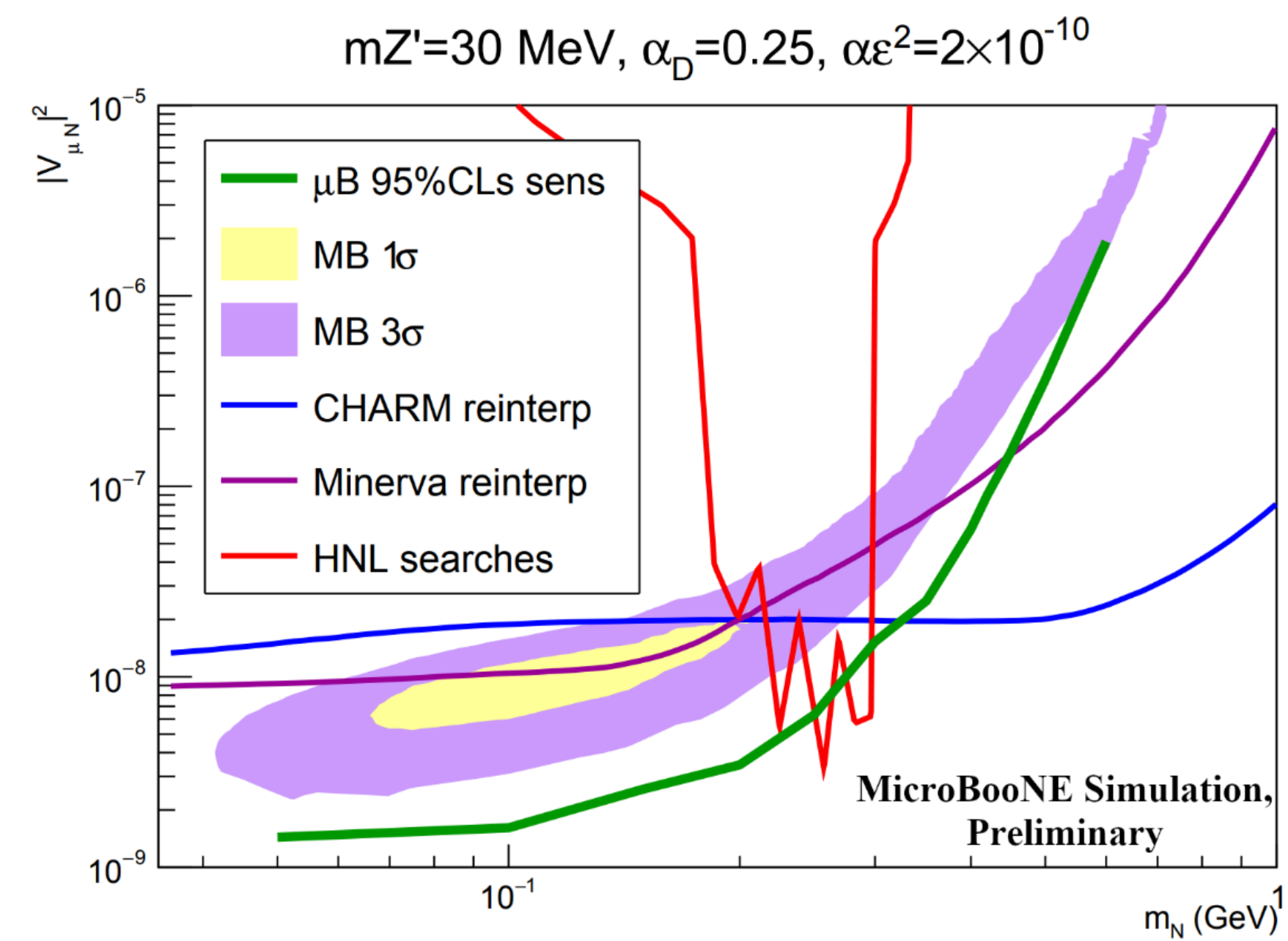


- Dark neutrino models
- Decay into \sim collinear e^+e^- pairs via dark gauge boson, Z'
- Mimics LEE signature with single shower topology
- Single or multiple dark neutrino states

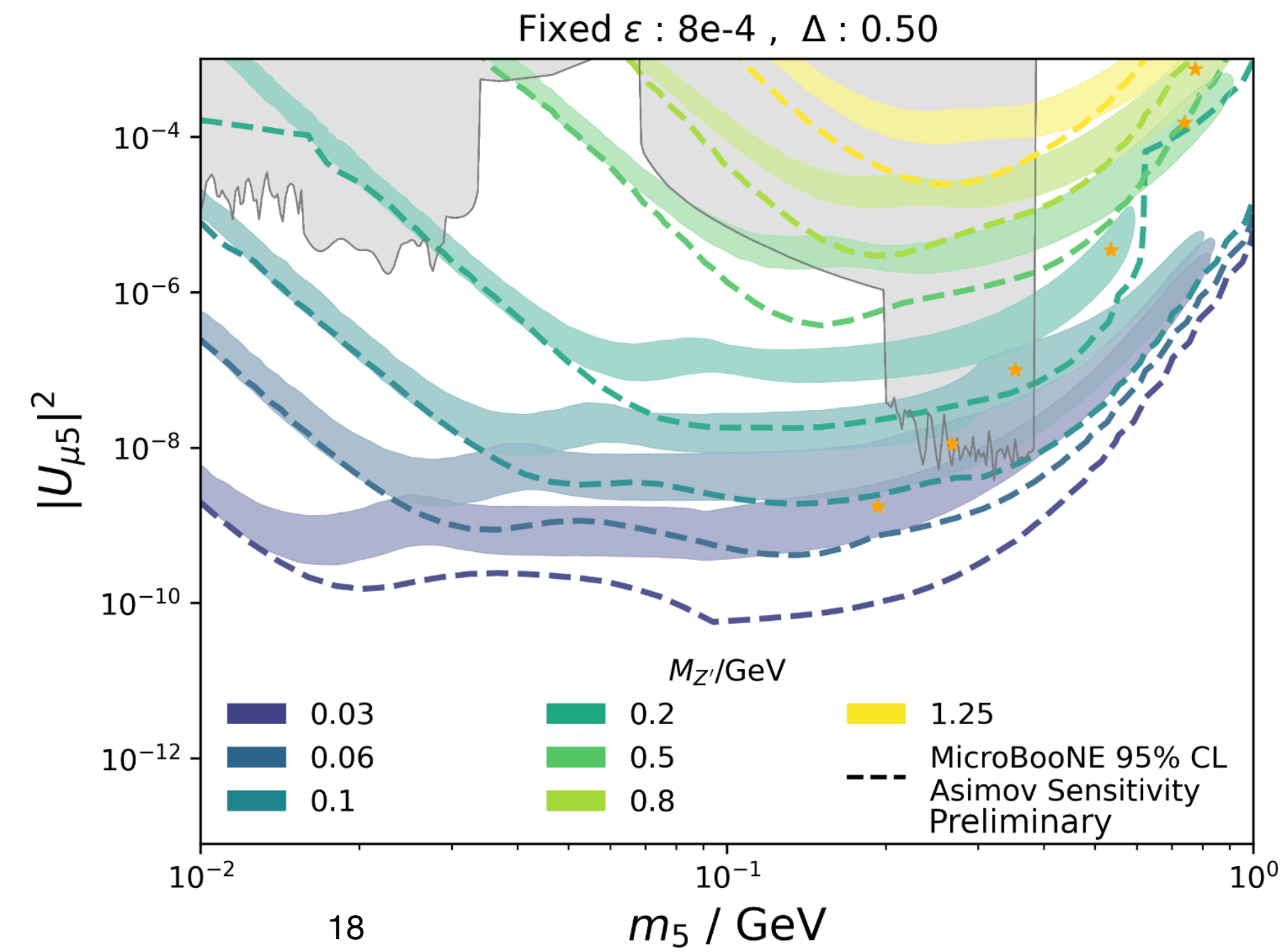


Ballet, Pascoli, Ross-Lonergan
PRD 99 (2019) 071701

Bertuzzo, Jana, Machado,
Zukanovich Funchal
PRL 121 (2018) 24, 241801



MicroBooNE sensitivities



More details at:
[MICROBOONE-NOTE-1124-PUB](#)

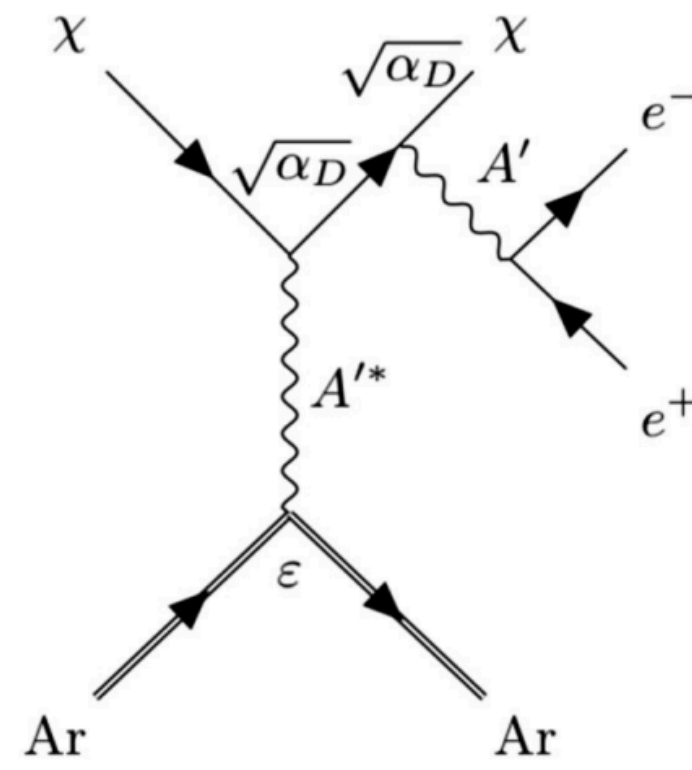
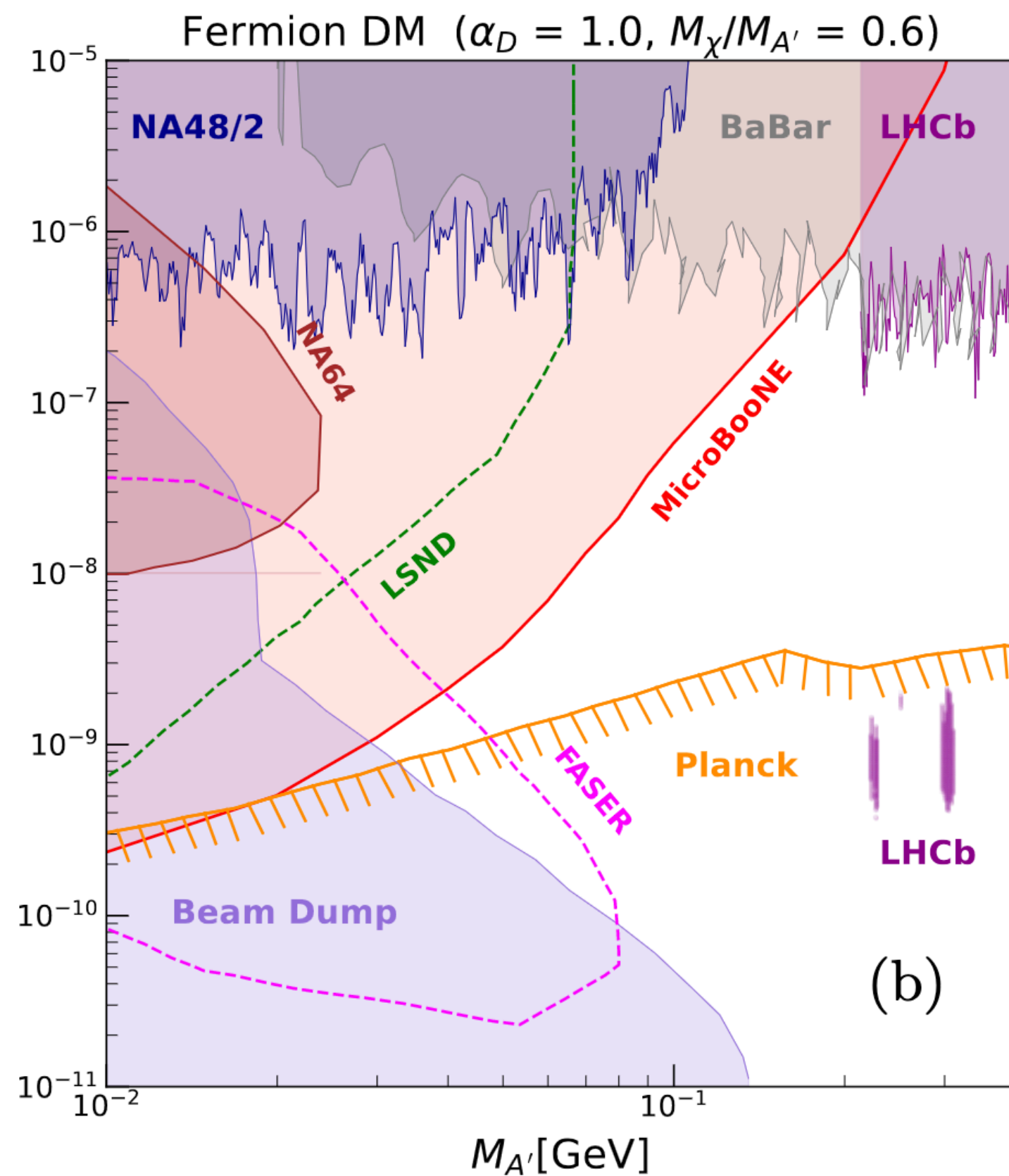
- Anomalous γ and e^+e^- Searches - [Erin Yandel](#)

HNL/Dark Sector Searches

NuMI

New Results! 

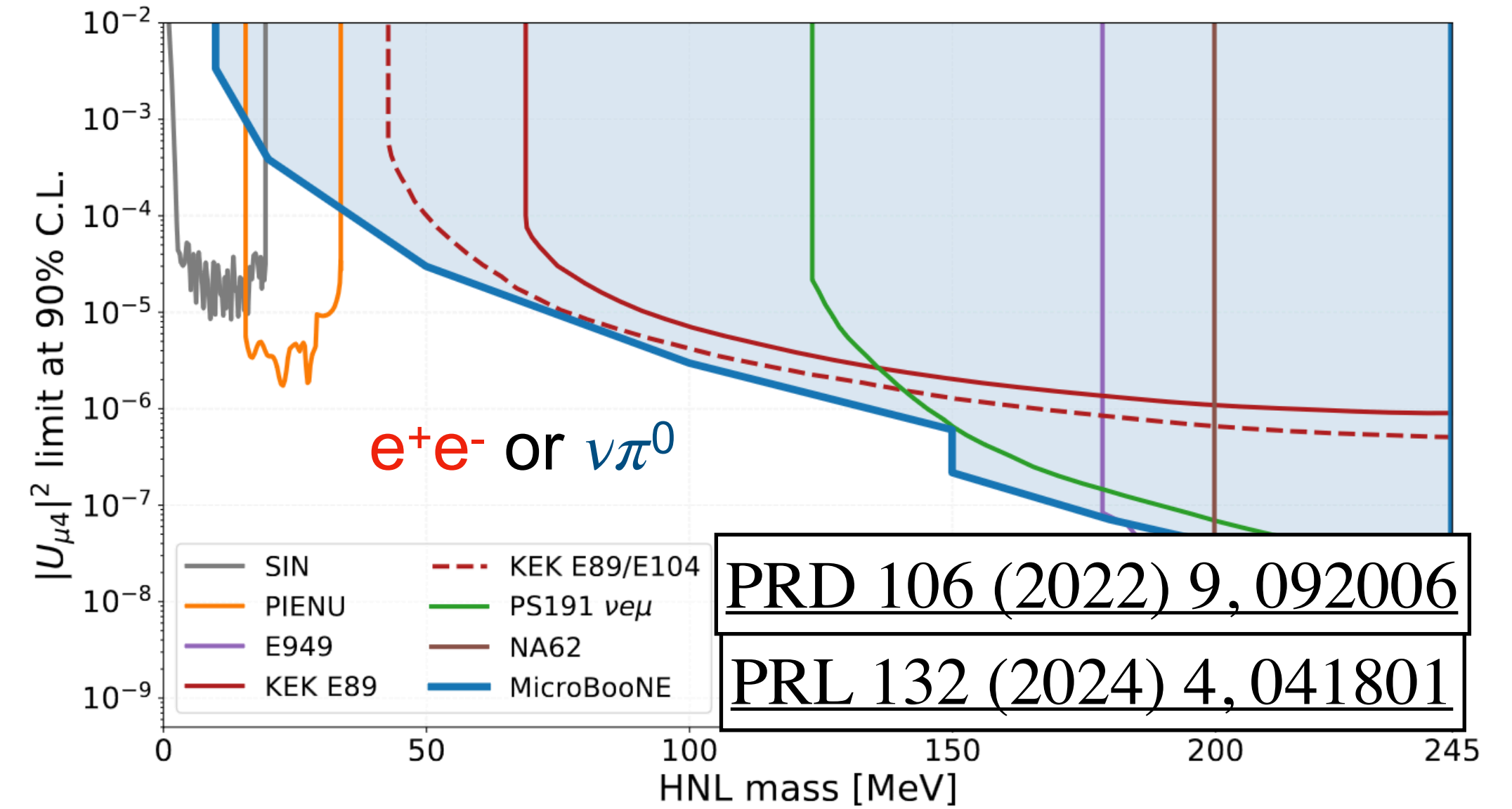
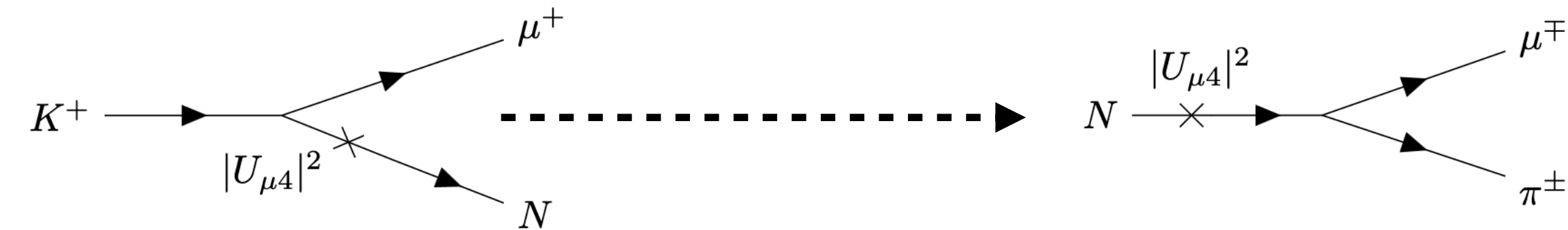
 - MicroBooNE's BSM Program - [Keng Lin](#)



- HNLs relevant for neutrino mass (see-saw), Baryon asymmetry, Dark matter
- Competitive limits across broad range of HNL mass, including < 100 MeV (multiple final states)

produced in beam via mixing

decay in the detector



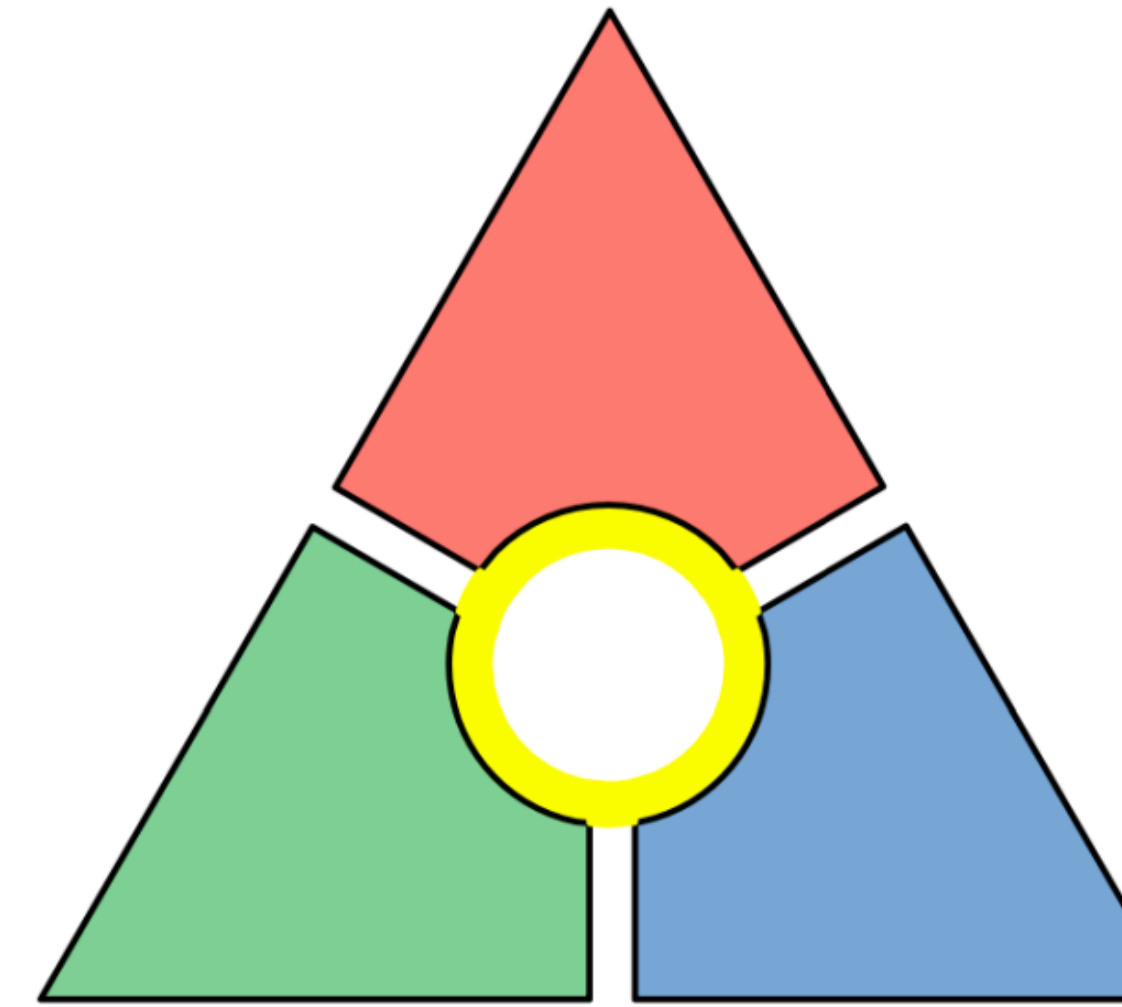
PRD 106 (2022) 9, 092006

PRL 132 (2024) 4, 041801

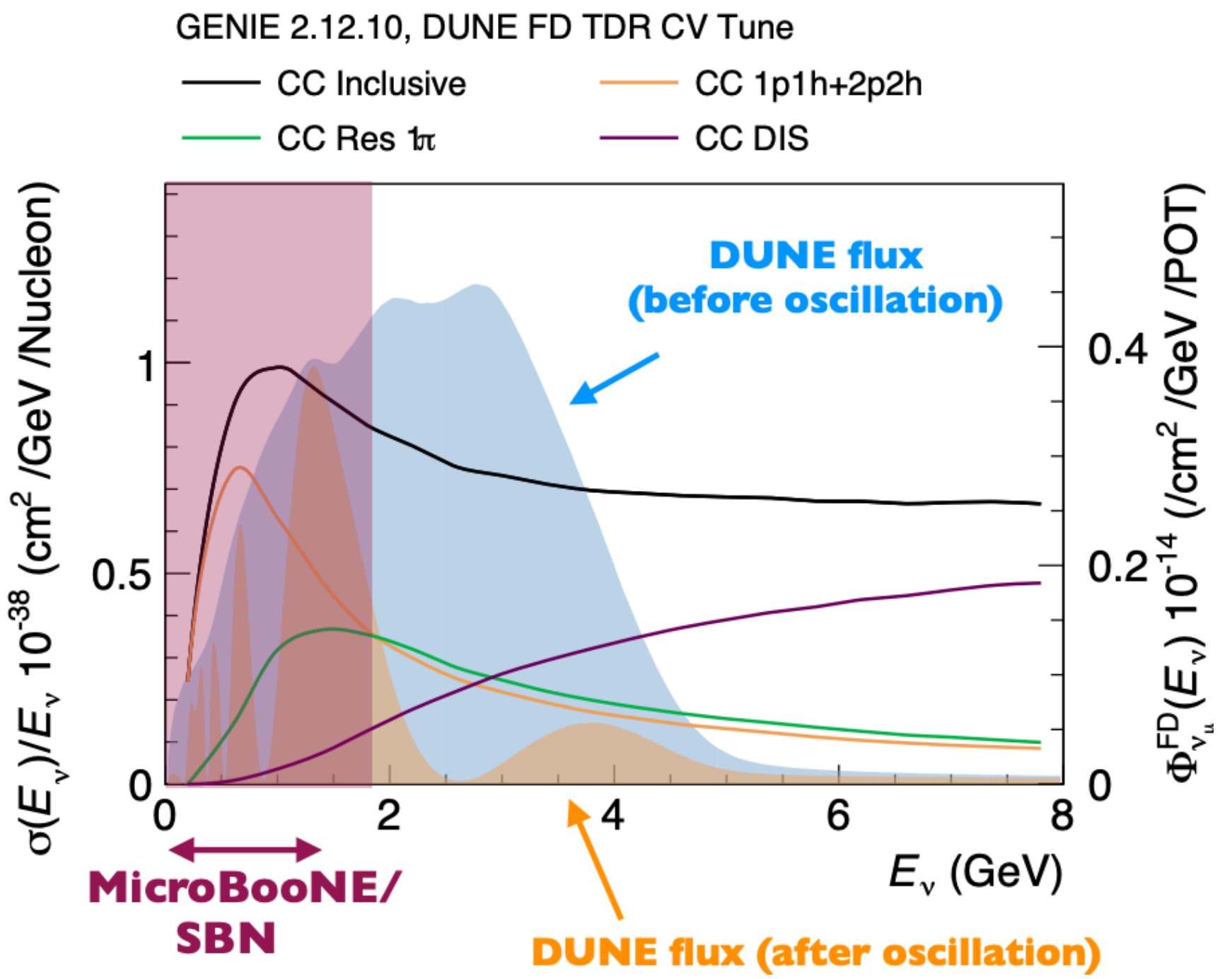
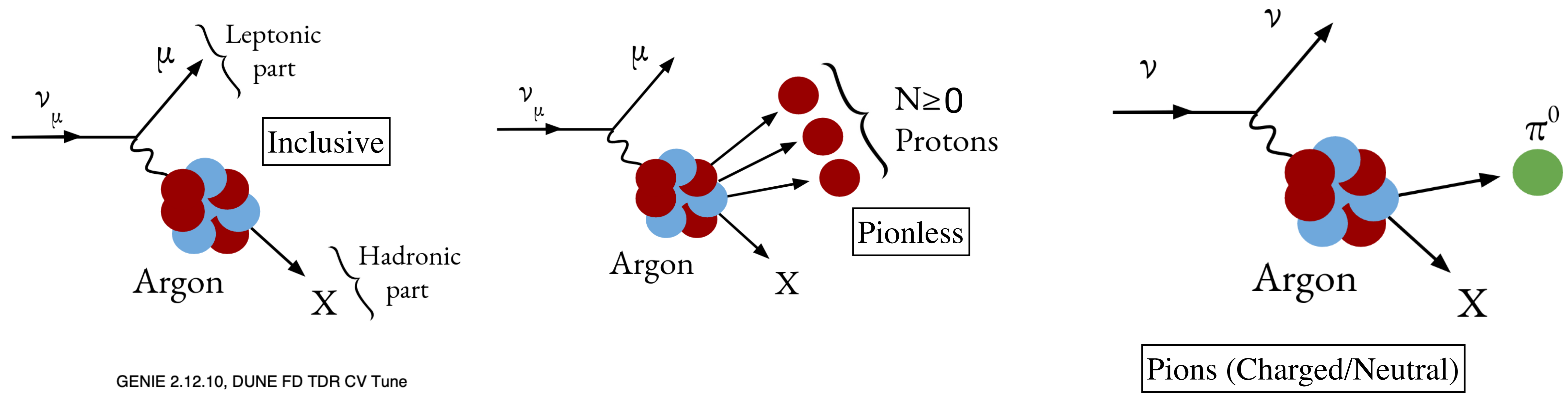
- Dark tridents -> light dark matter production via dark photon mediation -> e^+e^- topologies
- Higgs portal searches -> scalar Higgs produced via kaon decay @ NuMI -> di-lepton topologies
- Exploring new phase space and setting competitive limits!

MicroBooNE Science Goals

Looking Ahead to the Future



Neutrino Interactions



- MicroBooNE has a large and comprehensive neutrino cross-section program
- Aims to support both our BSM program and future LArTPC experiments like DUNE
- Probes nuclear effects at the GeV scale across multiple final state topologies

$\nu - Ar$ Datasets from MicroBooNE

CC inclusive

- 1D ν_μ CC inclusive @ BNB, [Phys. Rev. Lett. 123, 131801](#)
- 1D ν_μ CC E_ν @ BNB, [Phys. Rev. Lett. 128, 151801](#)
- 3D CC E_ν @ BNB, [arXiv:2307.06413](#)
- 1D ν_e CC inclusive @ NuMI, [Phys. Rev. D104, 052002](#)
[Phys. Rev. D105, L051102](#)
- 2D ν_μ CC0pNp inclusive @ BNB, [arXiv:2402.19216](#), [arXiv:2402.19281](#)

Pion production

- ν_μ NC π^0 @ BNB, [Phys. Rev. D 107, 012004](#)
- 2D ν_μ NC π^0 @ BNB, [arXiv:2404.10948](#)
- ν_μ CC π^0 @ BNB, [arXiv:2404.09949](#)

CC0 π

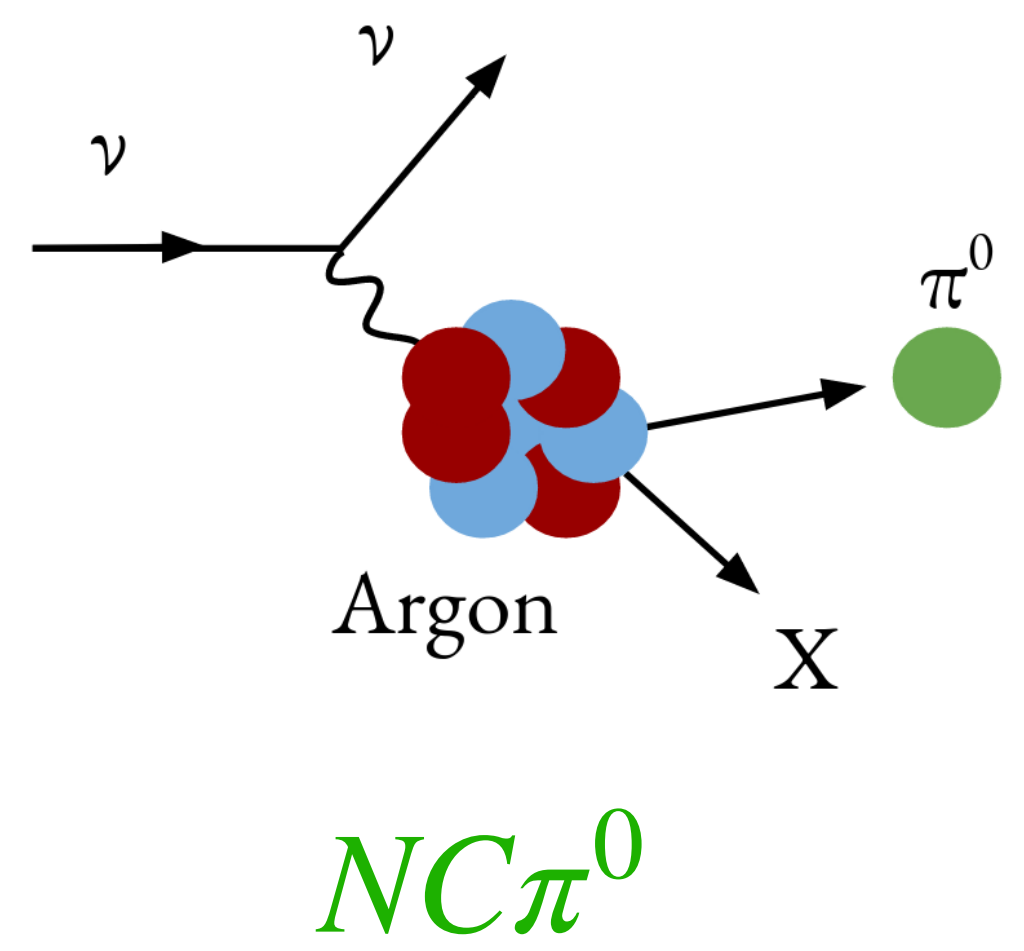
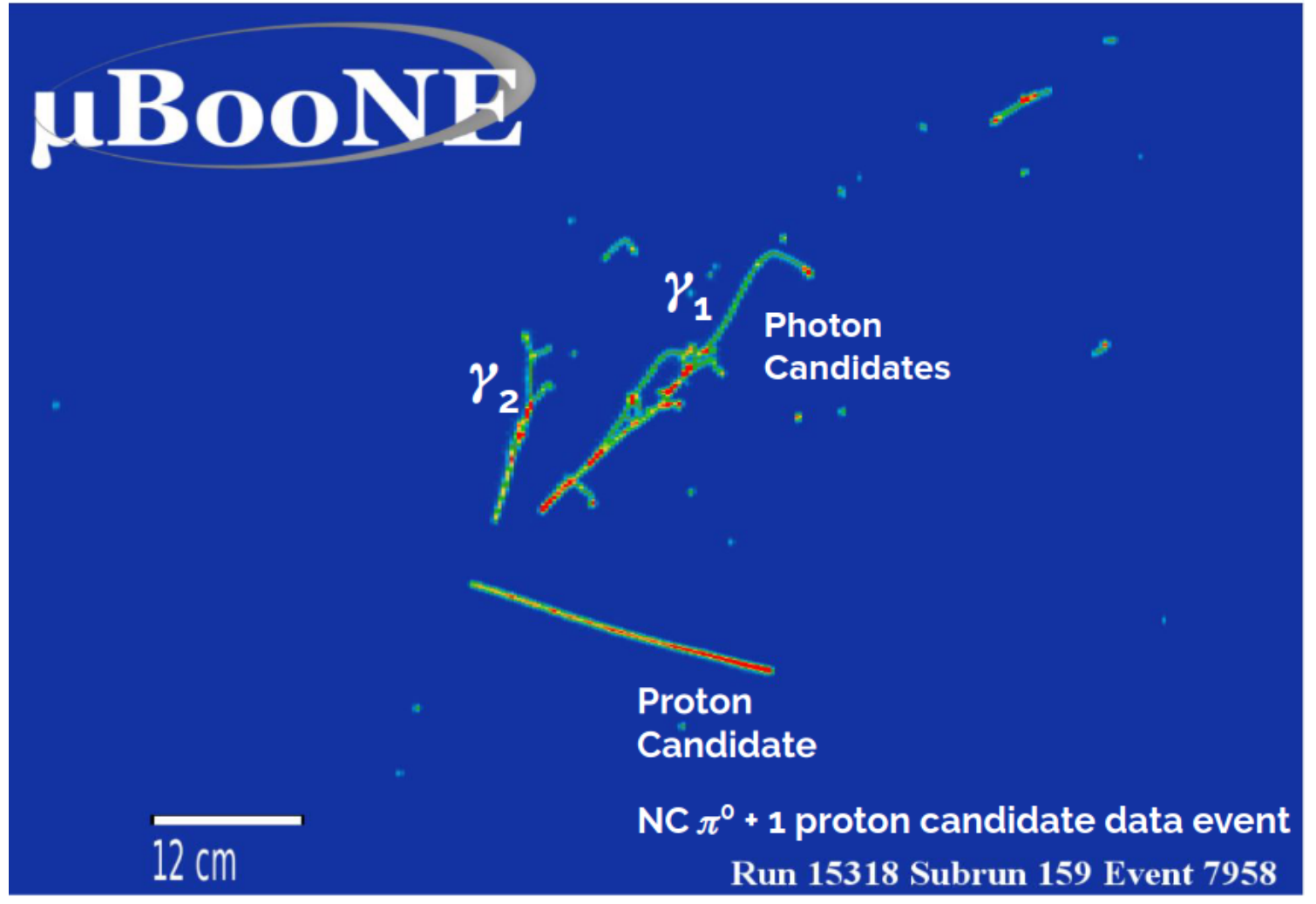
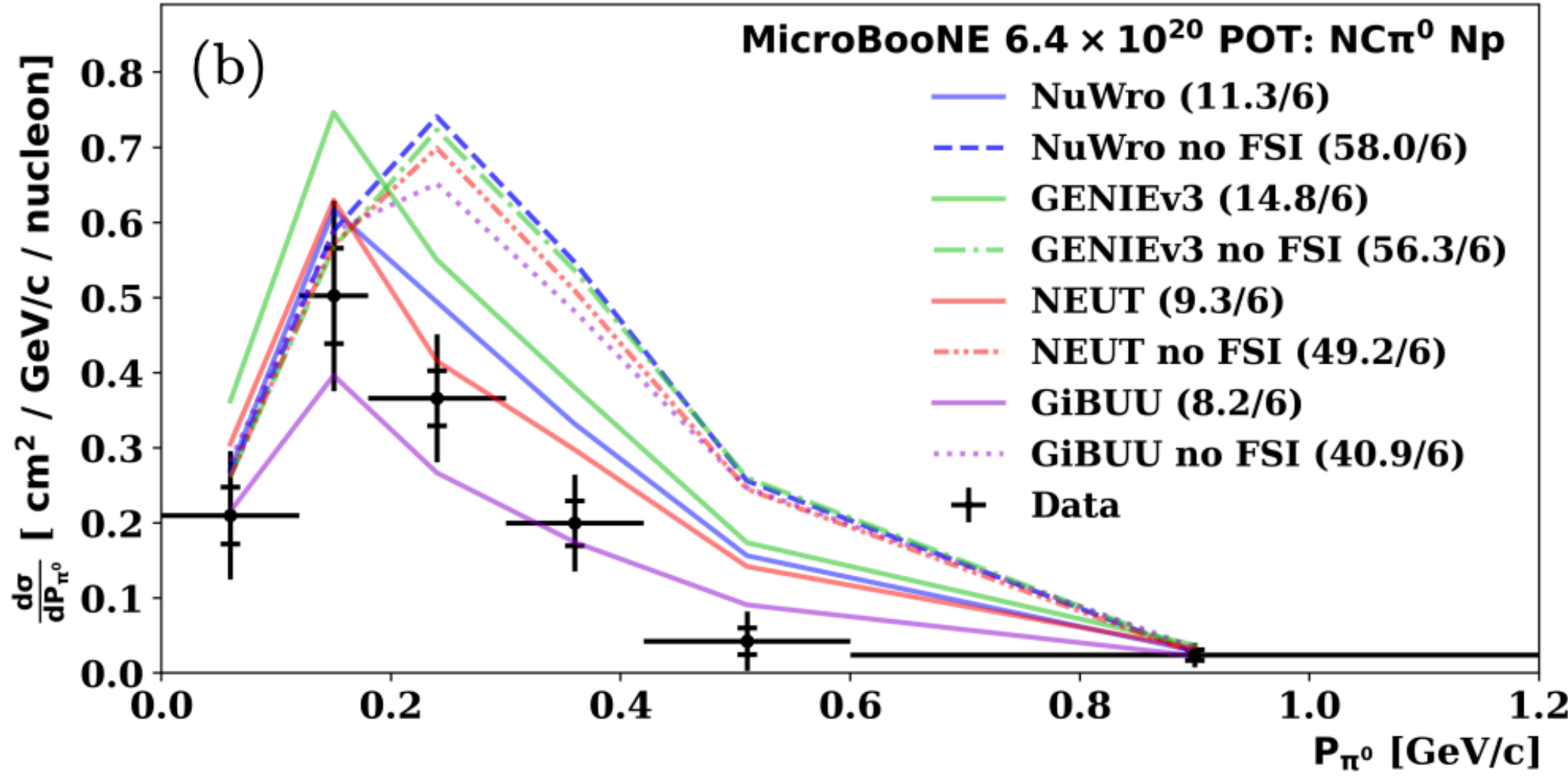
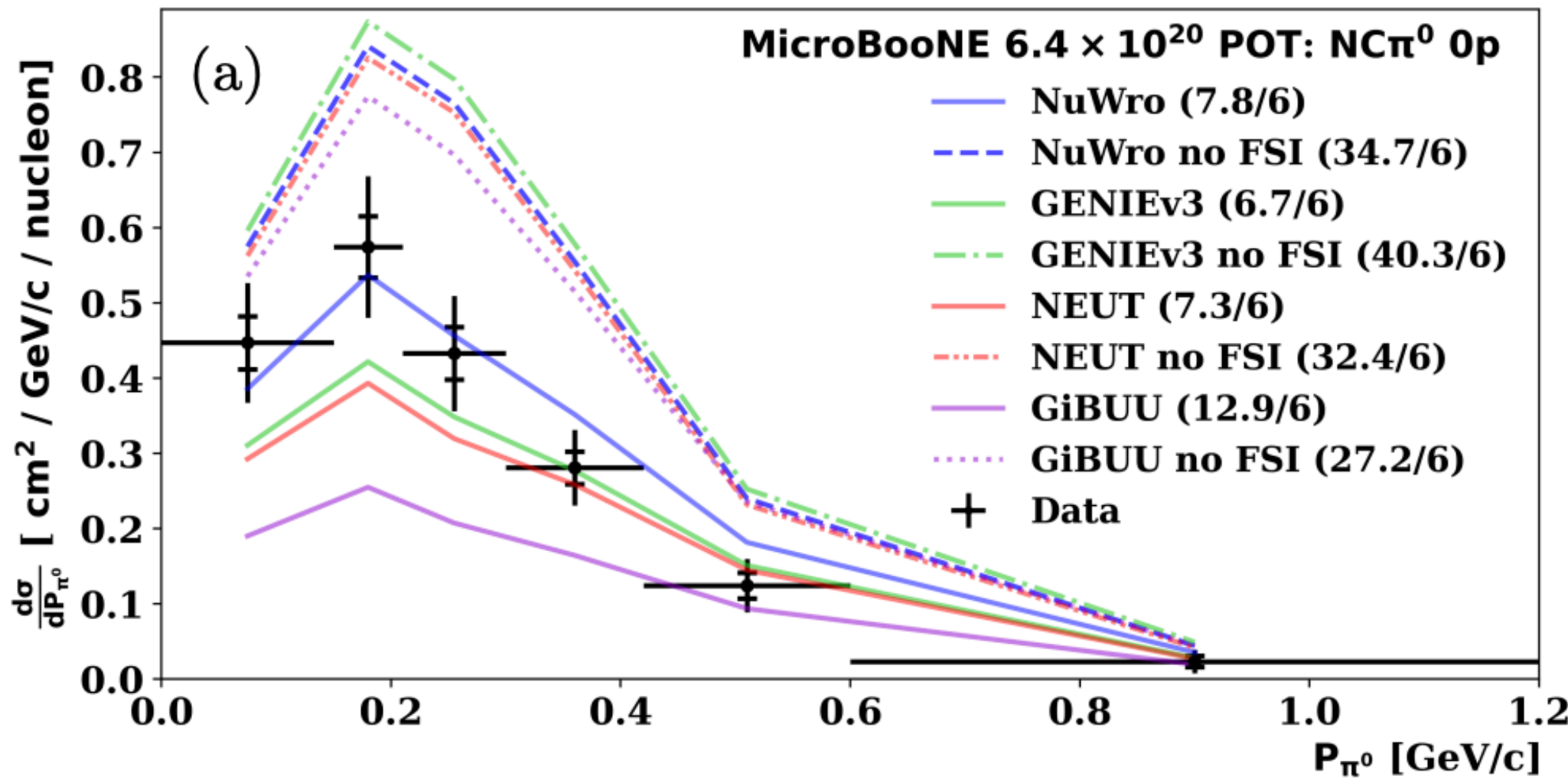
- 1D ν_e CCNp0 π @ BNB, [Phys. Rev. D 106, L051102](#)
- 1D & 2D ν_μ CC1p0 π transverse imbalance @ BNB, [Phys. Rev. Lett. 131, 101802](#)
[Phys. Rev. D 108, 053002](#)
- 1D & 2D ν_μ CC1p0 π generalized imbalance @ BNB, [Phys. Rev. D 109, 092007](#)
- 1D ν_μ CC1p0 π @ BNB, [Phys. Rev. Lett. 125, 201803](#)
- 1D ν_μ CC2p @ BNB, [arXiv:2211.03734](#)
- 1D ν_μ CCNp0 π @ BNB, [Phys. Rev. D102, 112013](#)
- 2D ν_μ CCNp0 π @ 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](#)

Measurements with Pions


New Results! 

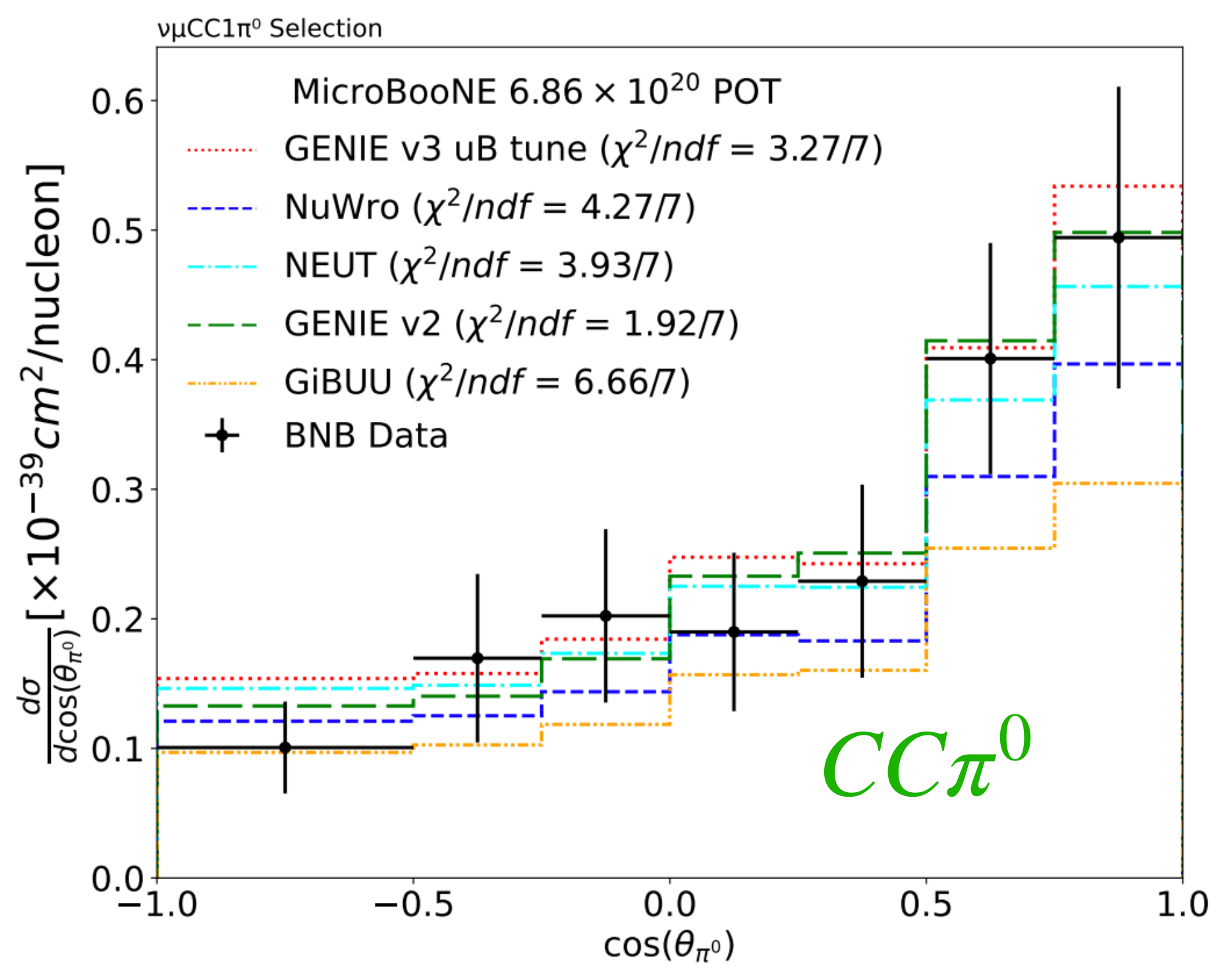
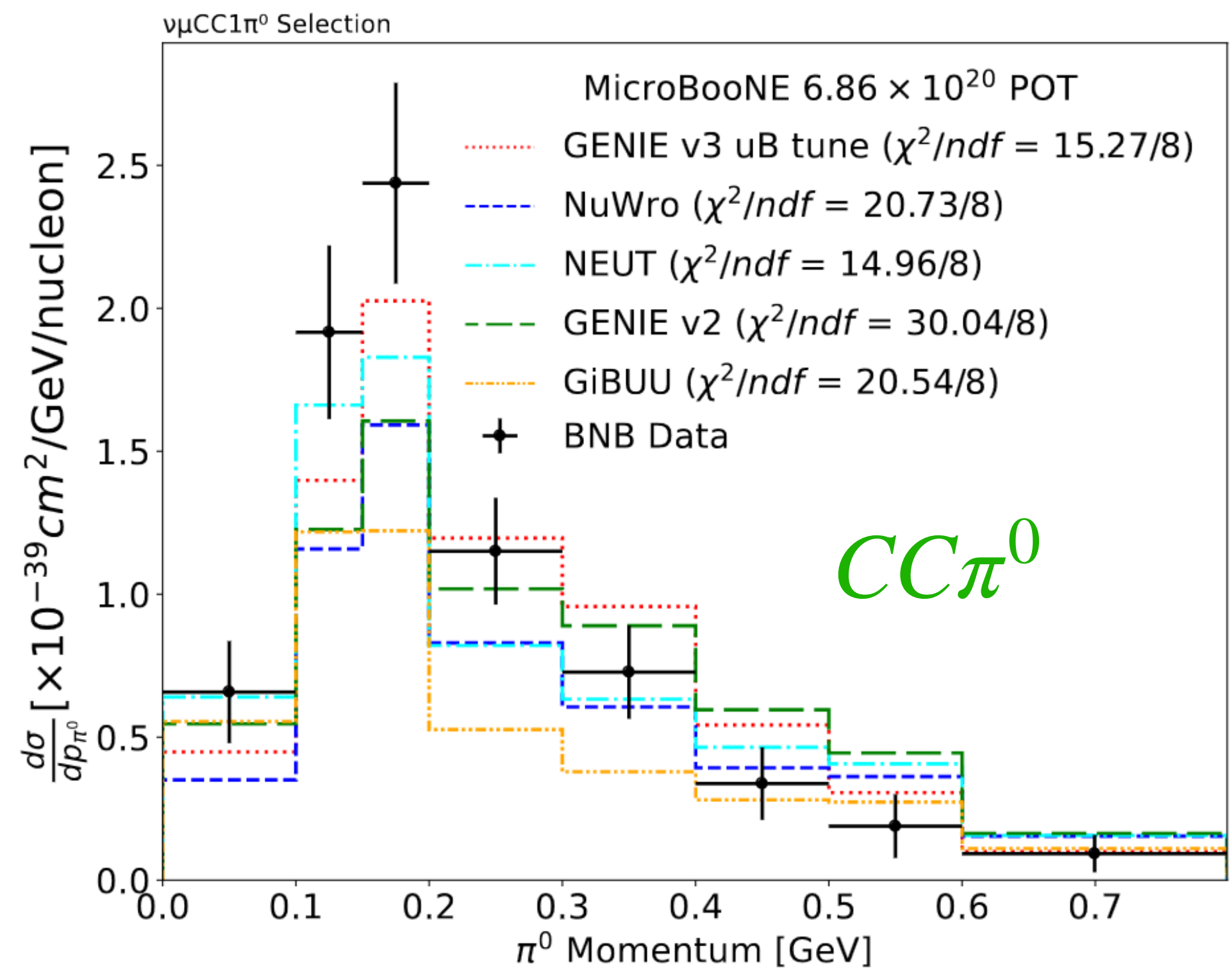


- All single- γ analyses have $NC\pi^0$ as main background
- We have dedicated cross-section measurements for this channel
- Informs not just nuclear modeling uncertainties but acts as an important SM-level handle

 - Pion Production Measurements - Patrick Green


Measurements with Pions

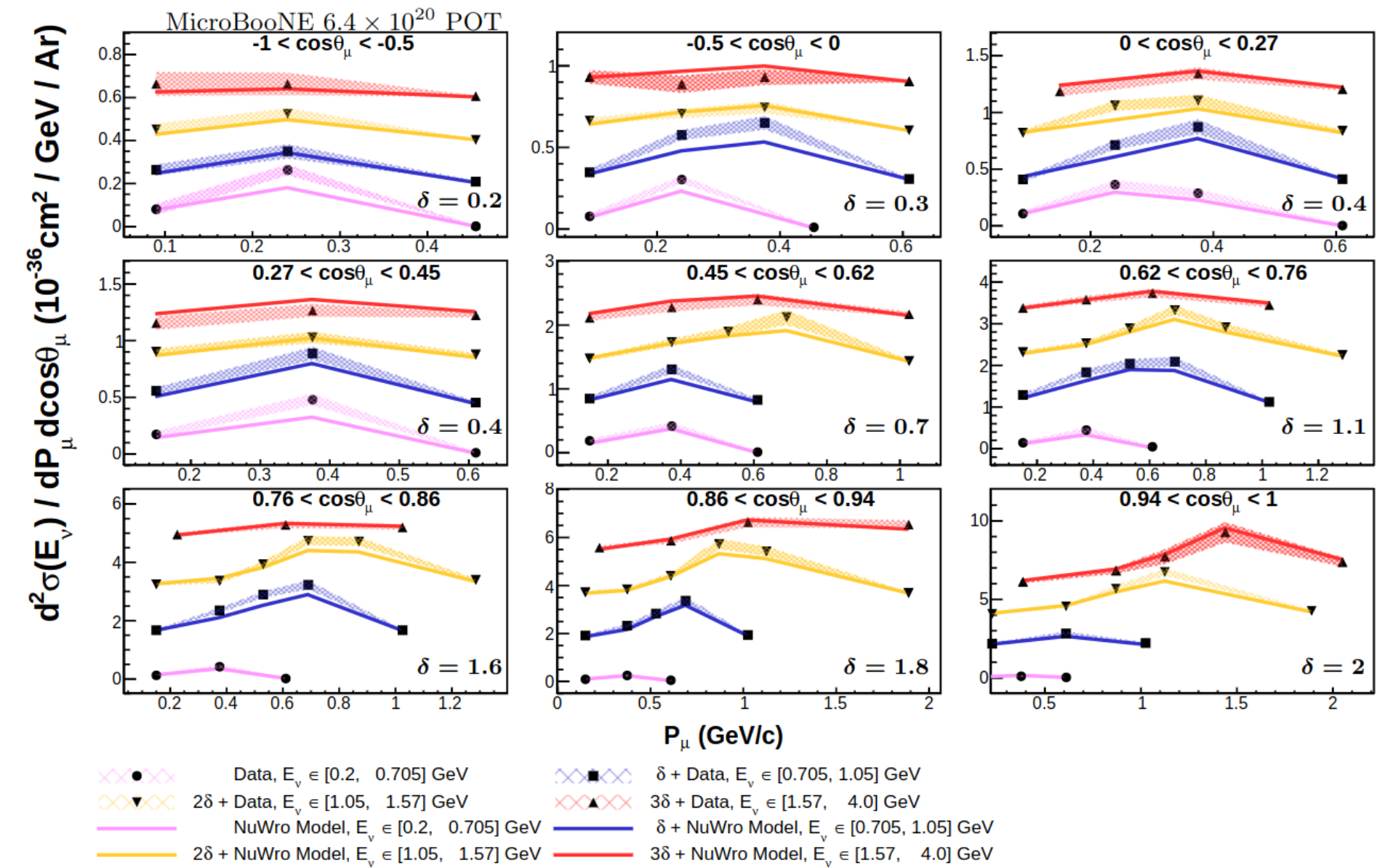
New Results! 



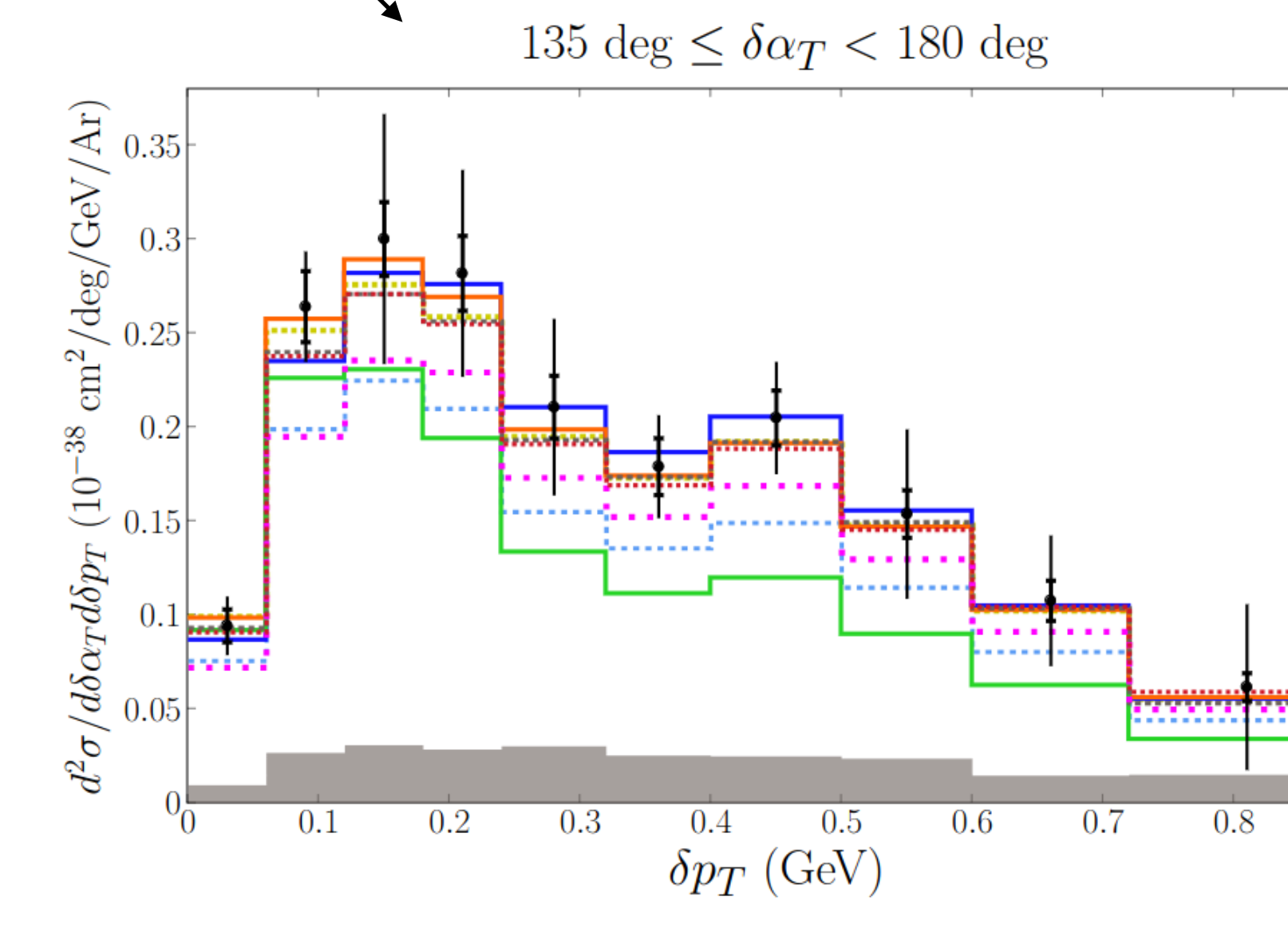
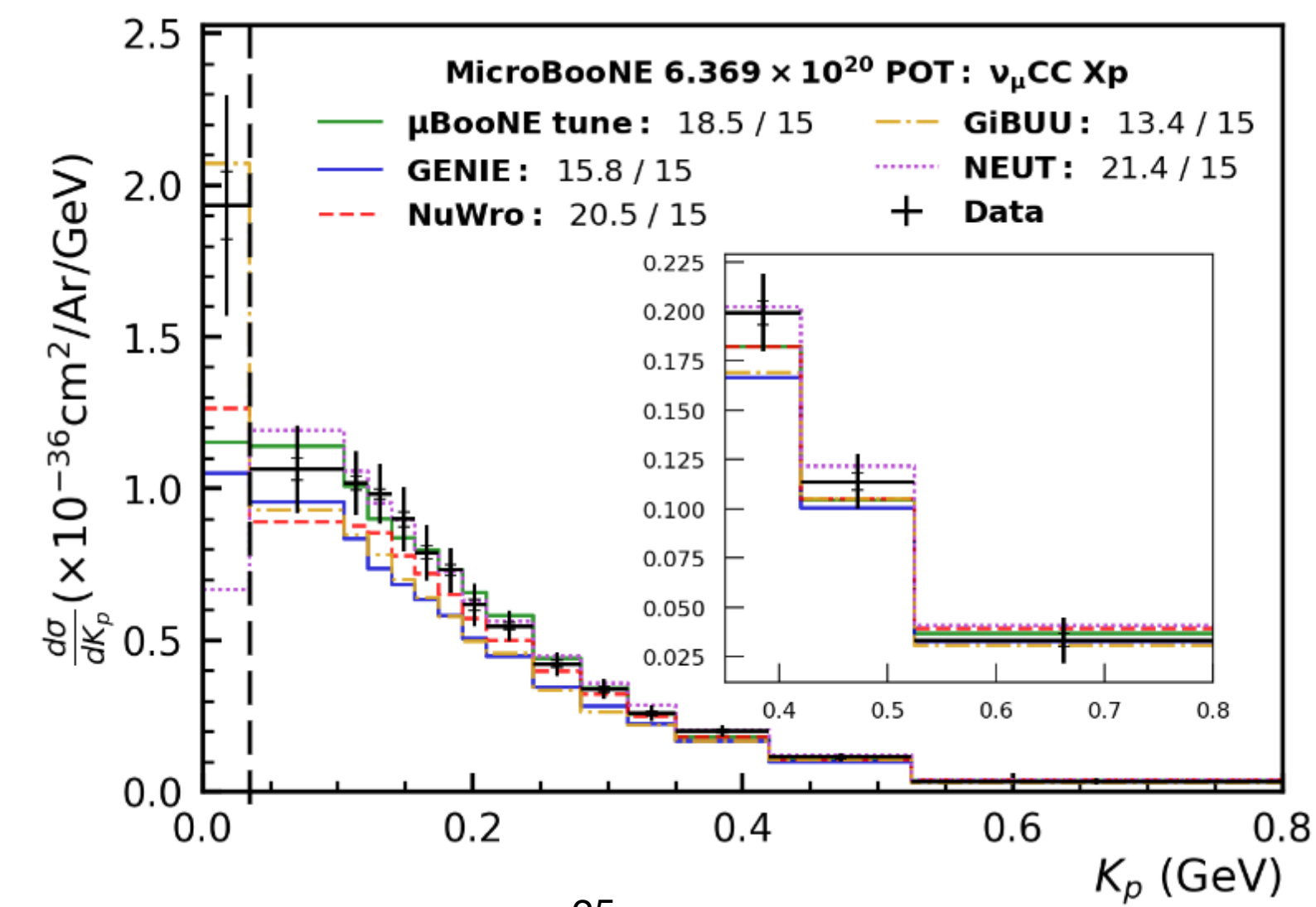
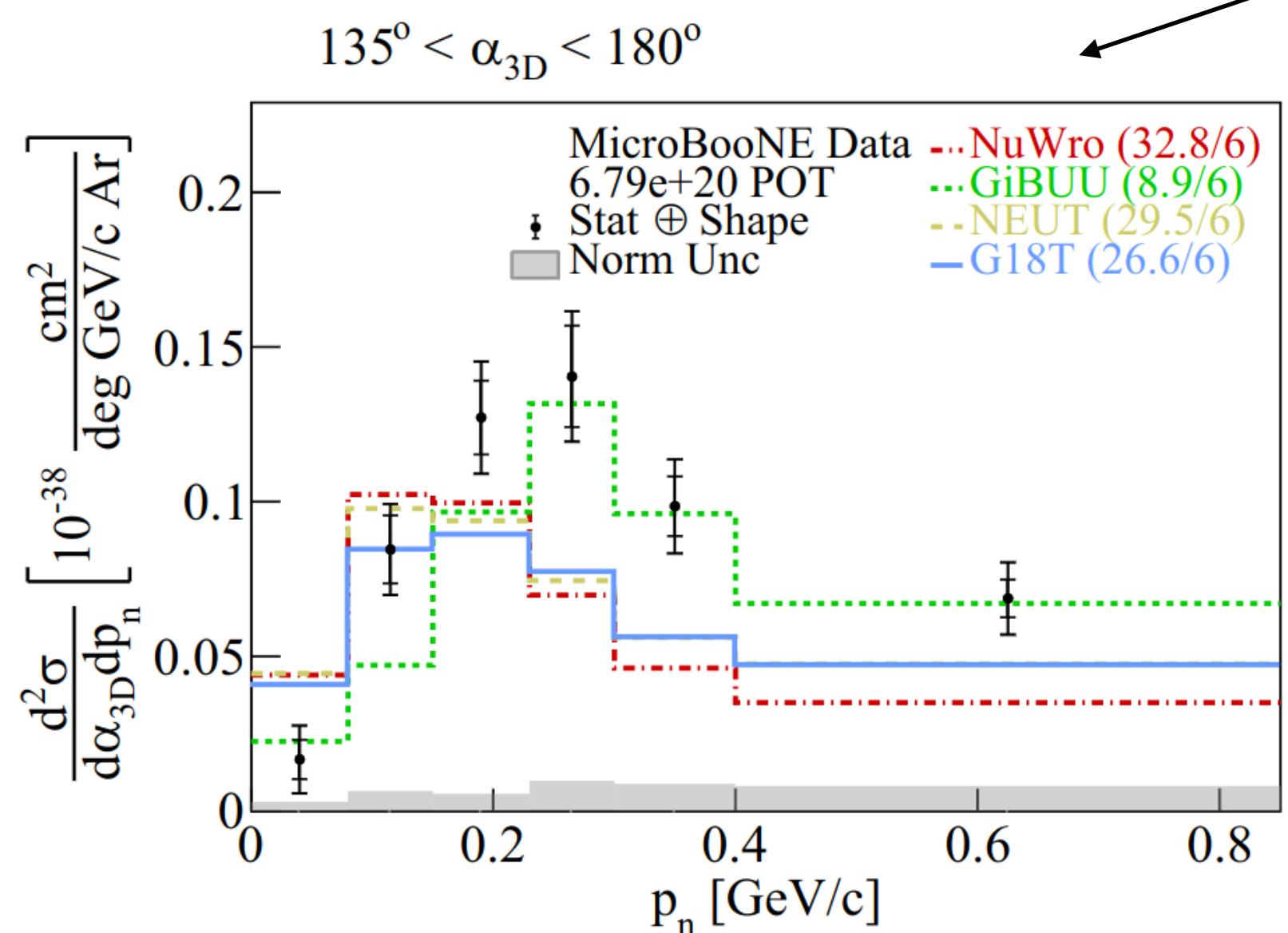
- Measurements in the resonance (RES) regime - $\Delta(1232)$
 - NC and CC π^0 released, π^{\pm} final states also being analysed
 - Detailed description over π^0 kinematics
 - Also able to measure higher order resonances with η -production
 - Novel EM calibration sources, improvements to reconstruction relevant for proton decay @ DUNE
- 🤖 - Pion Production Measurements - [Patrick Green](#)
 - 🤖 - Rare Mesons - [Jairo Rodriguez](#)
 - 🤖 - Charged Pions - [Philip Detje](#)

$\nu_\mu CC$ Inclusive + Pionless


New Results! 

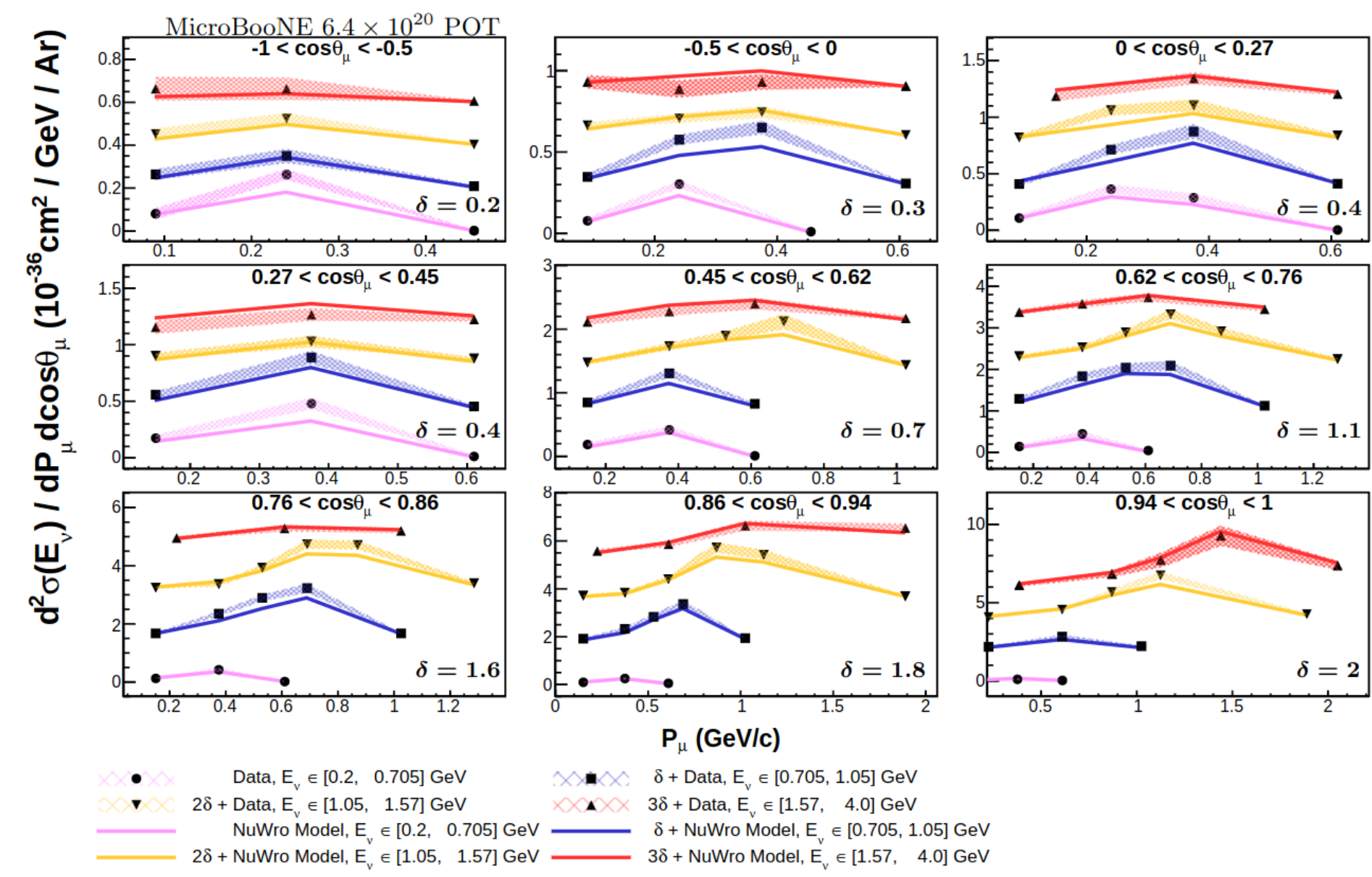


- High statistics based, 3D phase space coverage with $\sigma(E_\nu, P_\mu, \cos\theta_\mu)$ measurement
- Further probe hadronic modeling using $0p/Np$ topologies
- Measurement in kinematic imbalance variables (missing momentum etc) to get sensitive probe into final-state interactions and other nuclear effects
- Significant model discrimination power across the board! Will inform next generation improvements in interaction model

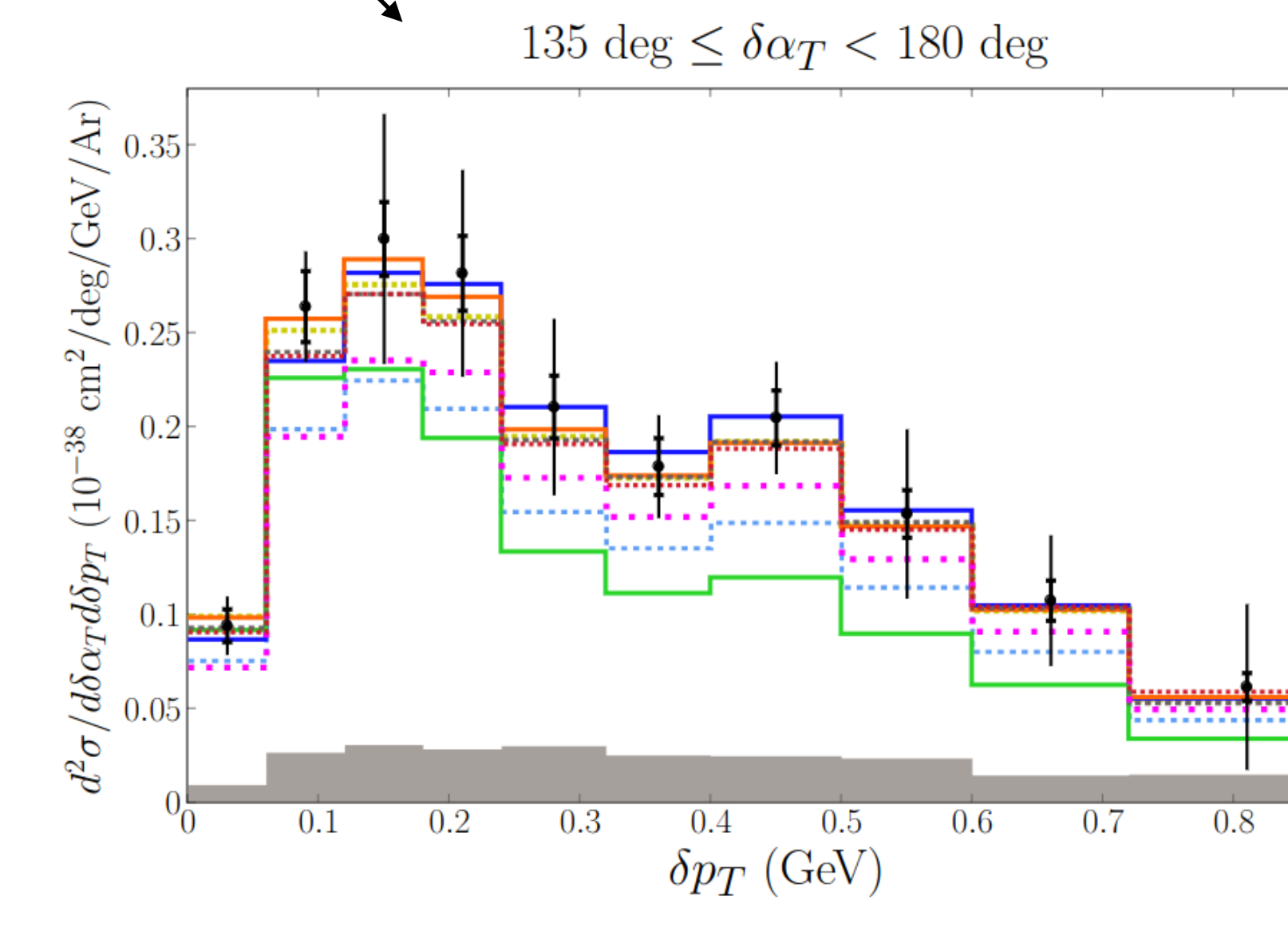
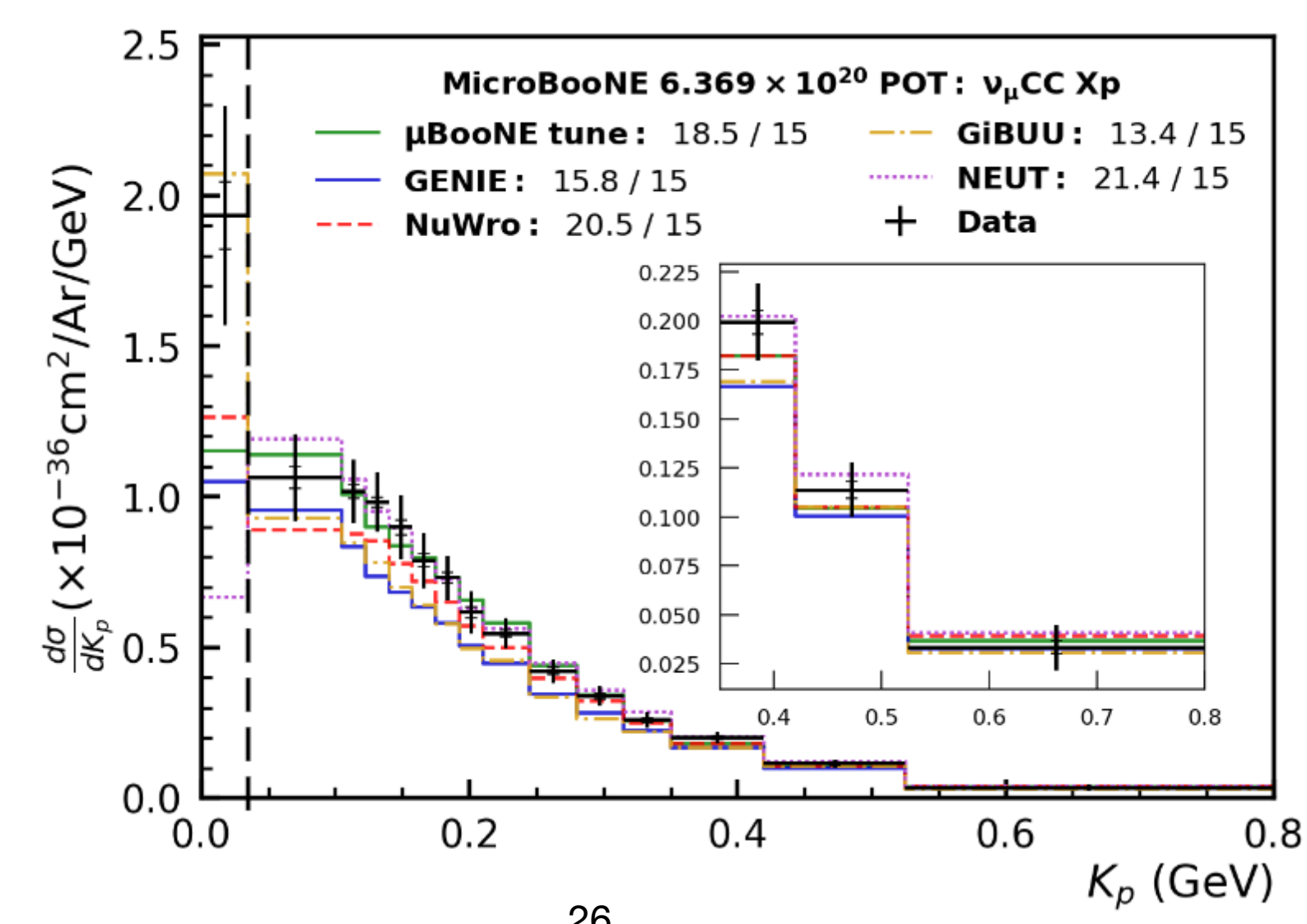
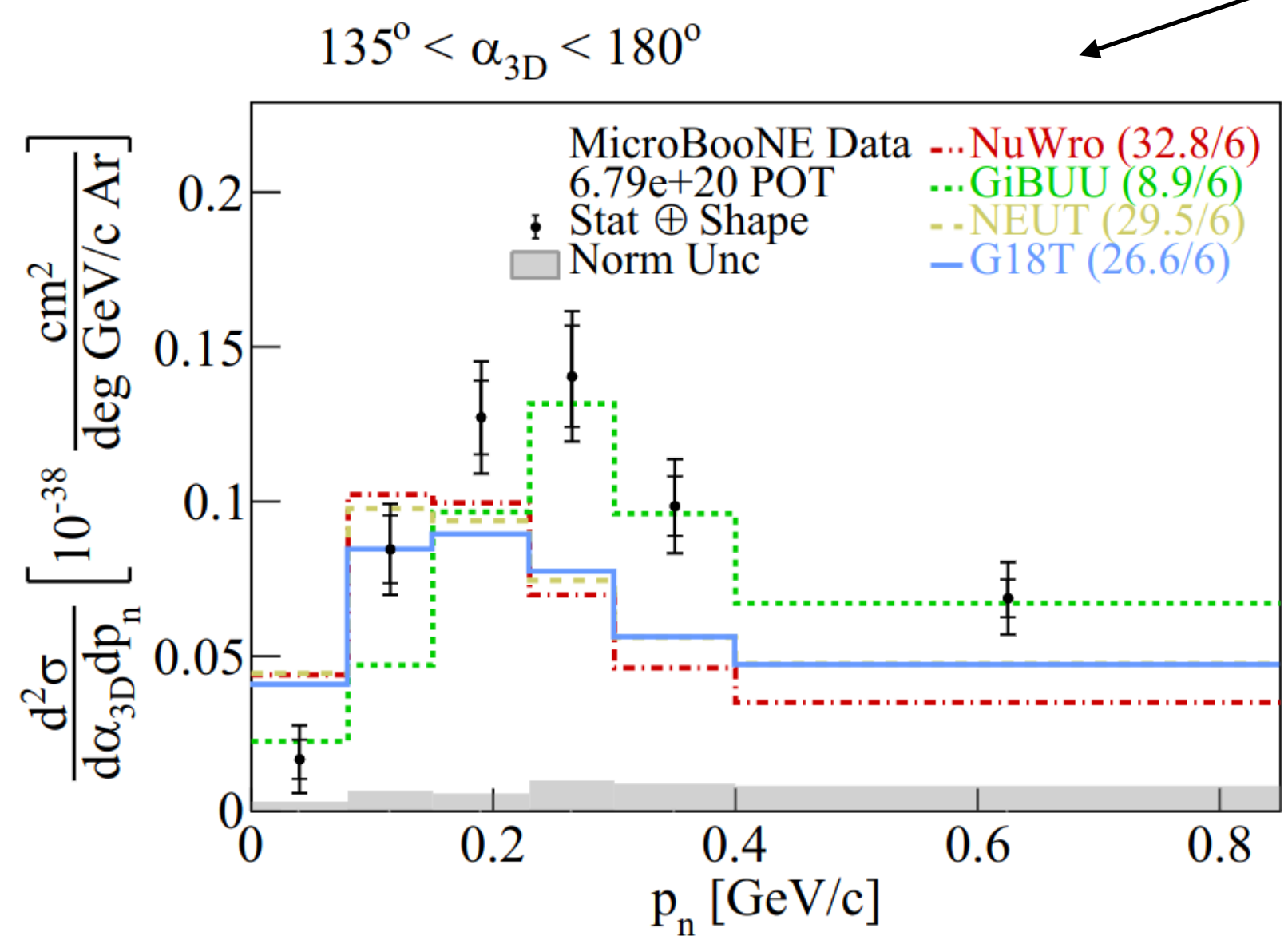


$\nu_\mu CC$ Inclusive + Pionless

New Results! 



- 🤔 - Inclusive and Pionless Measurements - Dan Barrow
- 🤔 - $\nu_\mu CC$ Inclusive - London Cooper-Troendle
- 🤔 - $\nu_\mu CC 2p$ - Dan Barrow
- 🤔 - $\nu_\mu CC 0\pi$ - Panos Englezos
- 🤔 - $\nu_\mu CC 0p/Np$ - Ben Bogart

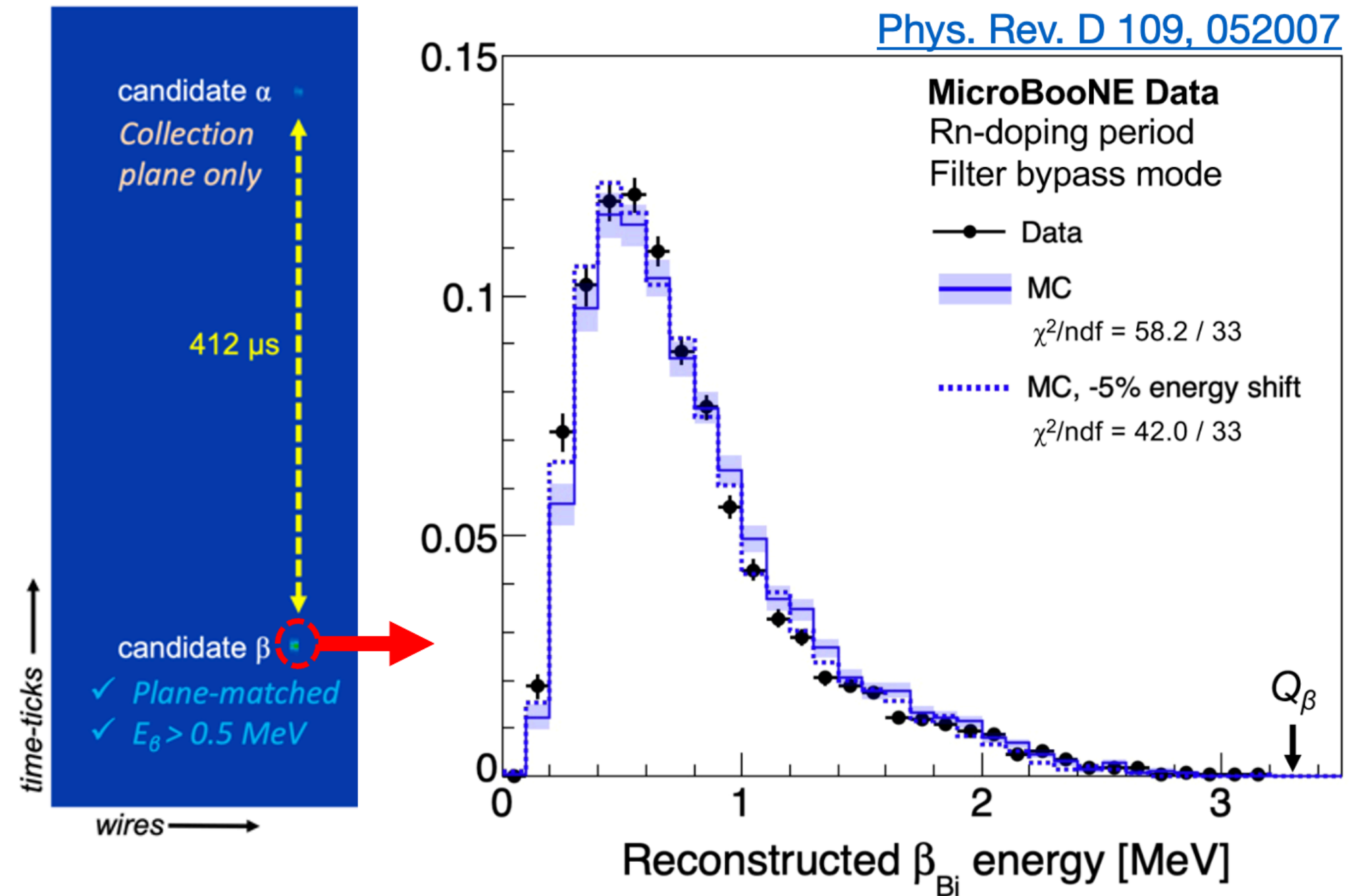
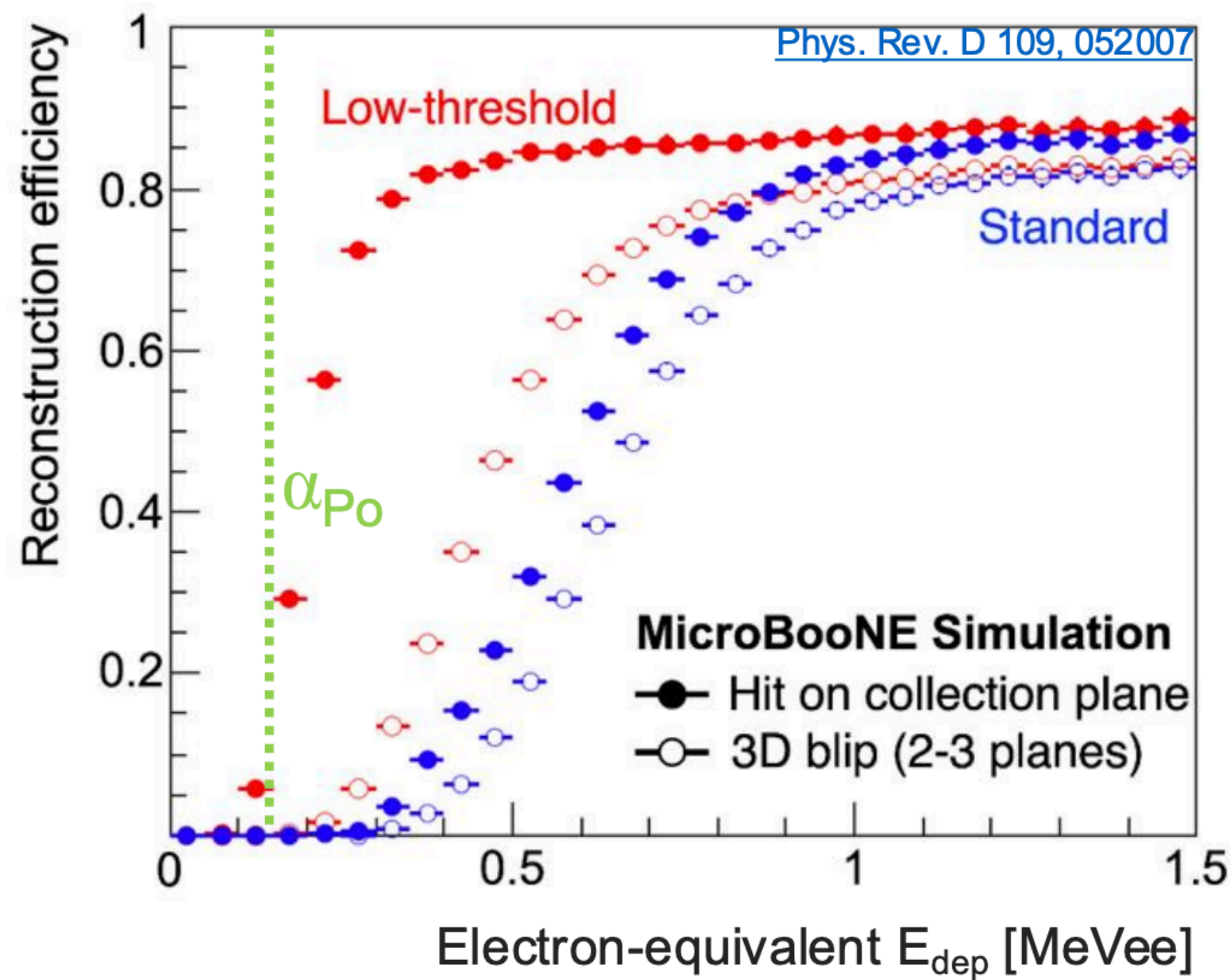


MeV-scale physics

New Results! 

[PRD109 \(2024\) 052007](#)


$^{214}\text{Bi} \rightarrow ^{214}\text{Po}$ decays



- Techniques to reconstruct “blips” (isolated $\mathcal{O}(\text{MeV})$ energy depositions from various sources) pioneered at ArgoNeut
- Can leverage to dramatically improve thresholds at low energies
- Measurements of Rn^{222} decays during calibration runs
 - Important for assessing radiopurity and radiological backgrounds
 - Important for DUNE supernova and BSM physics

- 🤔 - MeV-Scale Radon Measurements - [Will Foreman](#)
- 🤔 - MeV-Scale Physics - [Diego Andrade](#)

Novel LArTPC techniques

New Results! 

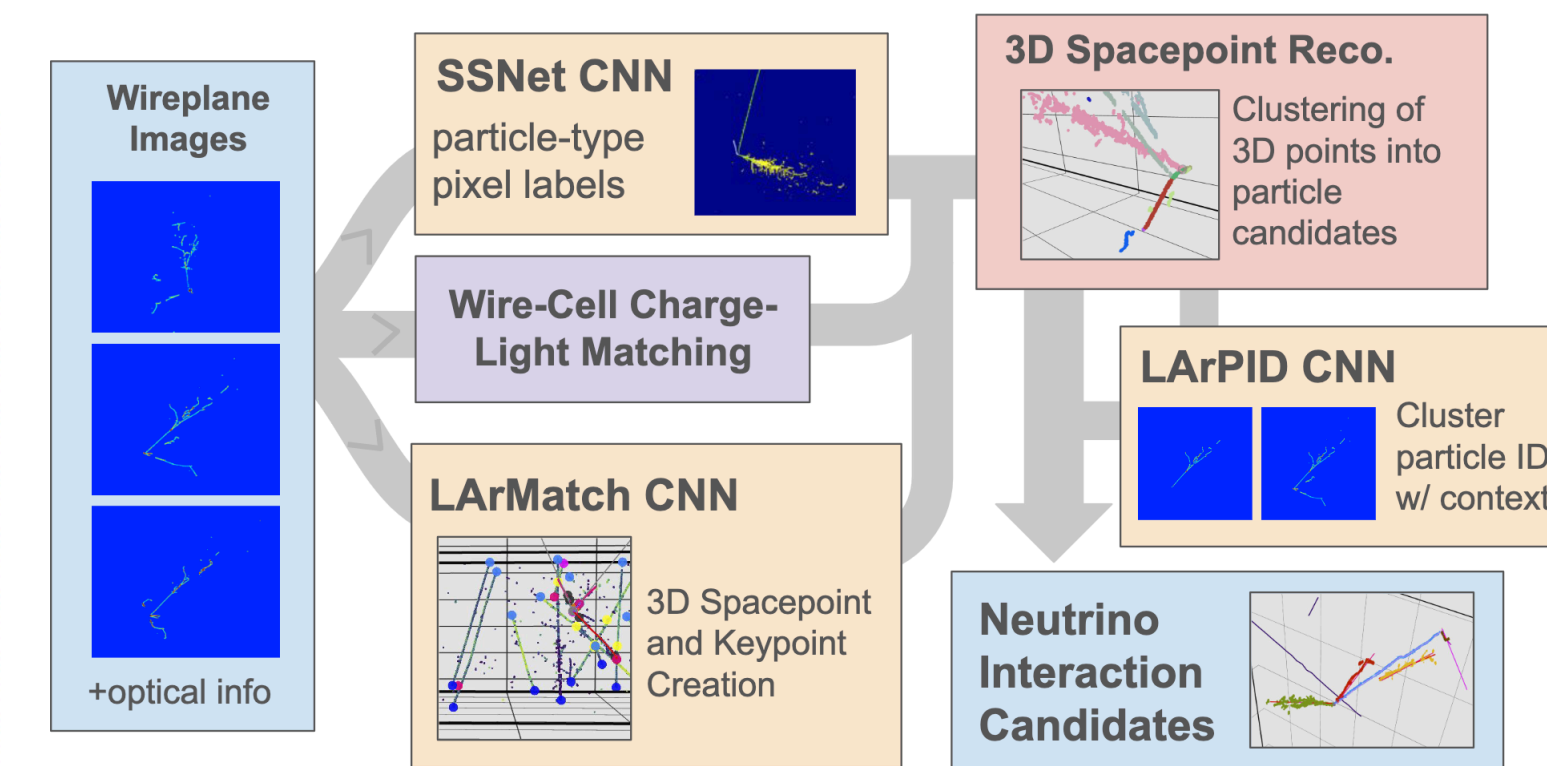
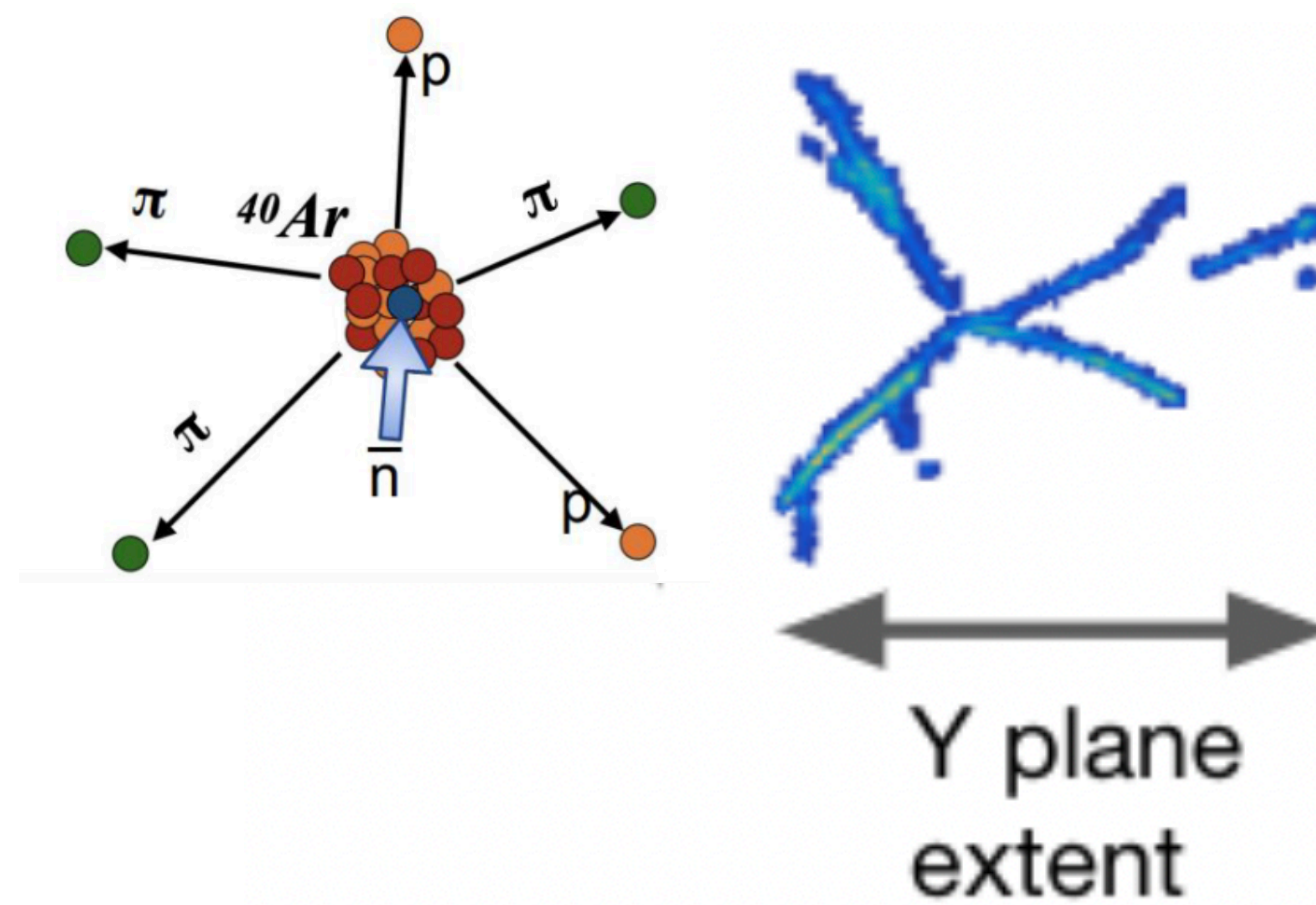
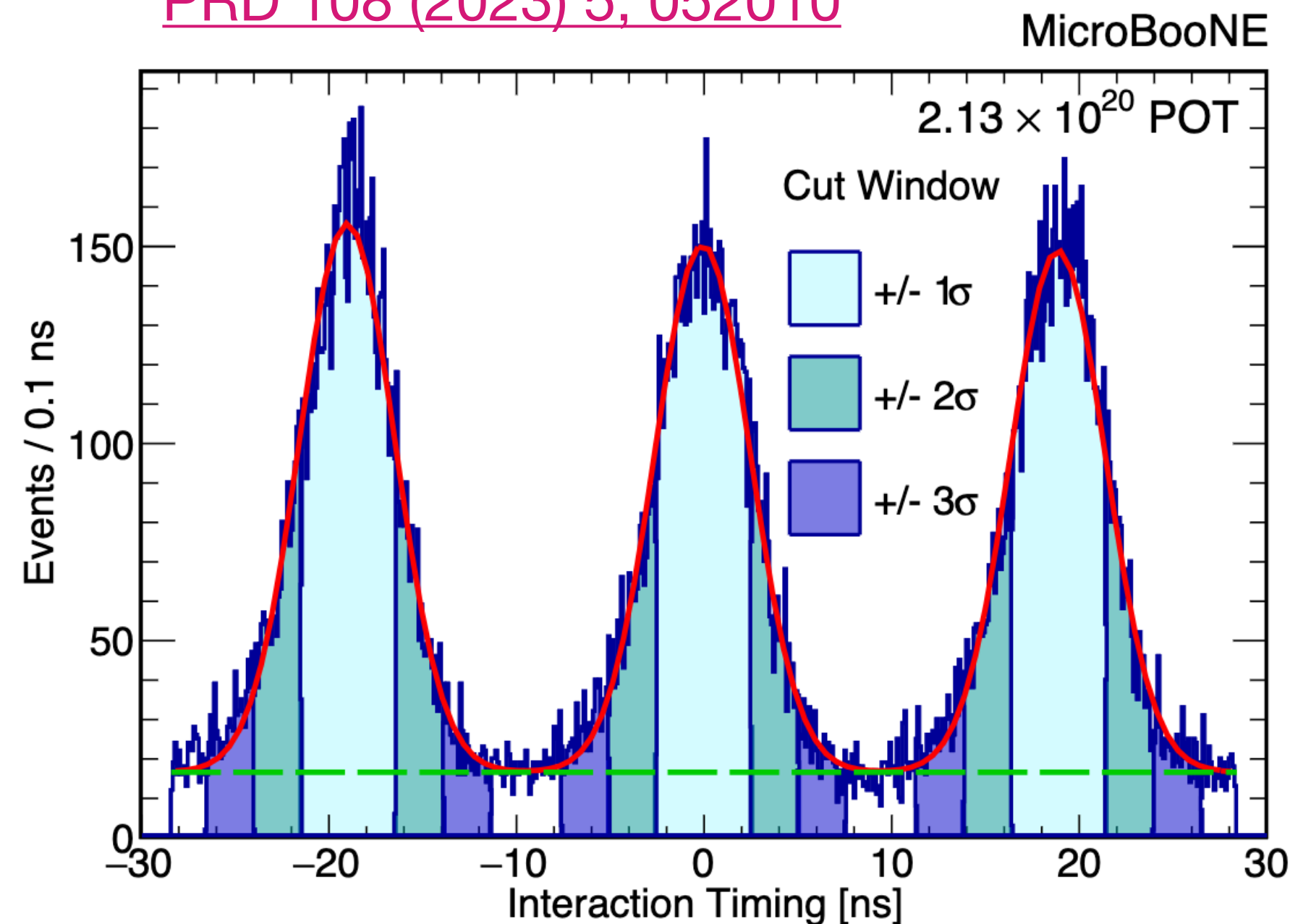
nanosecond beam timing in LArTPCs

First n-nbar demonstration in LArTPCs!

Other Deep-learning based reconstruction

[PRD 108 \(2023\) 5, 052010](#)

[JINST \(2024\) 19 P07032](#)



[MICROBOONE-NOTE-23-PUB](#)

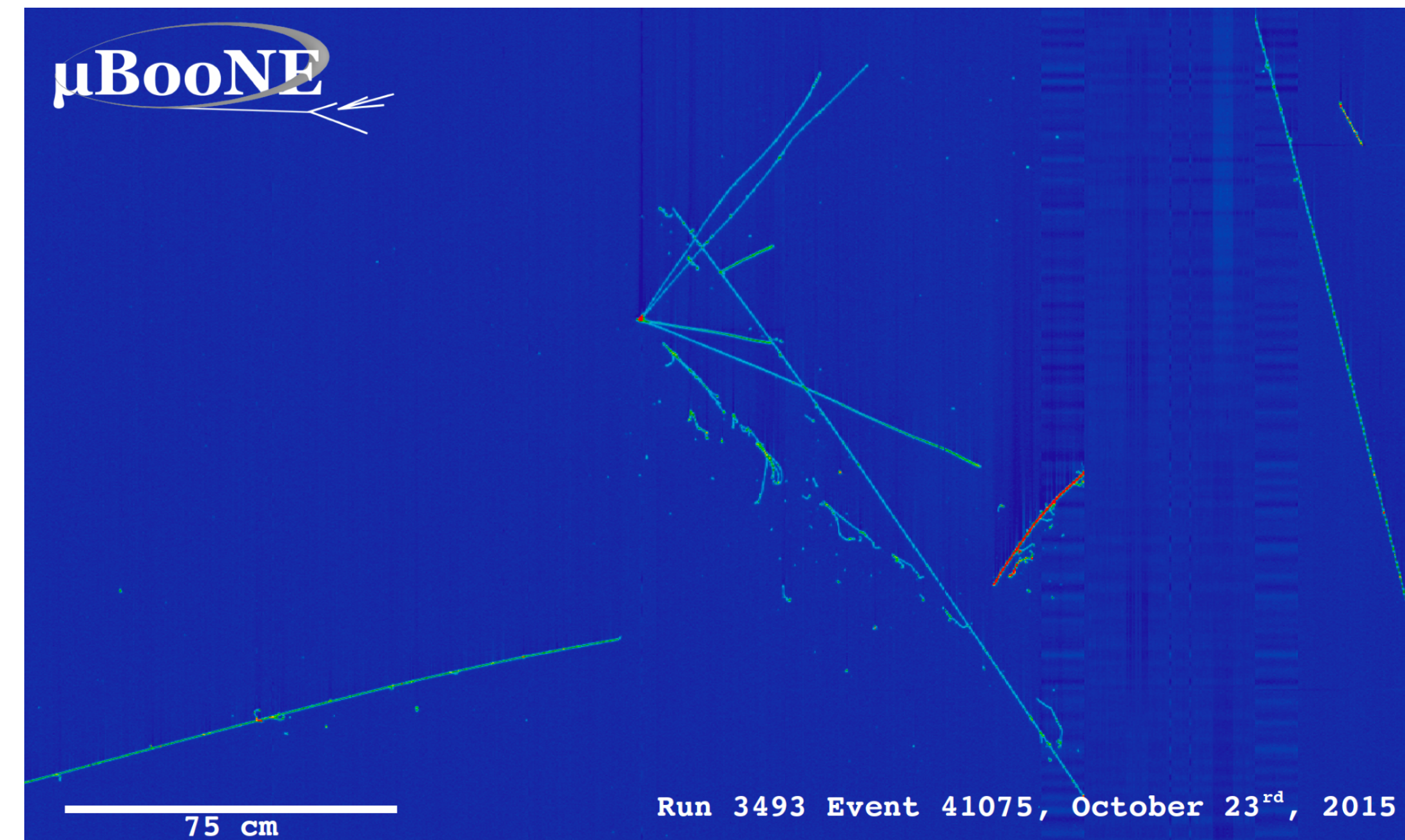
[arXiv:2406.10123](#)

- Use fine-timing from PMTs and beam spill to extract ns-resolution
 - Enables long-lived BSM particle searches, better cosmic rejection
- Demonstrate new LArTPC reconstruction techniques for exotic topologies, deep-learning based methods for 3D reconstruction, neutrino energy estimation etc

Conclusions



- Wealth of new results across its science program
 - New LEE results rejecting ν_e -like interpretation at >99% CL!
 - New results on HNLs and Dark tridents
 - Upcoming results for single- γ and e^+e^- based BSM searches
 - Upcoming 3+1 sterile neutrino search with unique “one detector, two beams” analysis
 - Continues to lead the community in its cross-section program with diverse results across multiple topologies
 - Able to probe much deeper into nuclear initial state and final state modeling
 - Pioneering new techniques for MeV-scale reconstruction
 - Other novel techniques for LArTPCs looking forward to next generation experiments
- Stay tuned for more results!

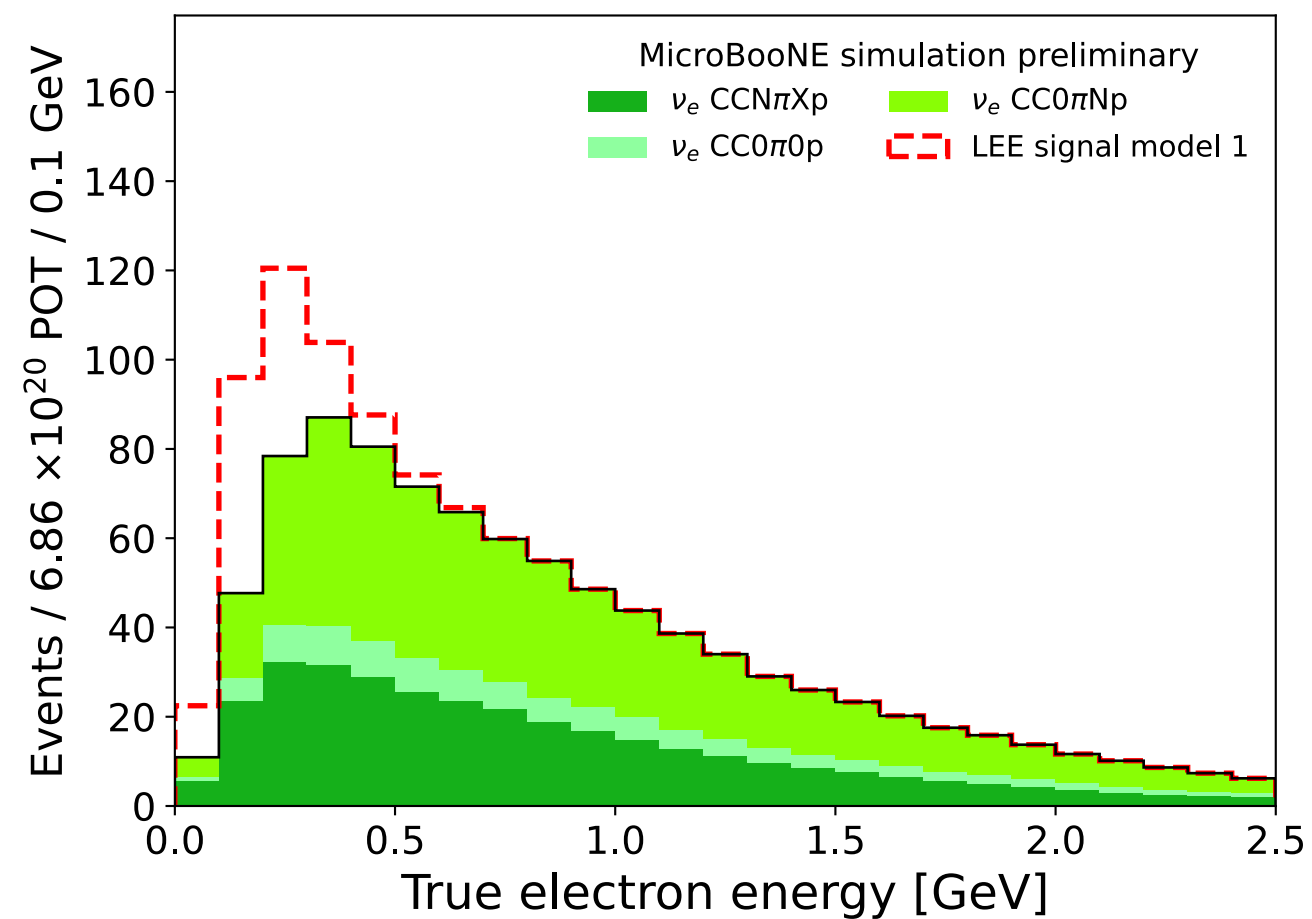
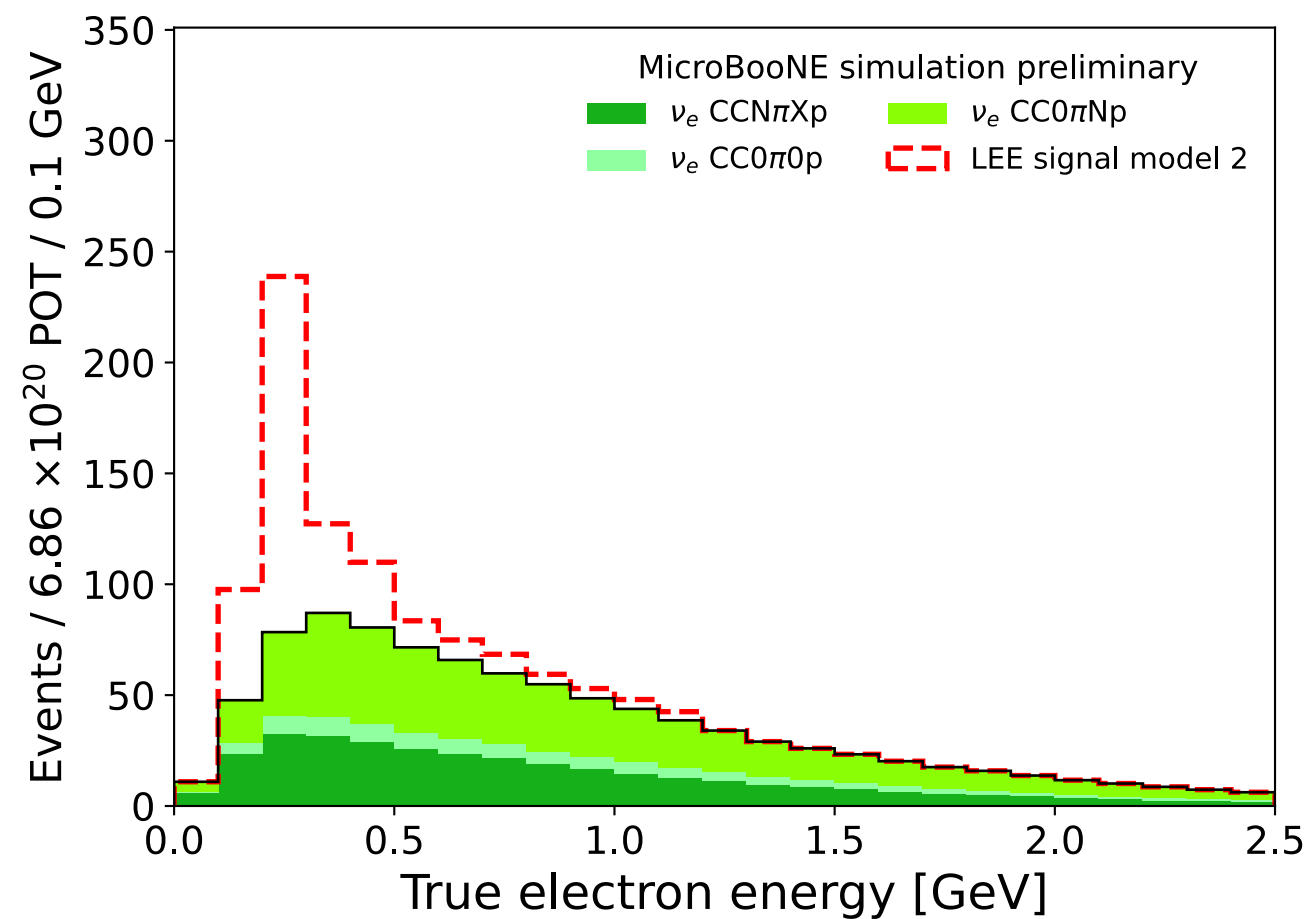
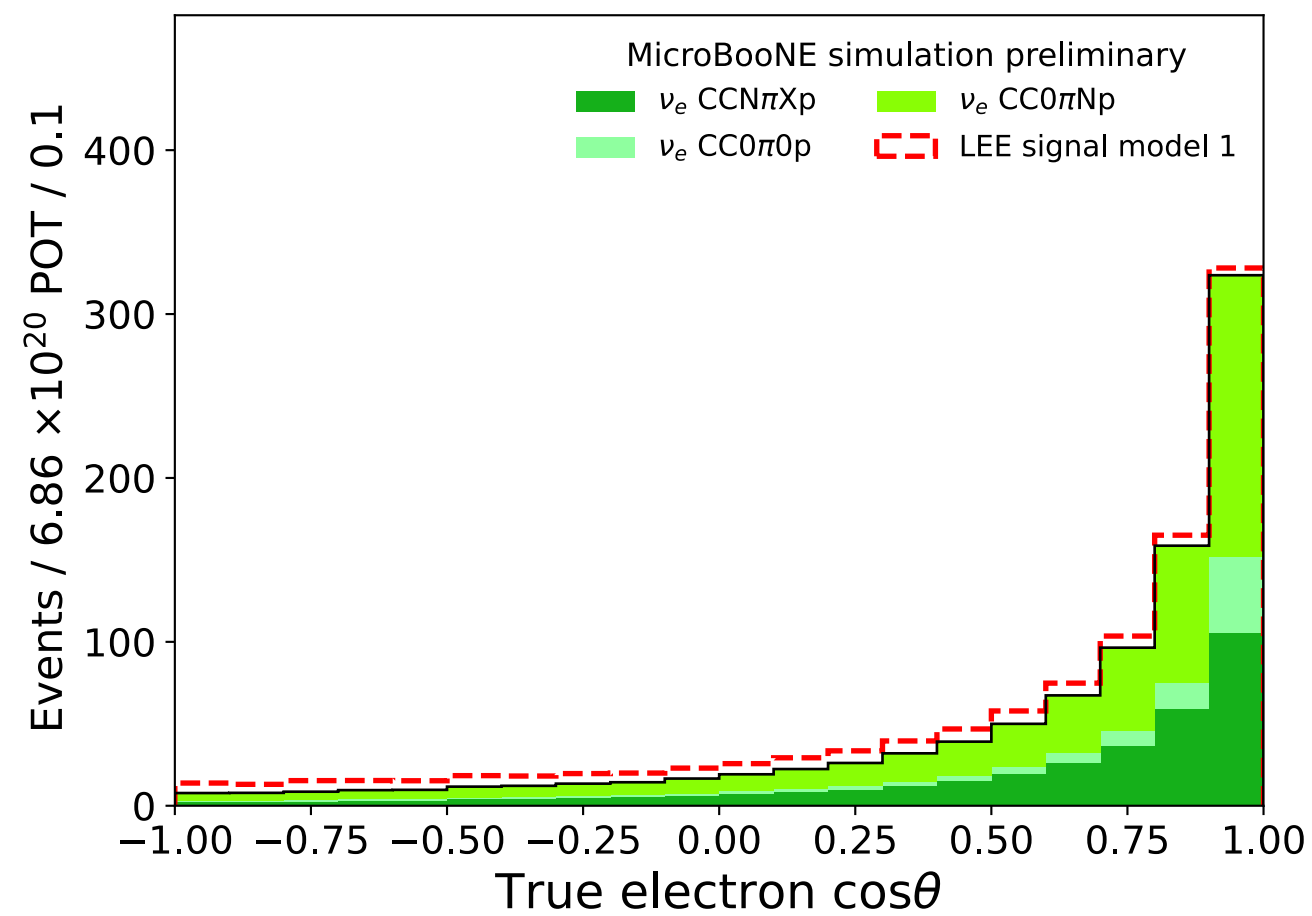
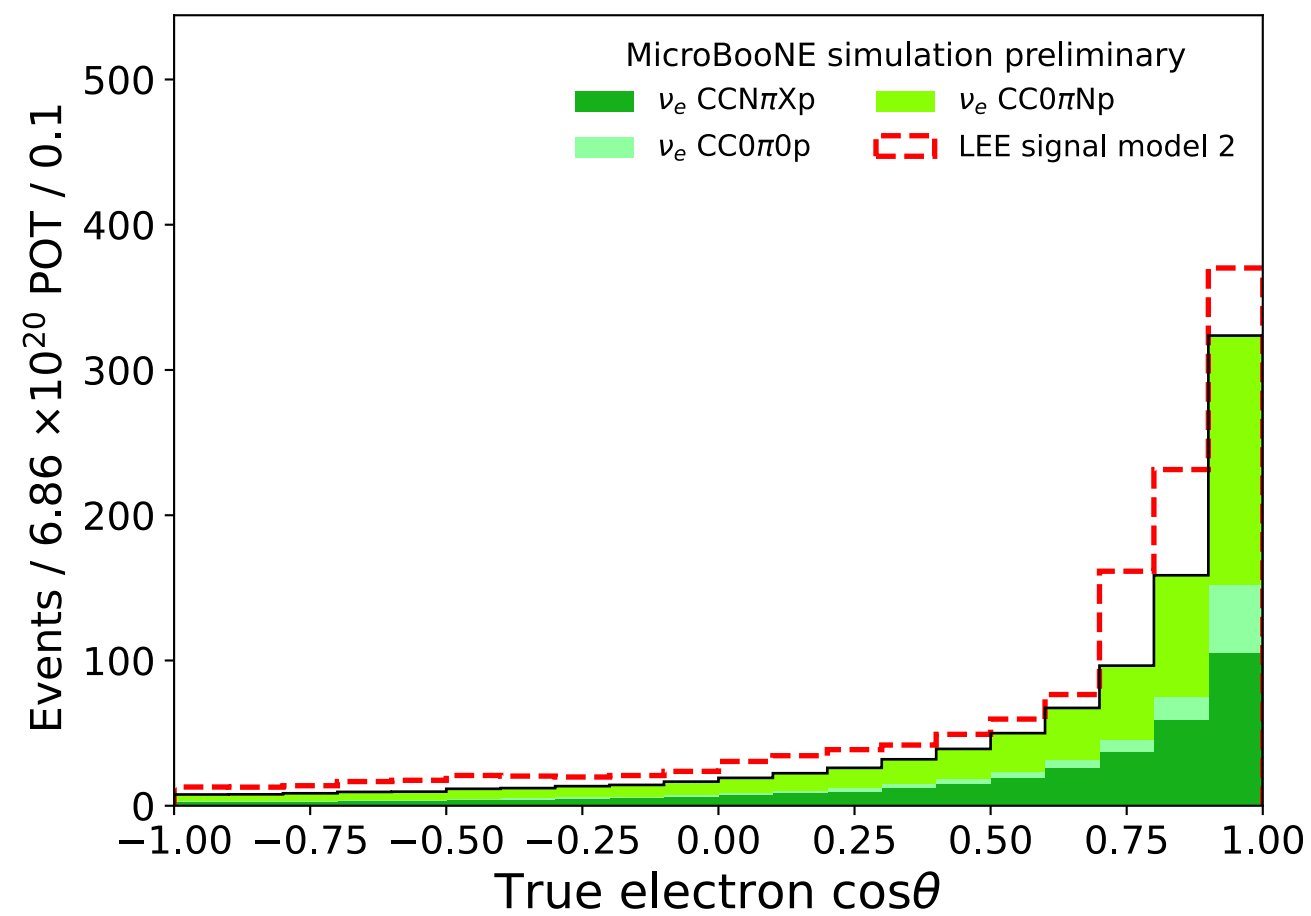


Thank you!



Backup

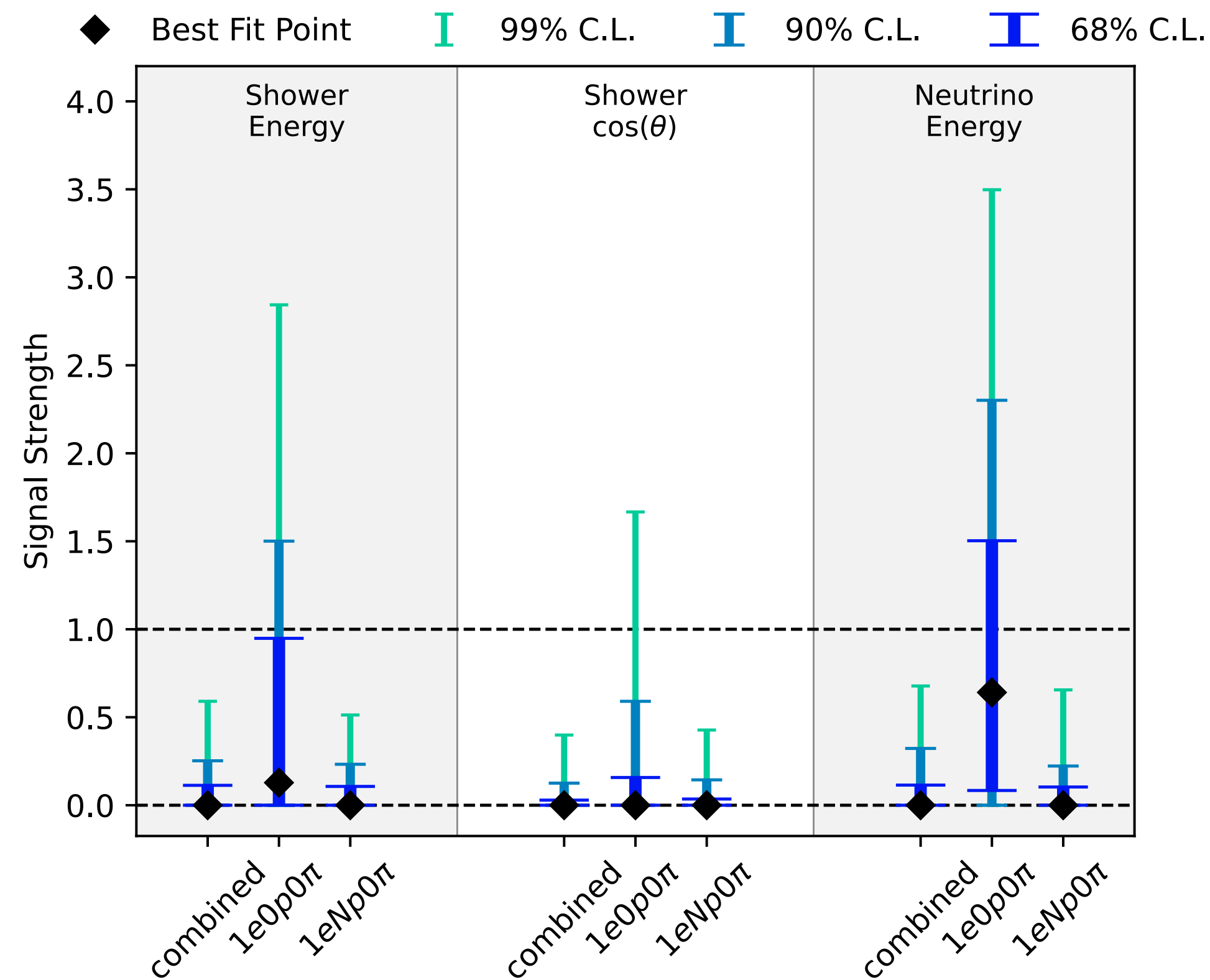
ν_e LEE models and results



shower kinematics signal model
[model #2]

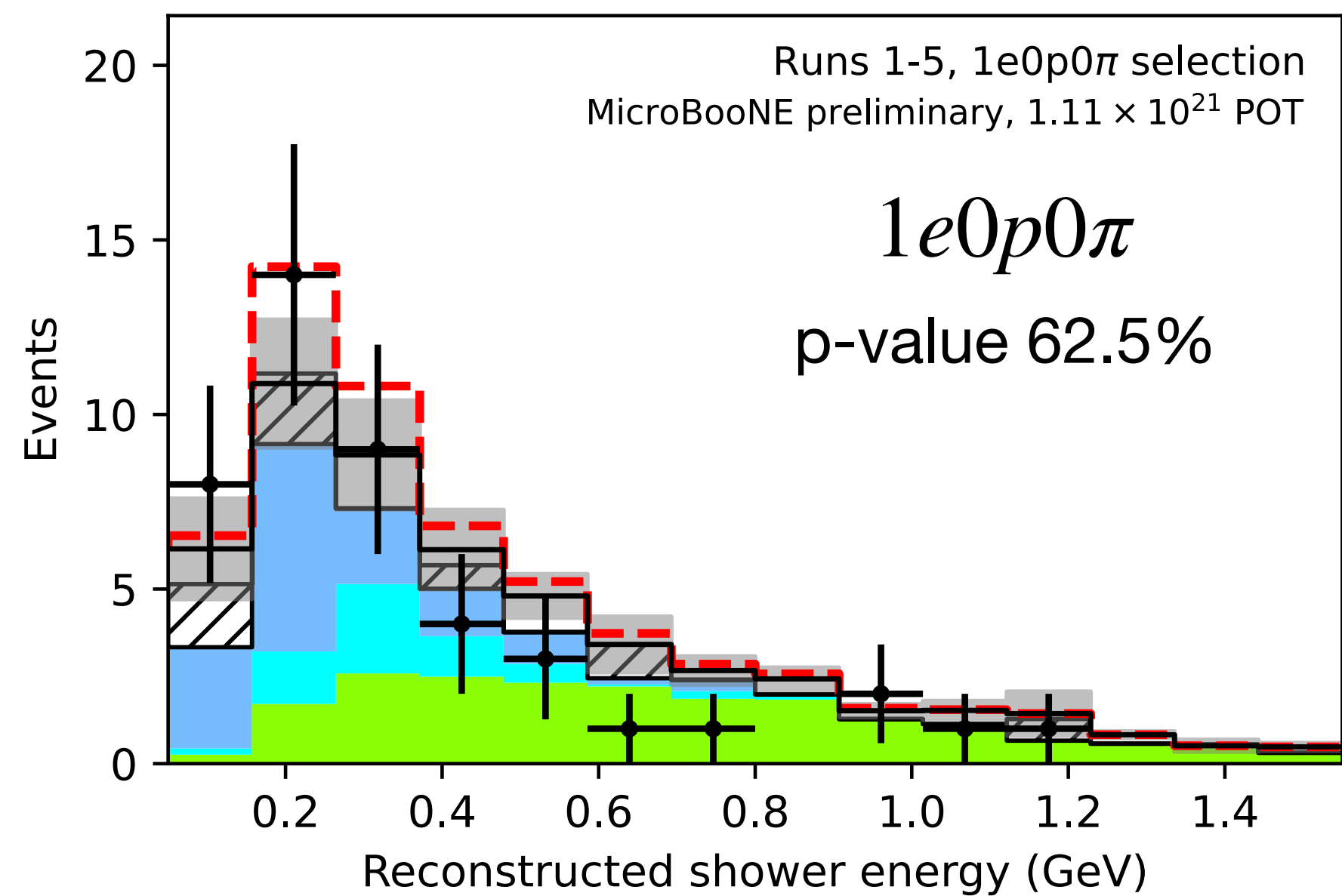
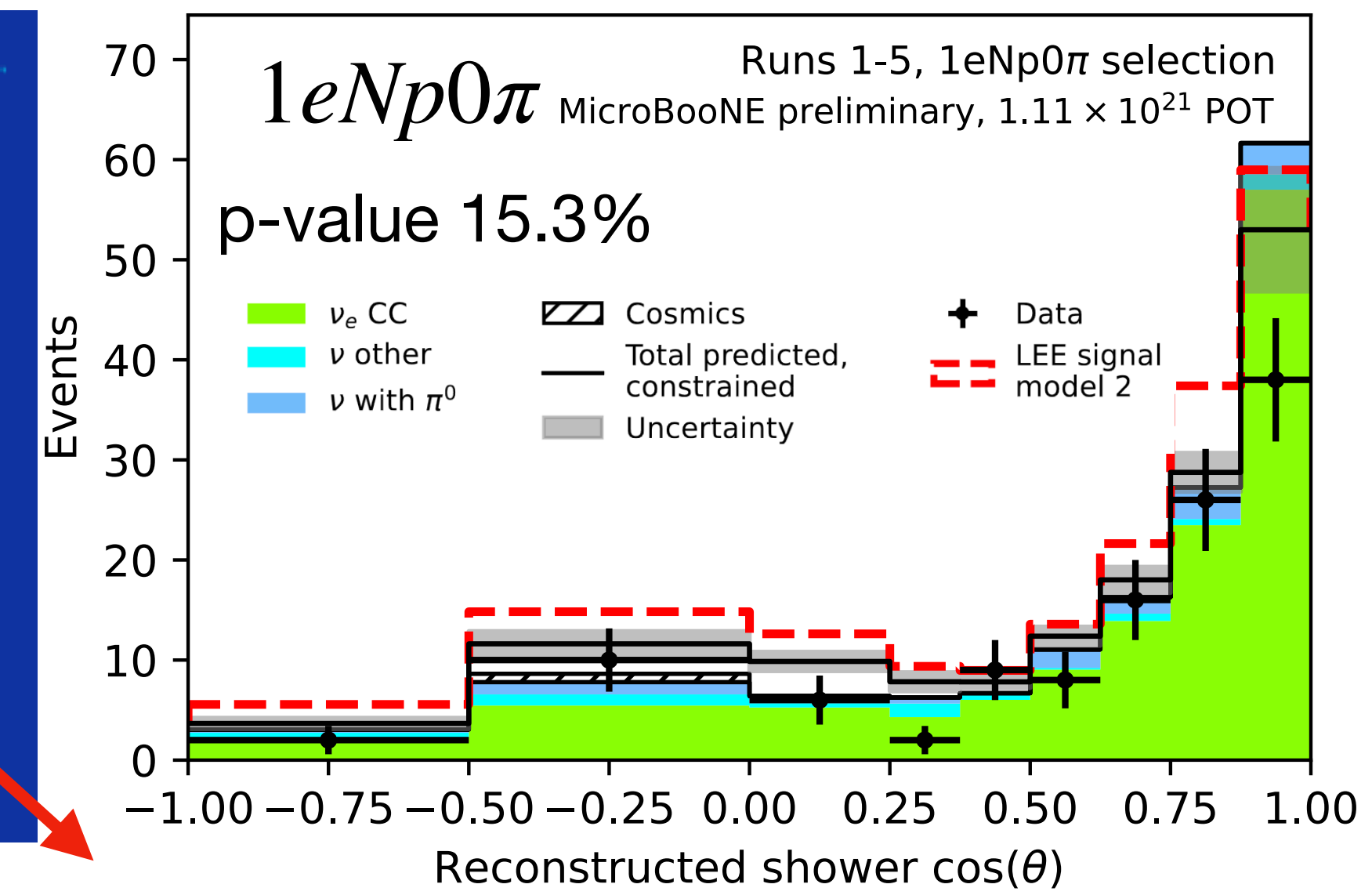
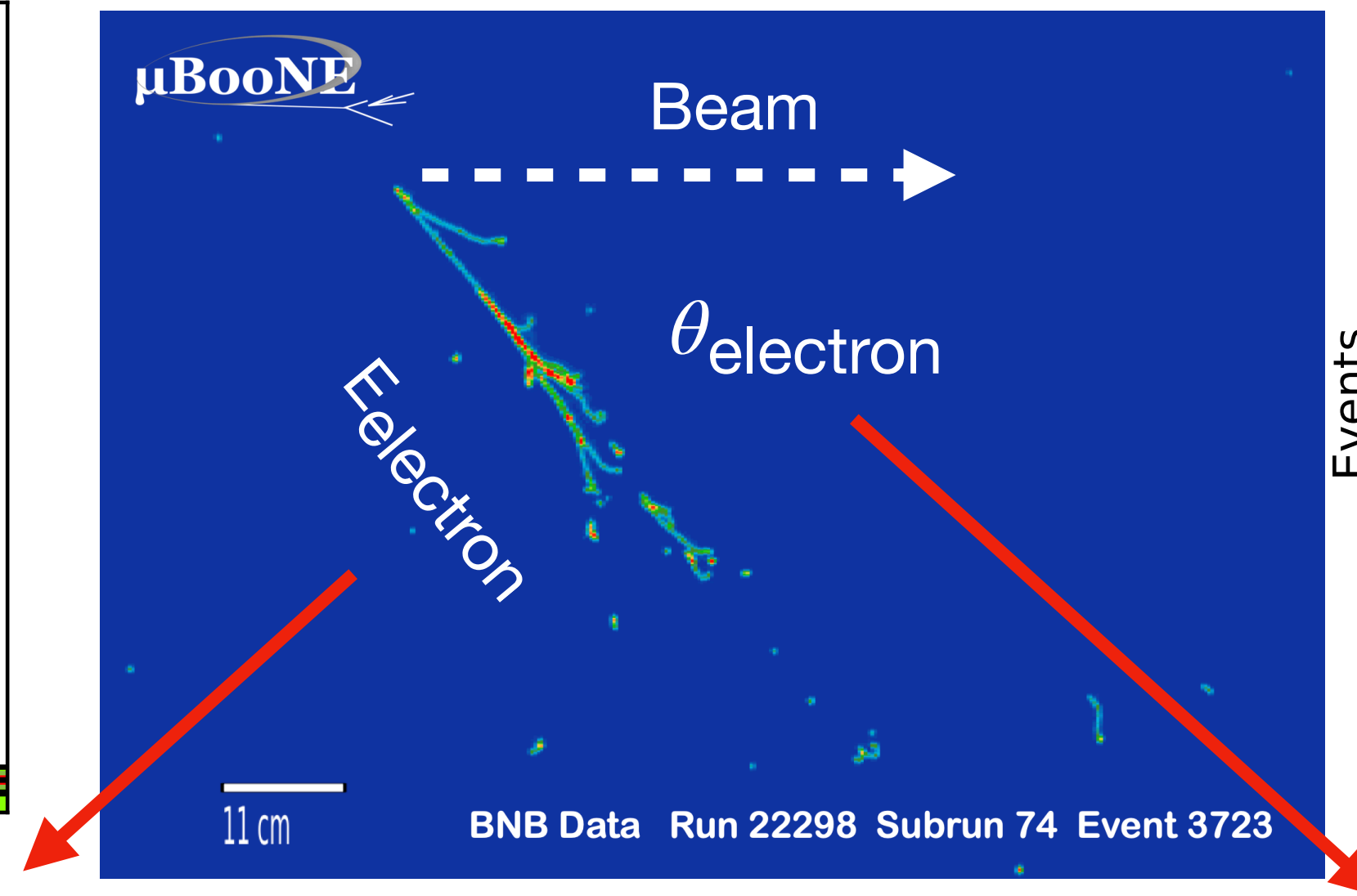
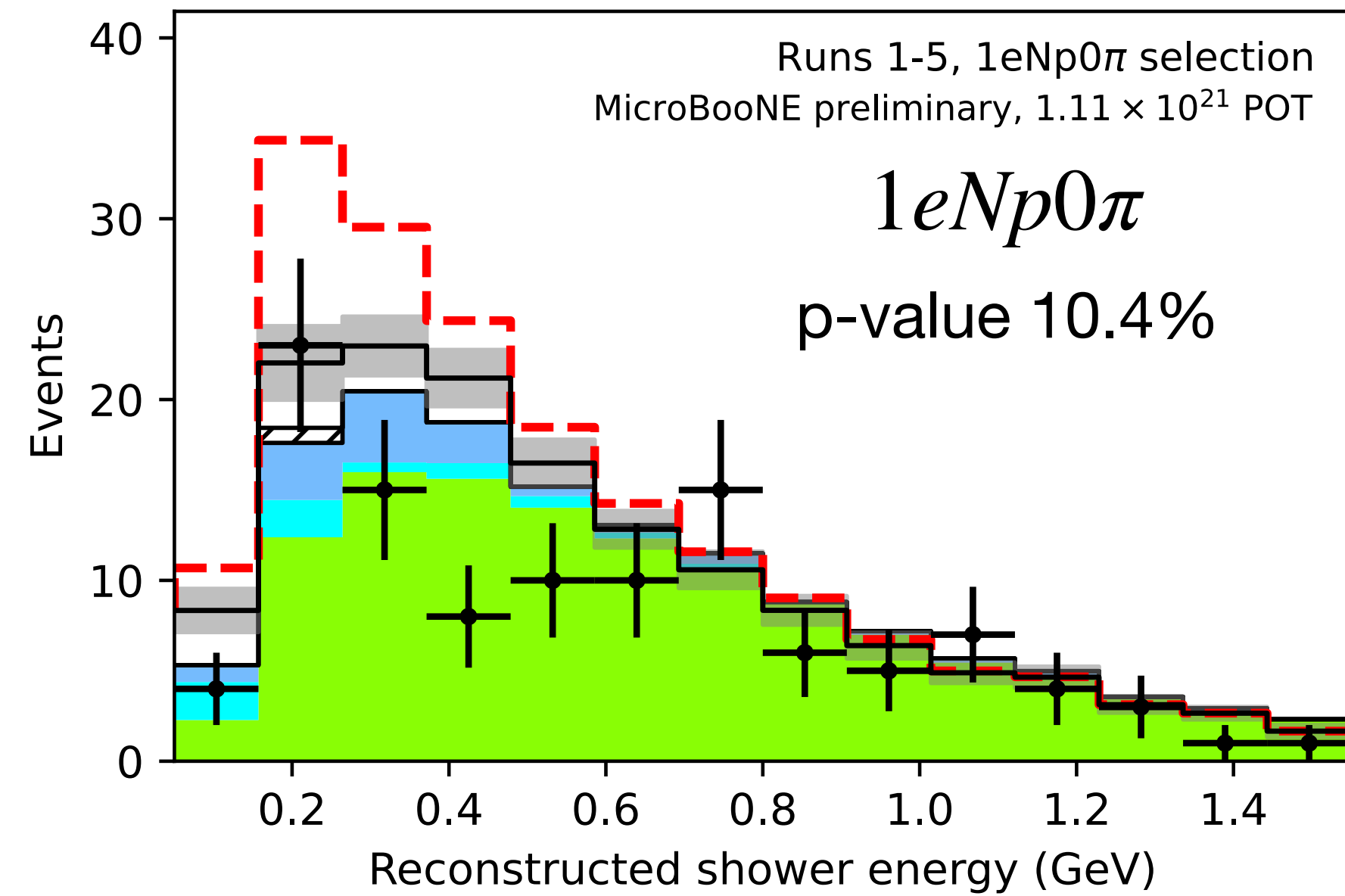
Neutrino energy signal model
[model #1]

ν_e LEE analysis



Results in Np / 0p channels separately and combined

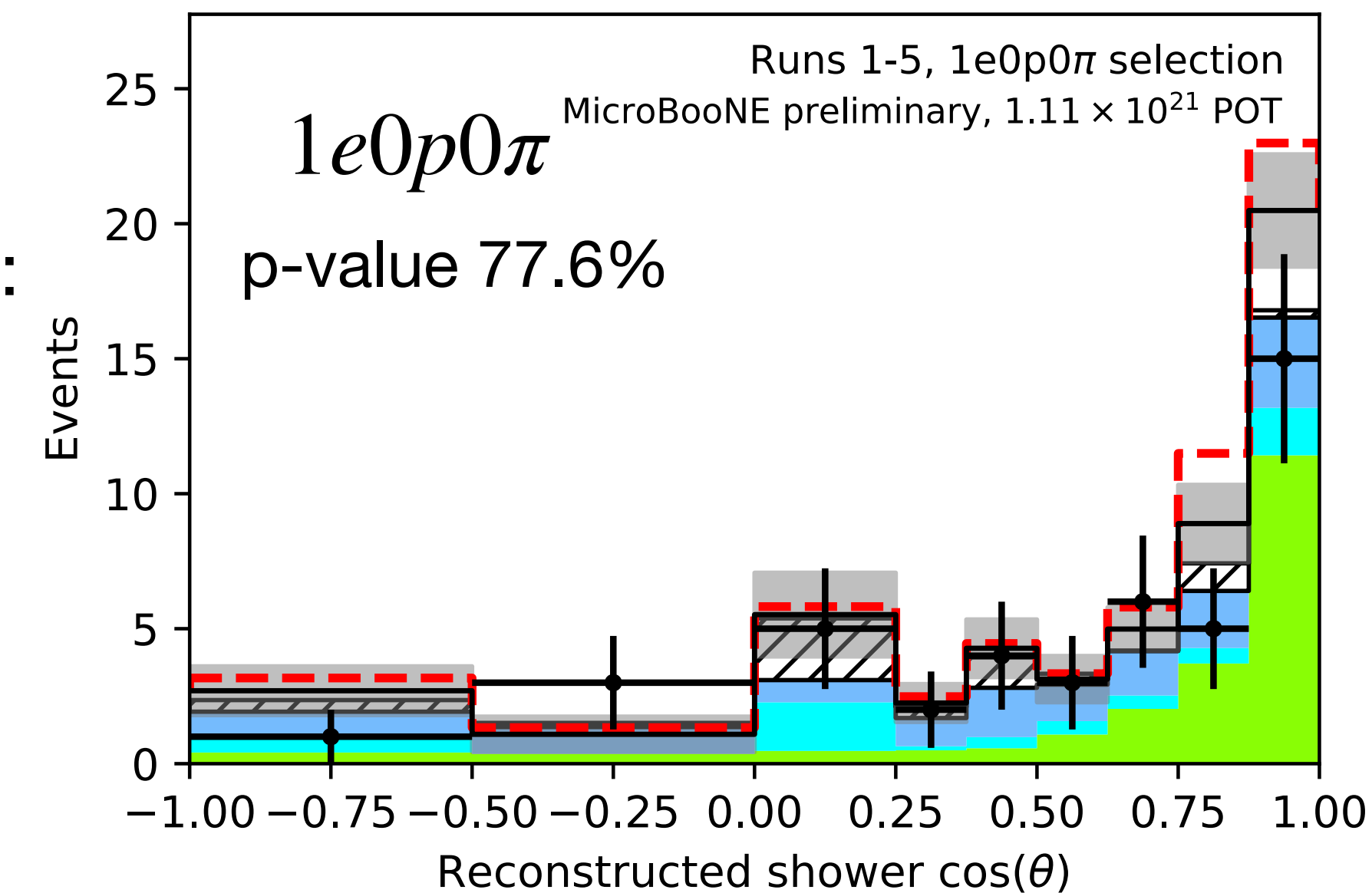
LEE Search: ν_e results



Shower kinematics-based model:

combined Np & 0p channels:

exclude model at $> 99.9\%$ CL



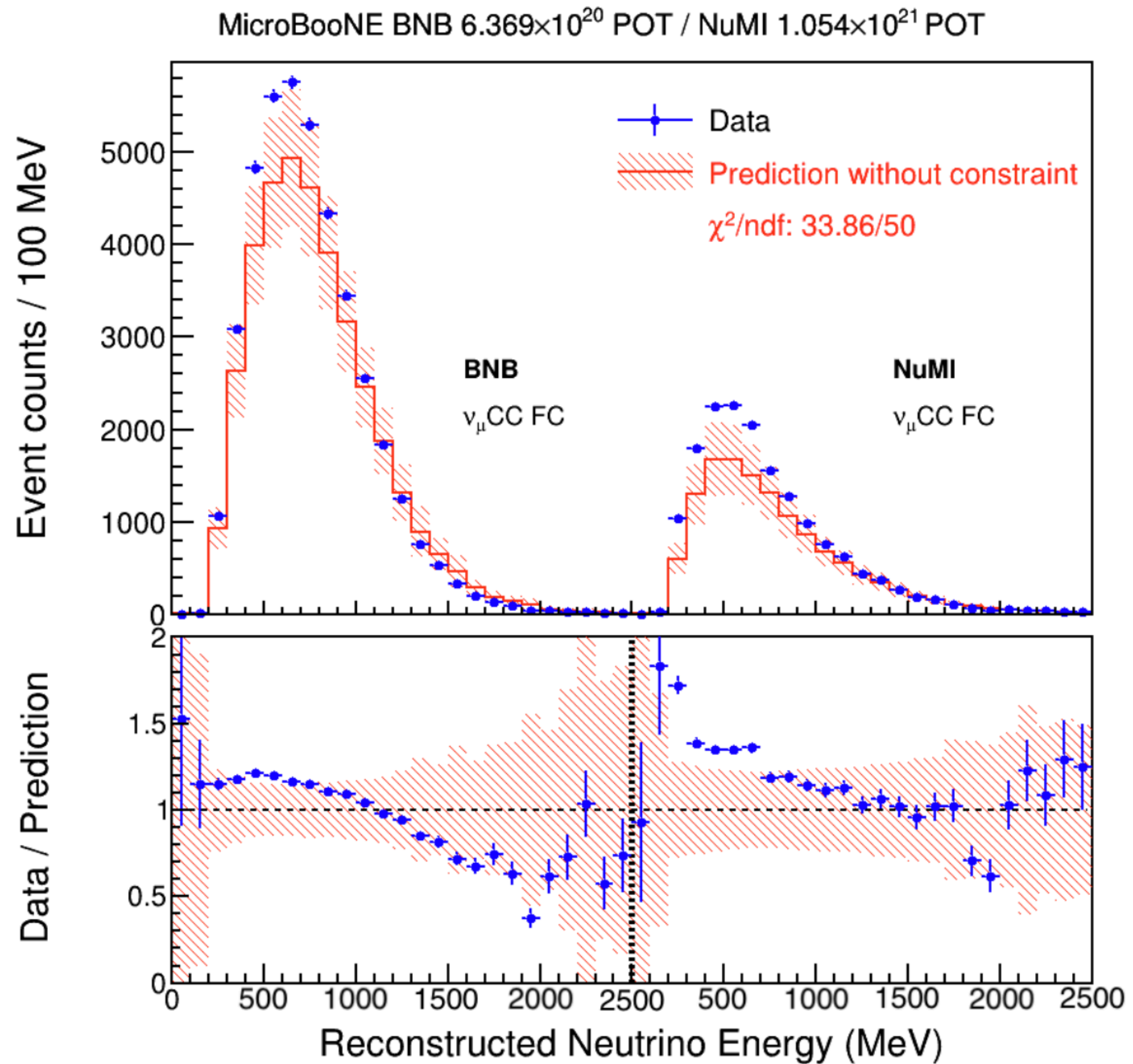
3+1 parametrization

$$\begin{aligned}
 P_{\nu_e \rightarrow \nu_e} &= 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2 \Delta_{41}, \\
 \text{Full 3+1 search} \longrightarrow P_{\nu_\mu \rightarrow \nu_\mu} &= 1 - 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2 \sin^2 \Delta_{41}, \\
 P_{\nu_\mu \rightarrow \nu_e} &= 4|U_{\mu 4}|^2|U_{e4}|^2 \sin^2 \Delta_{41}.
 \end{aligned}$$

$$\begin{aligned}
 \sin^2 2\theta_{ee} &= \sin^2 2\theta_{14} &= 4(1 - |U_{e4}|^2)|U_{e4}|^2 \\
 \sin^2 2\theta_{\mu\mu} &= 4 \cos^2 \theta_{14} \sin^2 \theta_{24} (1 - \cos^2 \theta_{14} \sin^2 \theta_{24}) &= 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2 \\
 \sin^2 2\theta_{\mu e} &= \sin^2 2\theta_{14} \sin^2 \theta_{24} &= 4|U_{\mu 4}|^2|U_{e4}|^2 \\
 \sin^2 2\theta_{es} &= \sin^2 2\theta_{14} \cos^2 \theta_{24} \cos^2 \theta_{34} &= 4|U_{e4}|^2|U_{s4}|^2 \\
 \sin^2 2\theta_{\mu s} &= \cos^4 \theta_{14} \sin^2 2\theta_{24} \cos^2 \theta_{34} &= 4|U_{\mu 4}|^2|U_{s4}|^2
 \end{aligned}$$

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

NuMI ν_μ data-simulation comparison

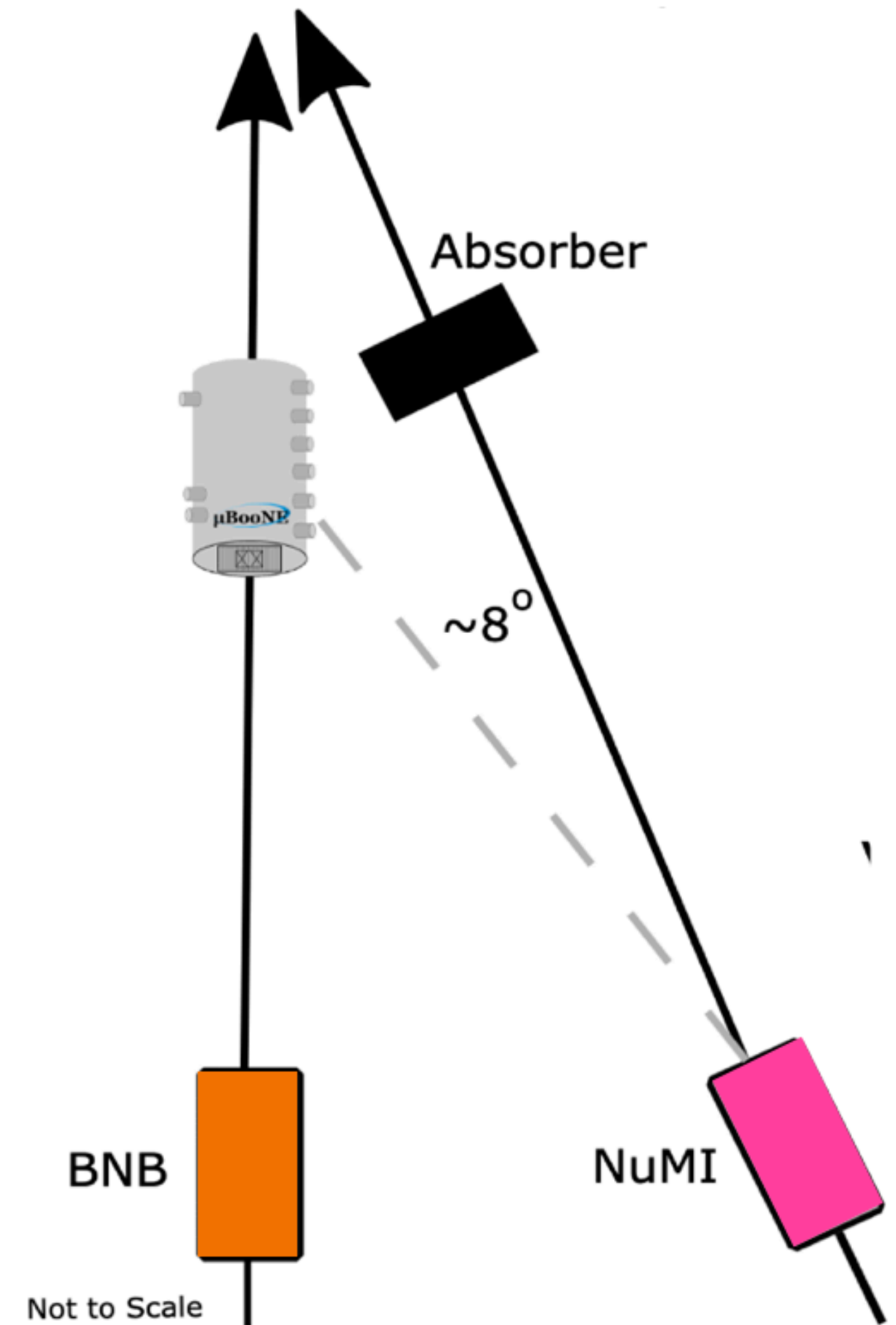
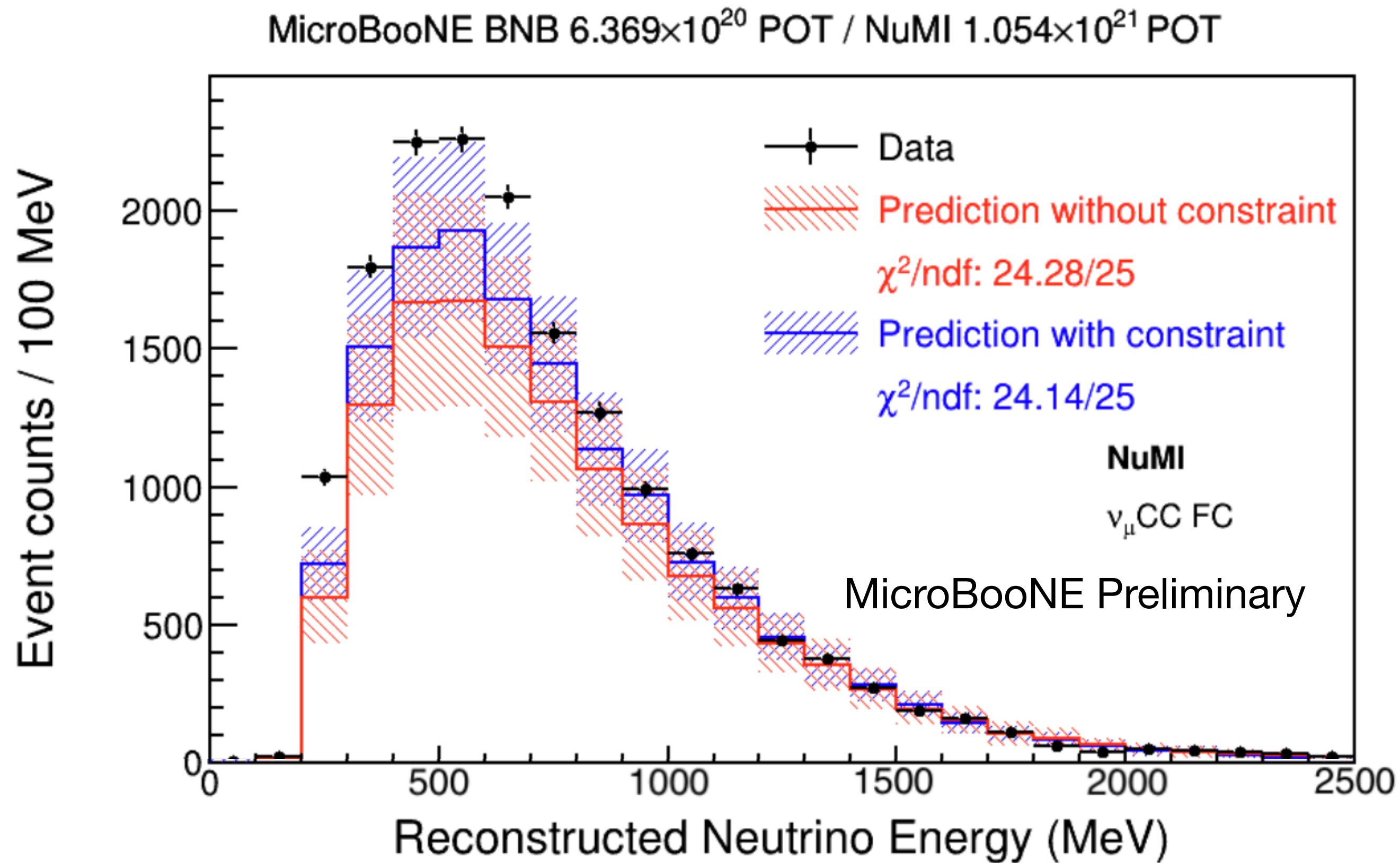


BNB and NuMI data/MC comparison side-by-side. Refers to both channels combined, with full correlation across the two channels.

MICROBOONE-NOTE-1132-PUB

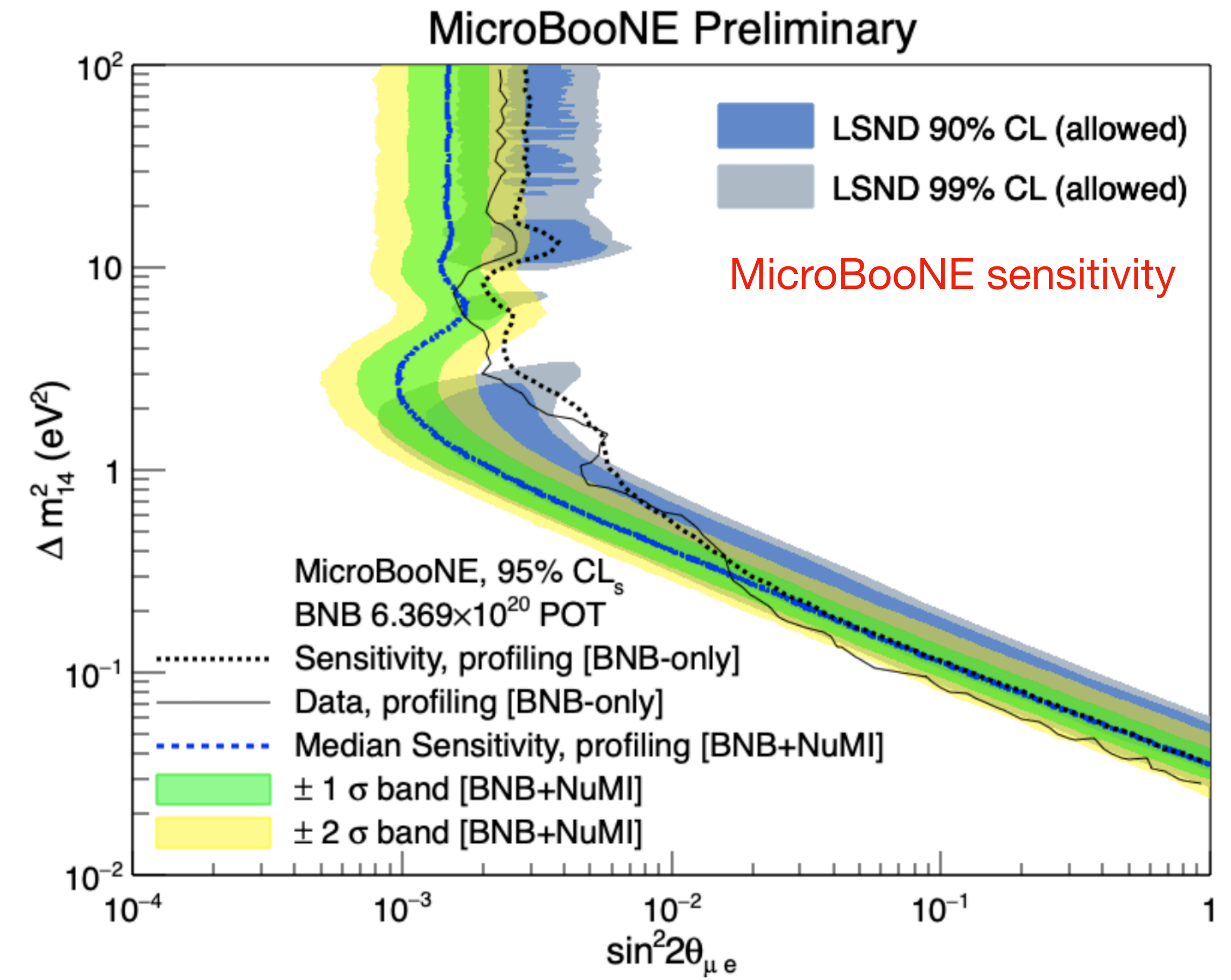
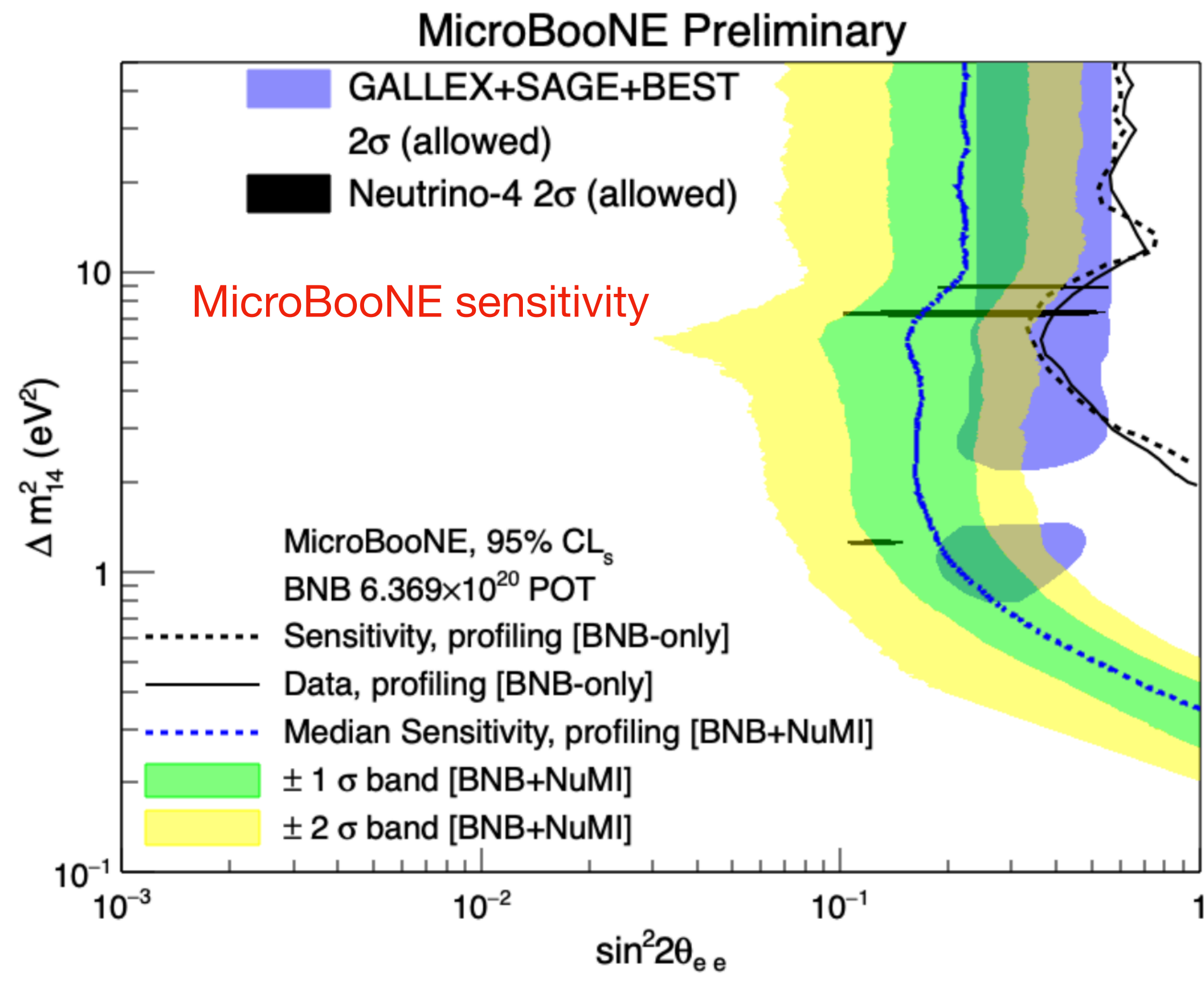
Updated NuMI flux @ MicroBooNE

MicroBooNE's updated NuMI flux prediction vs. ν_μ data:



Good data/MC agreement. Blue histogram shows NuMI ν_μ prediction constrained by BNB ν_μ which largely cancels out cross section and detector systematics.

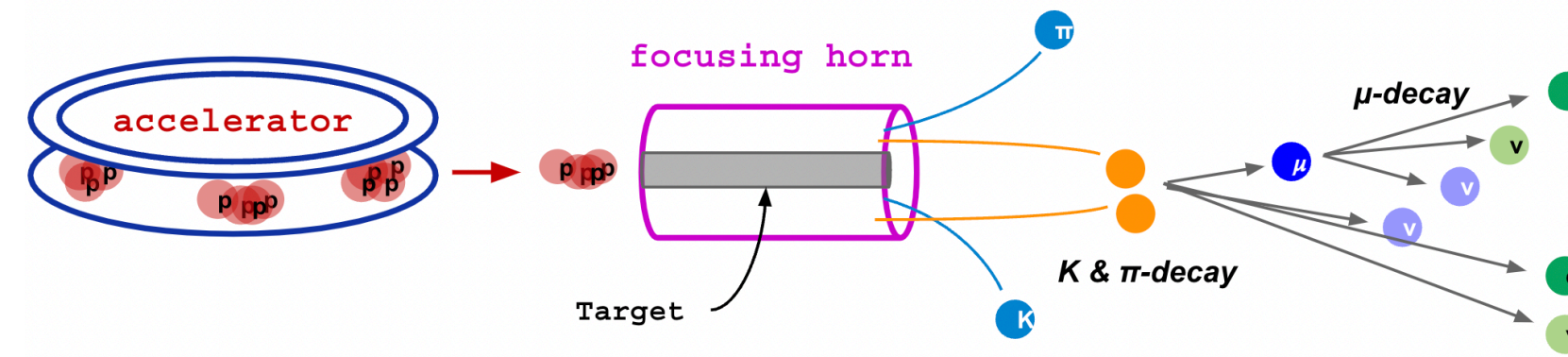
3+1 sensitivities



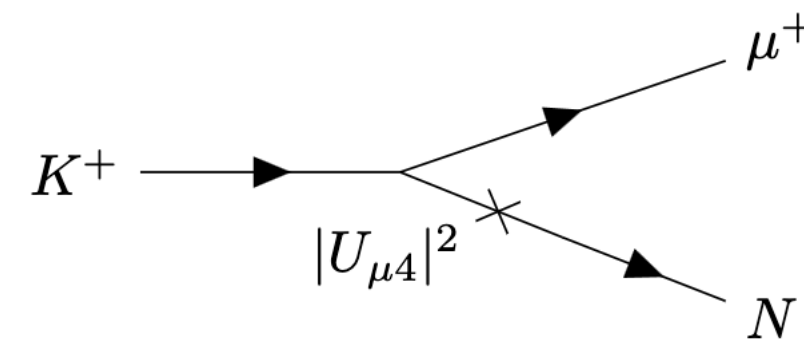
BNB + NuMI 3+1 MicroBooNE sensitivities

Heavy Neutral Lepton Searches

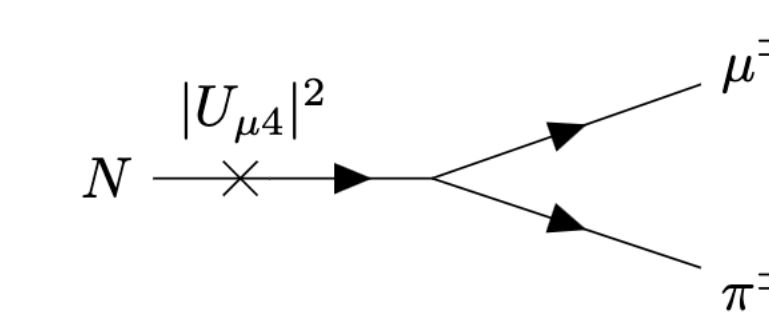
NuMI



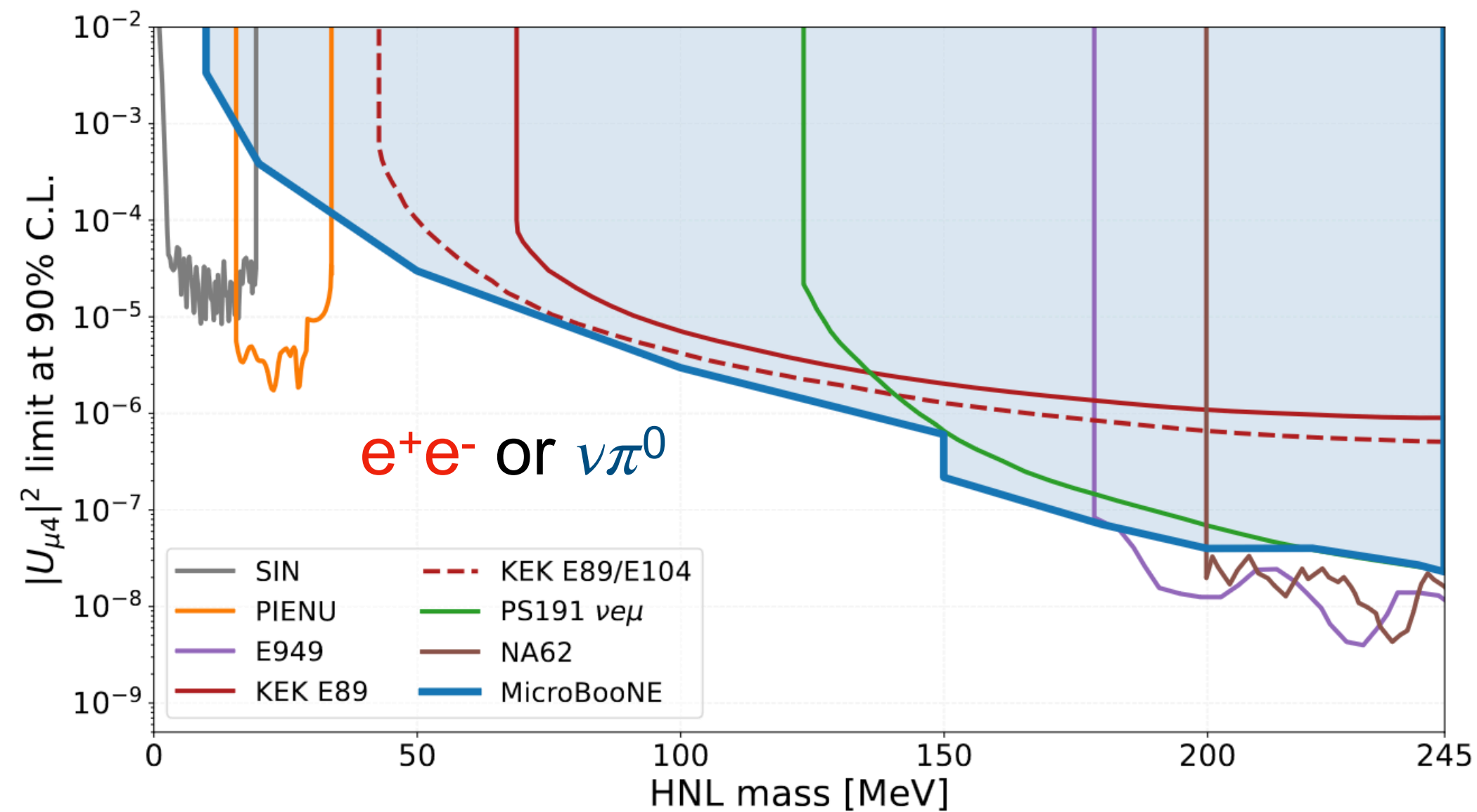
produced in beam via mixing



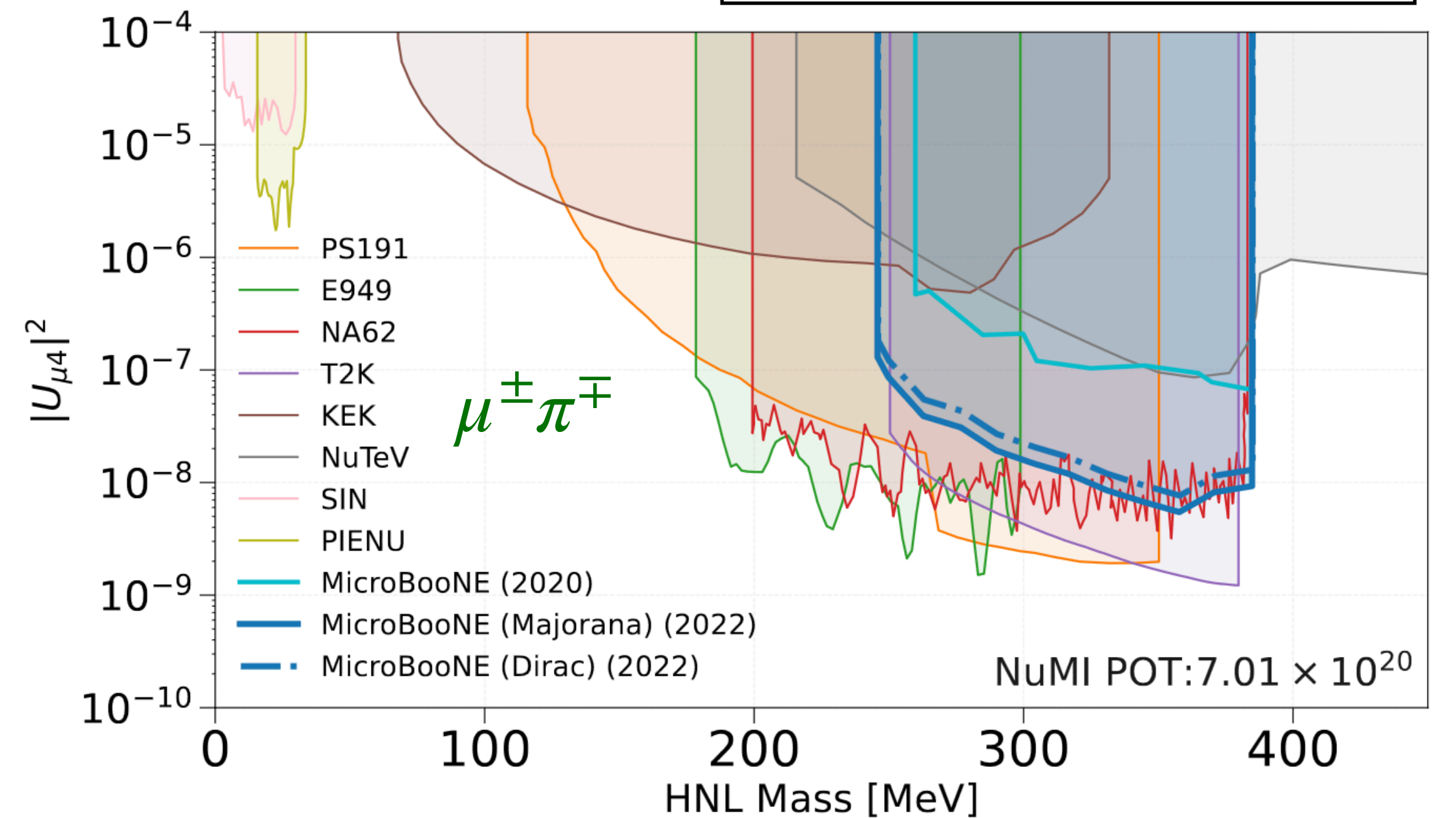
decay in the detector



PRL 132 (2024) 4, 041801

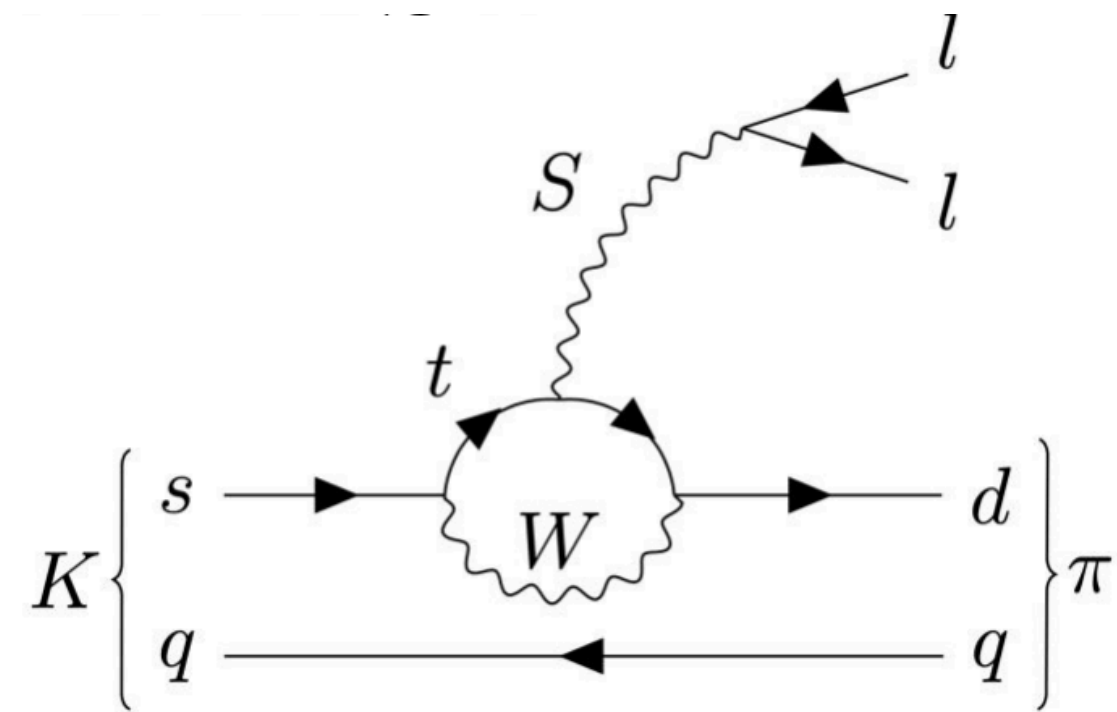
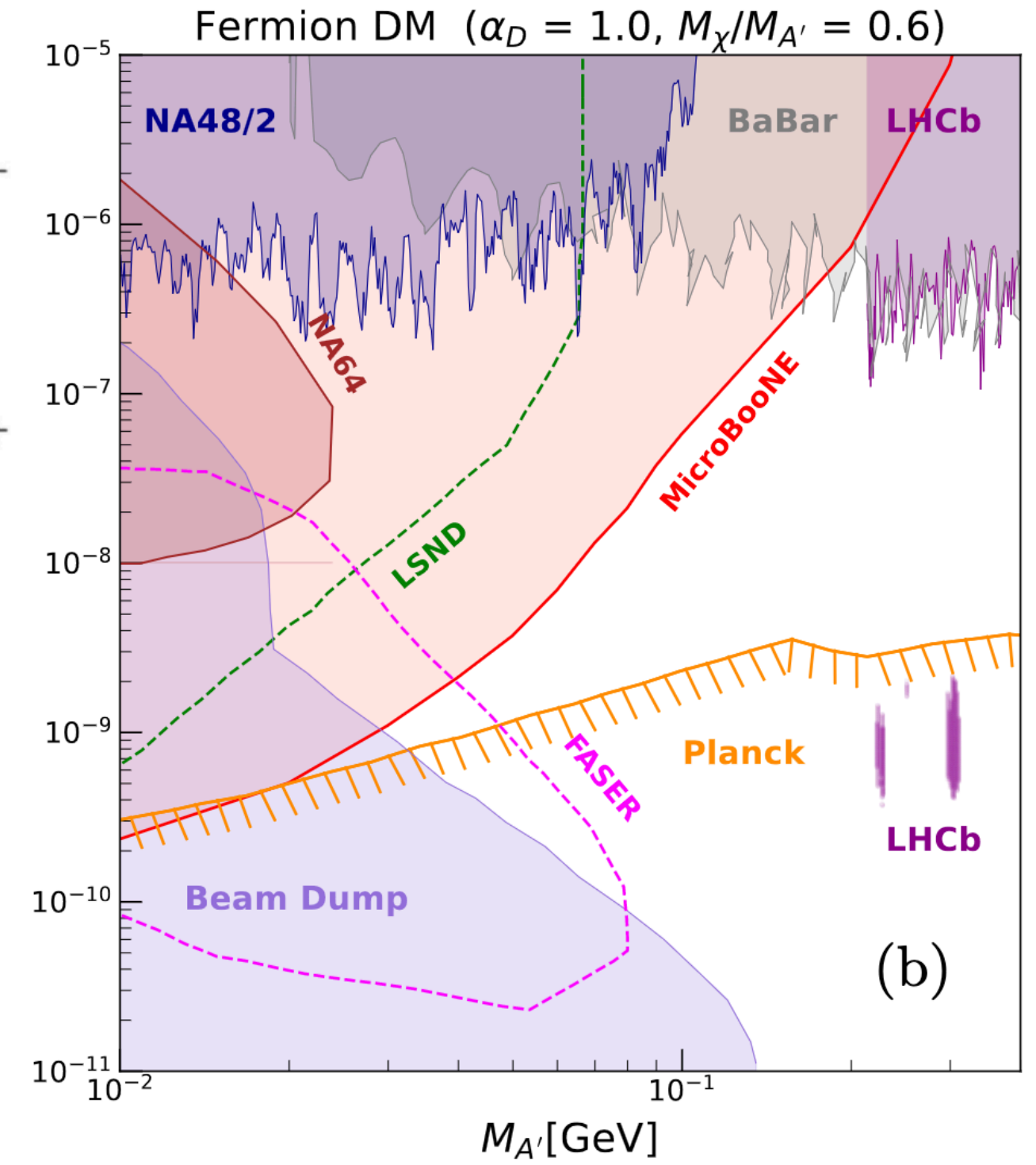
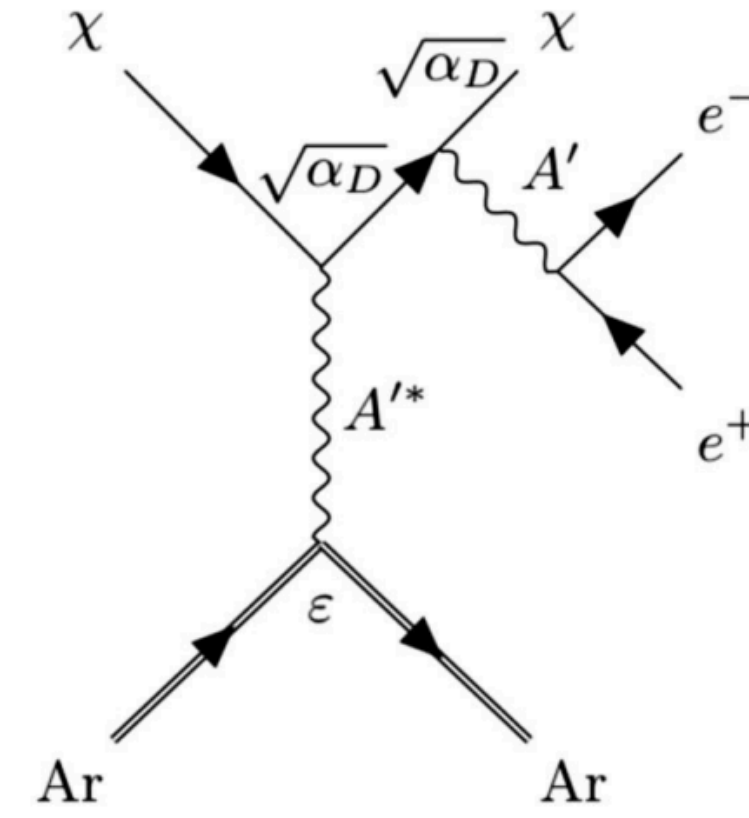
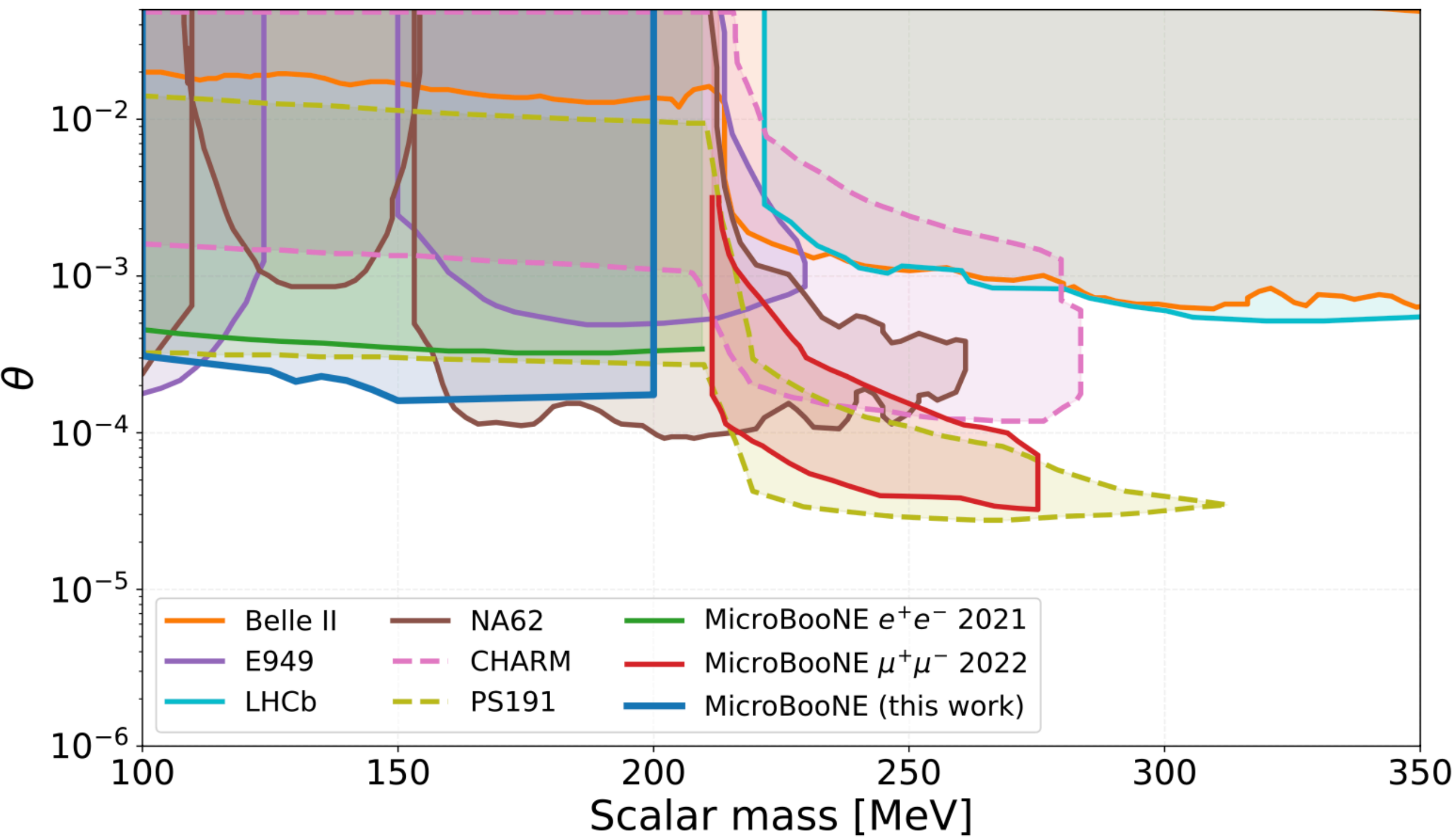


PRD 106 (2022) 9, 092006



Dark Tridents and Higgs Portal

NuMI



Rare Mesons and Baryons

