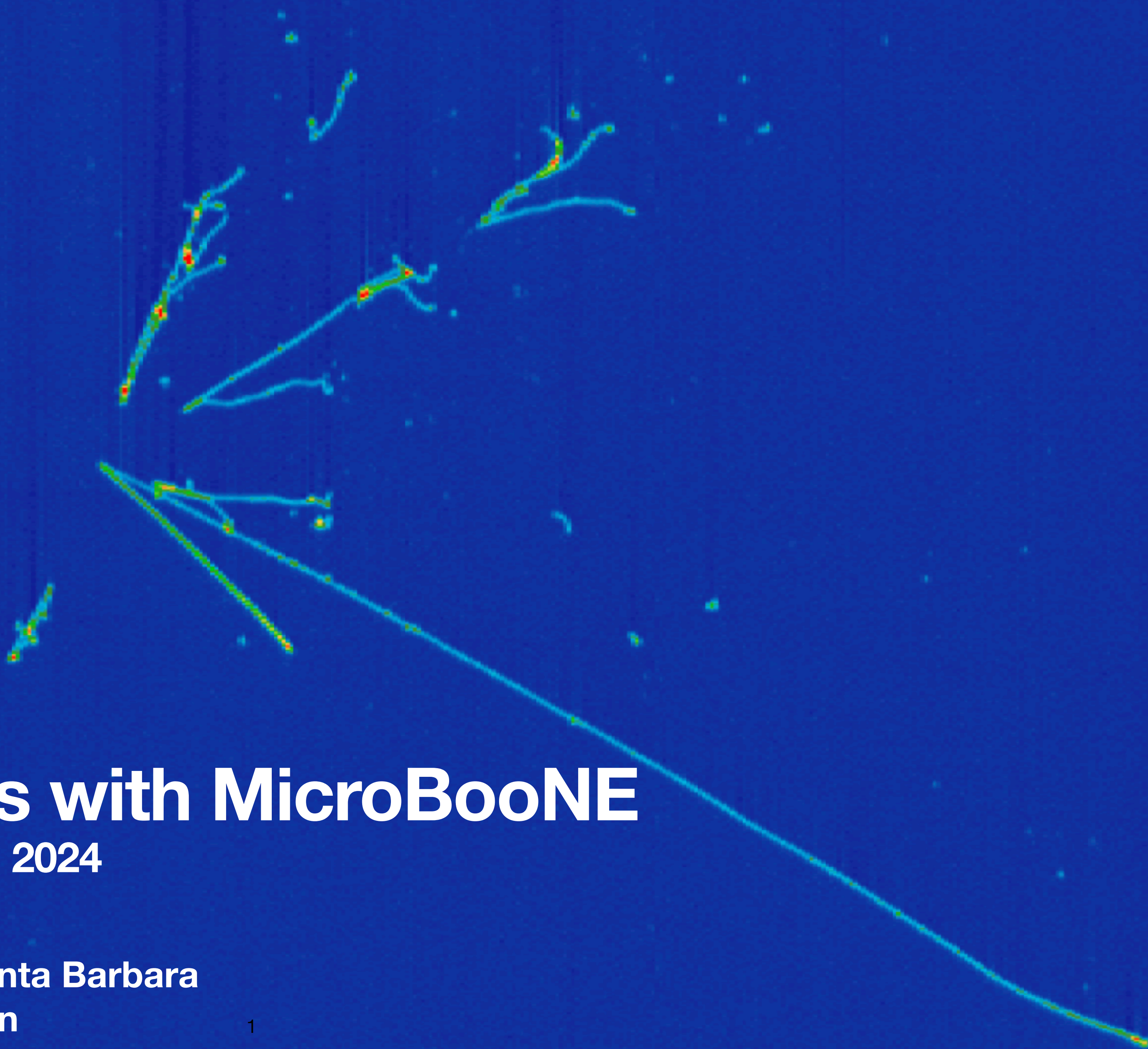


The logo for the MicroBooNE experiment, featuring the Greek letter mu followed by the text "BooNE" in a serif font. A blue oval is drawn around the text, and a black arrow points to the right from the end of the oval.

$\mu$ BooNE



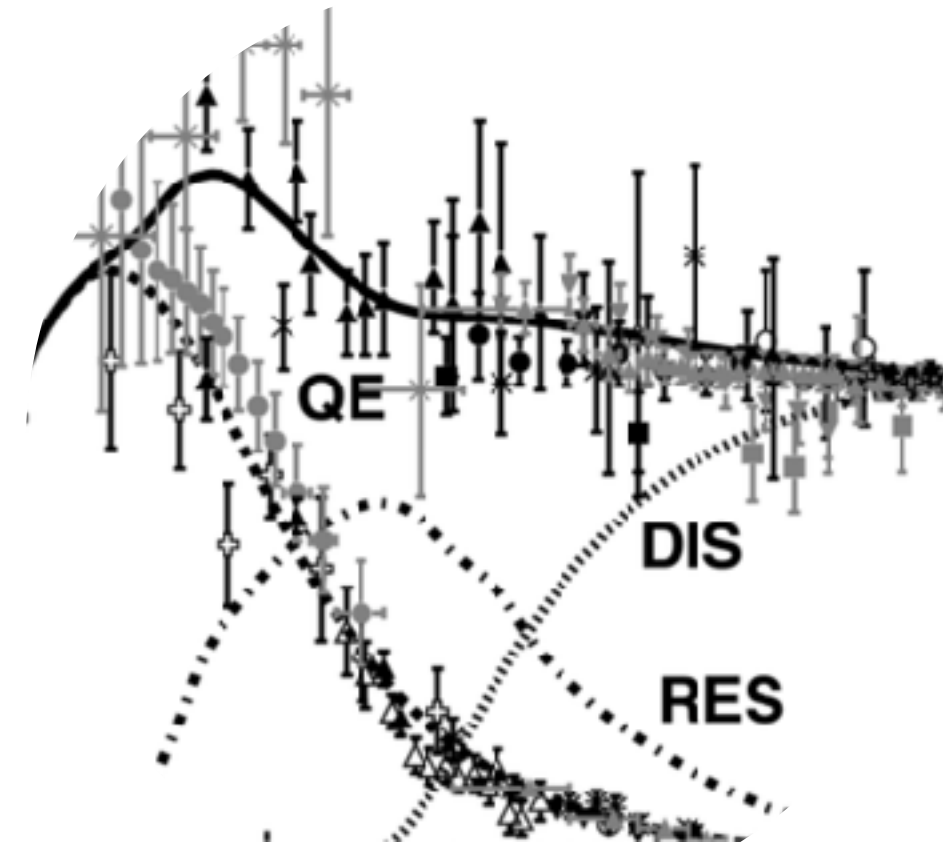
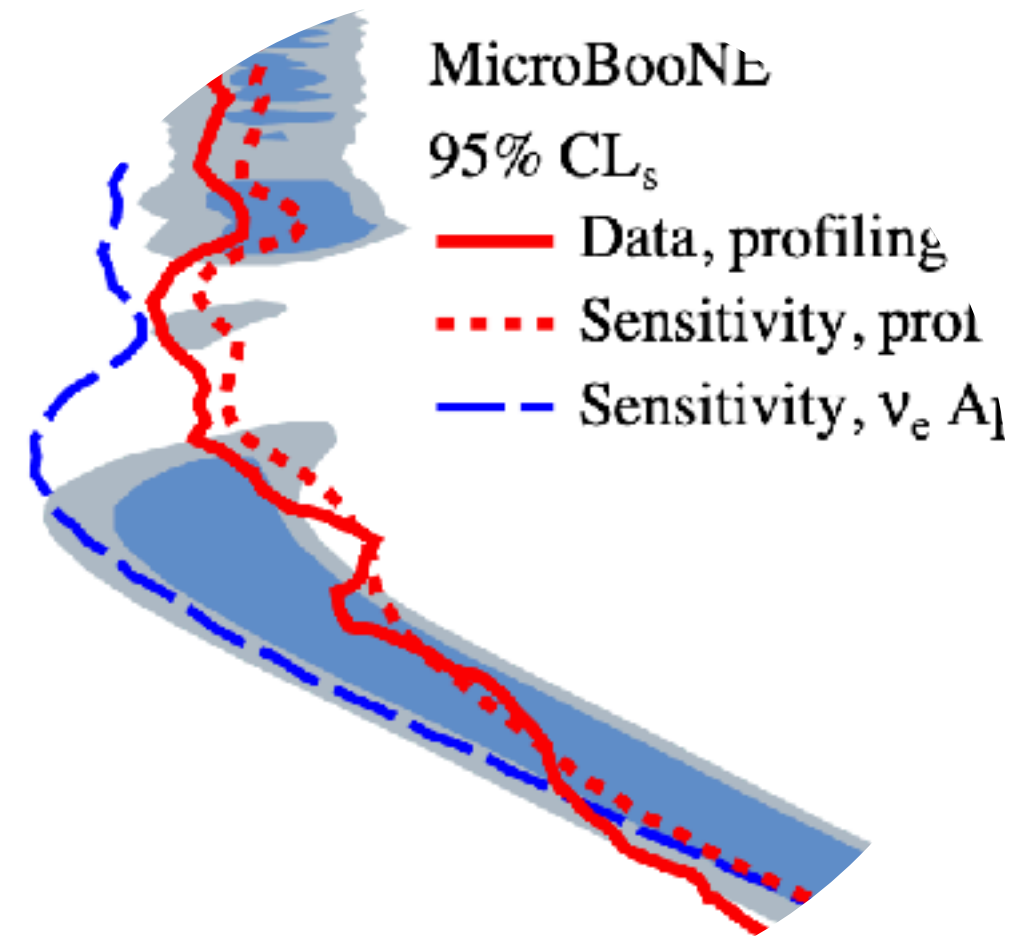
# New physics searches with MicroBooNE

Neutrino 2024 - Milan, Italy - June 17<sup>th</sup> 2024

David Caratelli, University of California Santa Barbara  
on behalf of the MicroBooNE Collaboration

# MicroBooNE's Physics Program

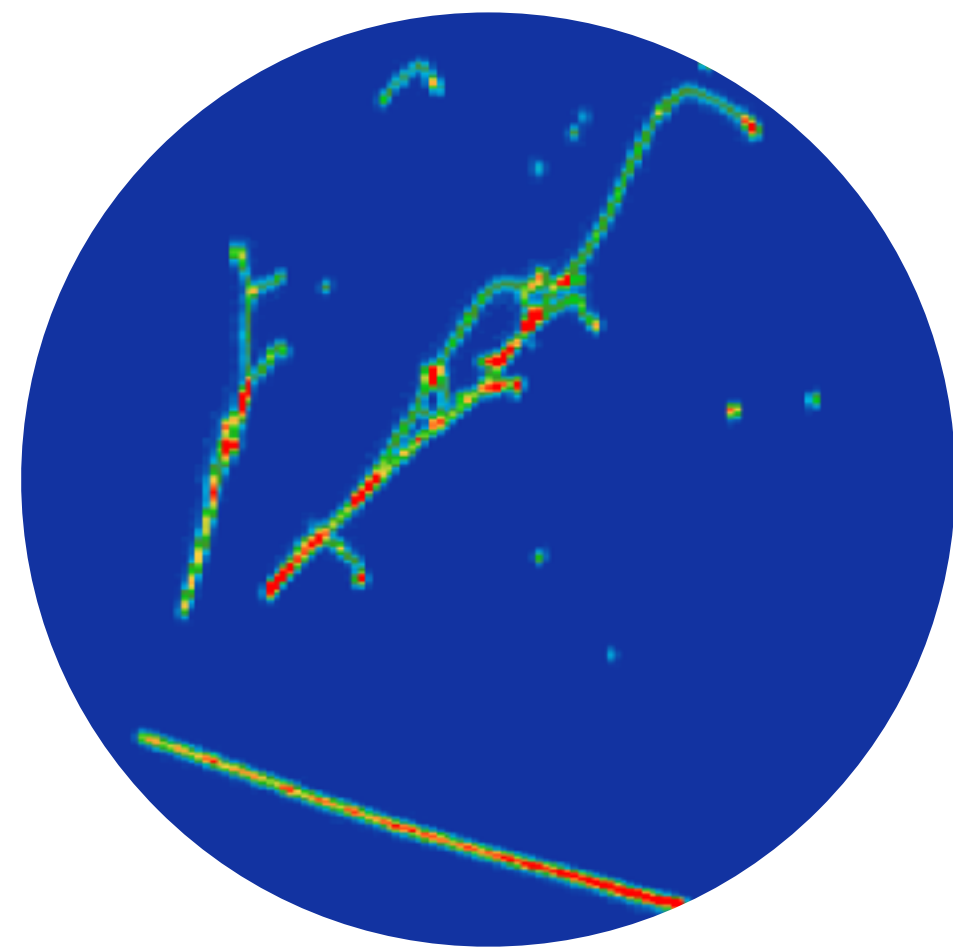
Beyond the Standard  
Model physics searches



$\nu$  - Ar scattering

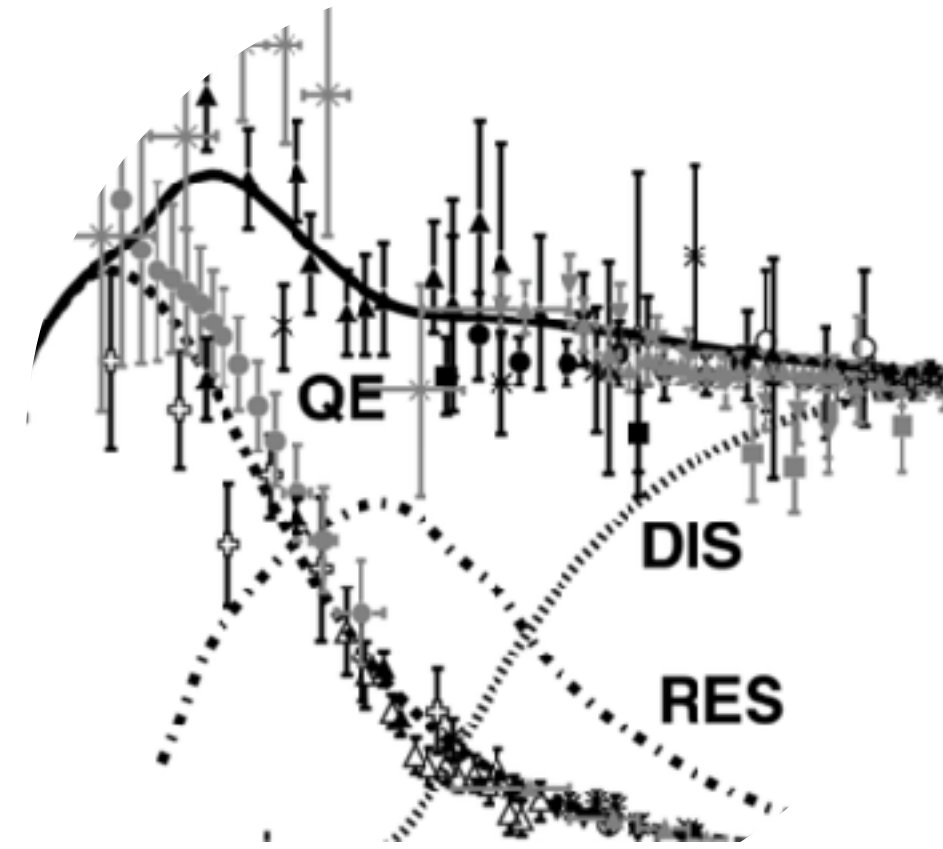
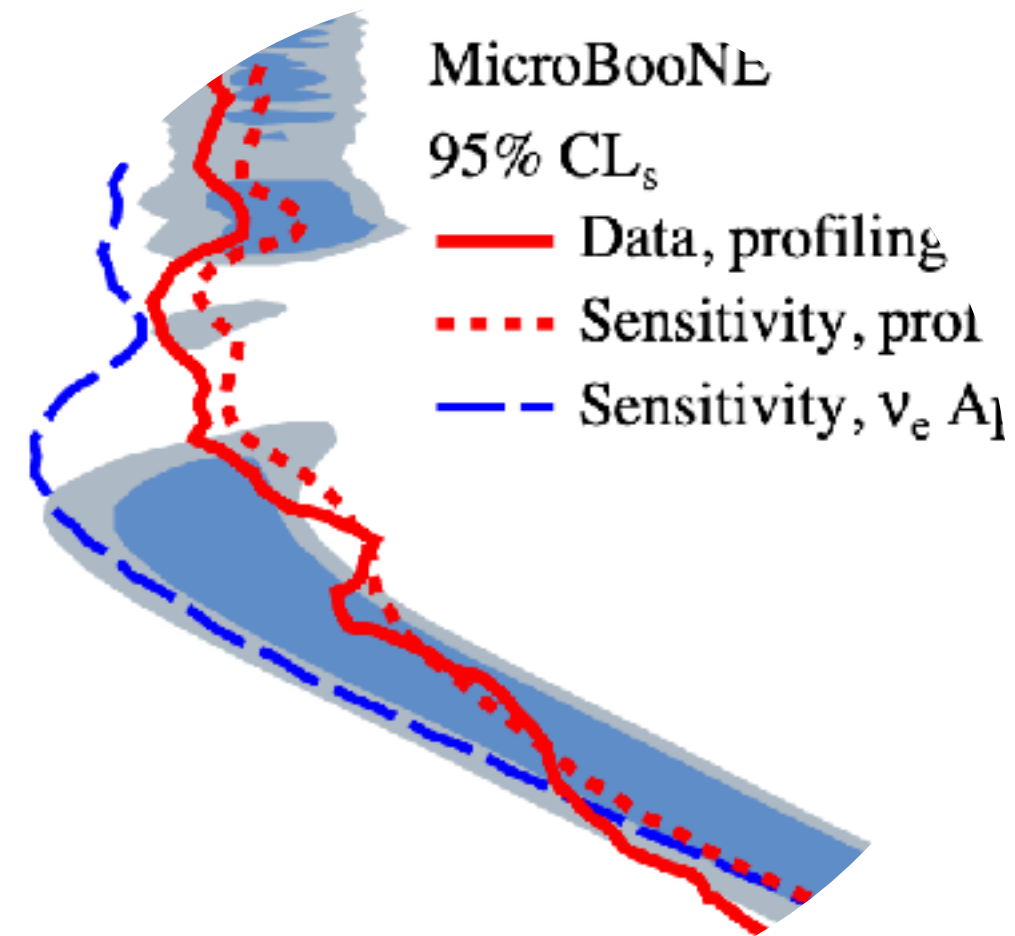


advancing LArTPC  
technology capabilities



# MicroBooNE's Physics Program

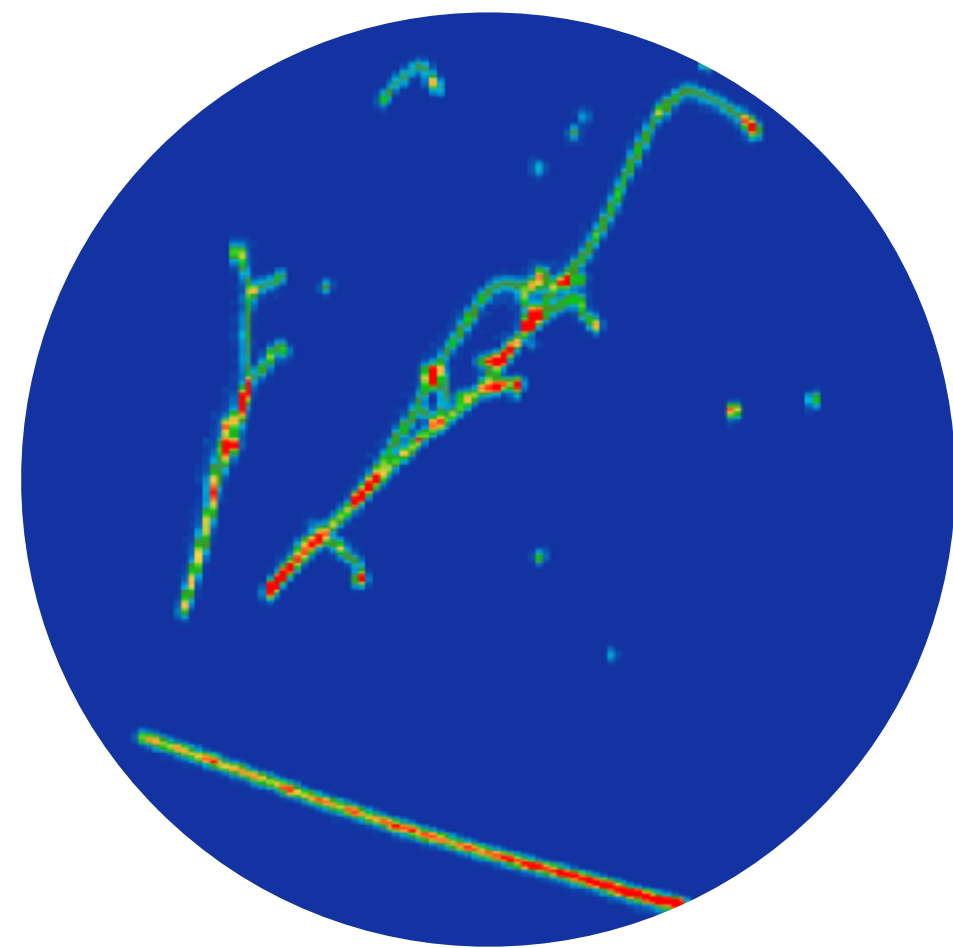
Beyond the Standard  
Model physics searches



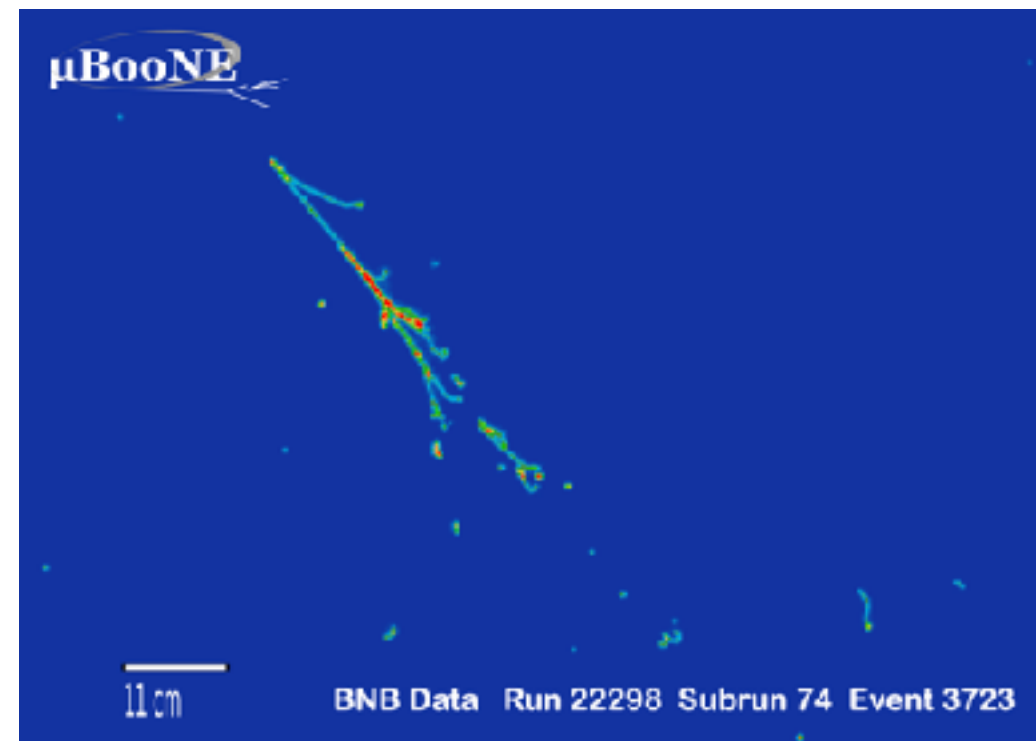
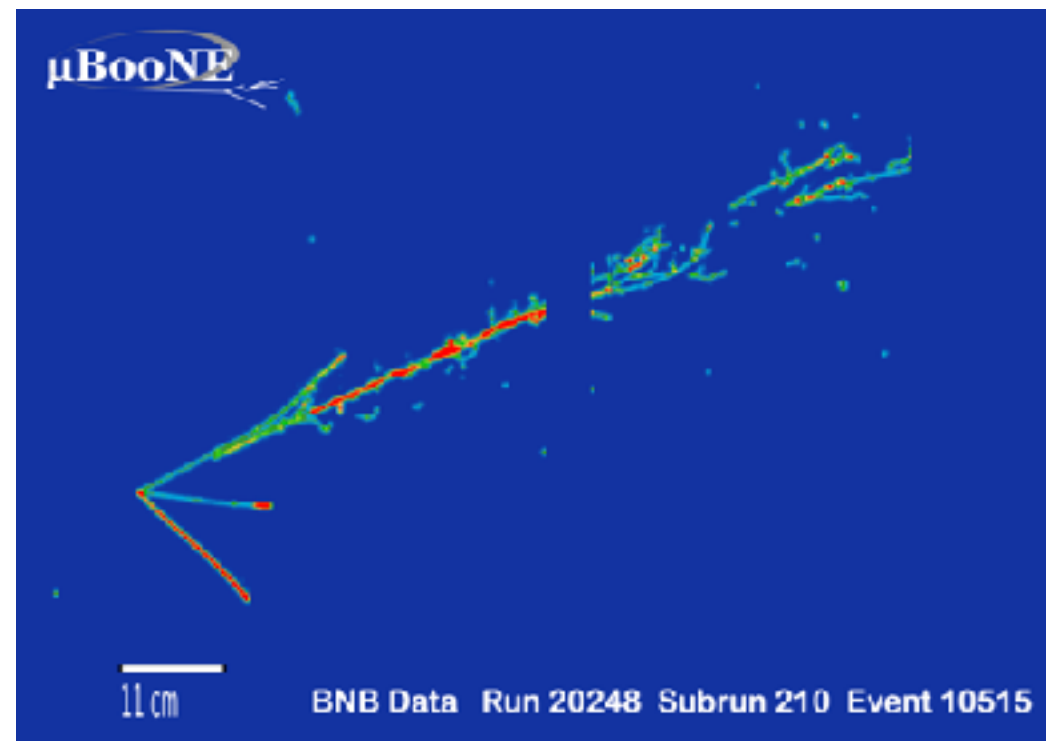
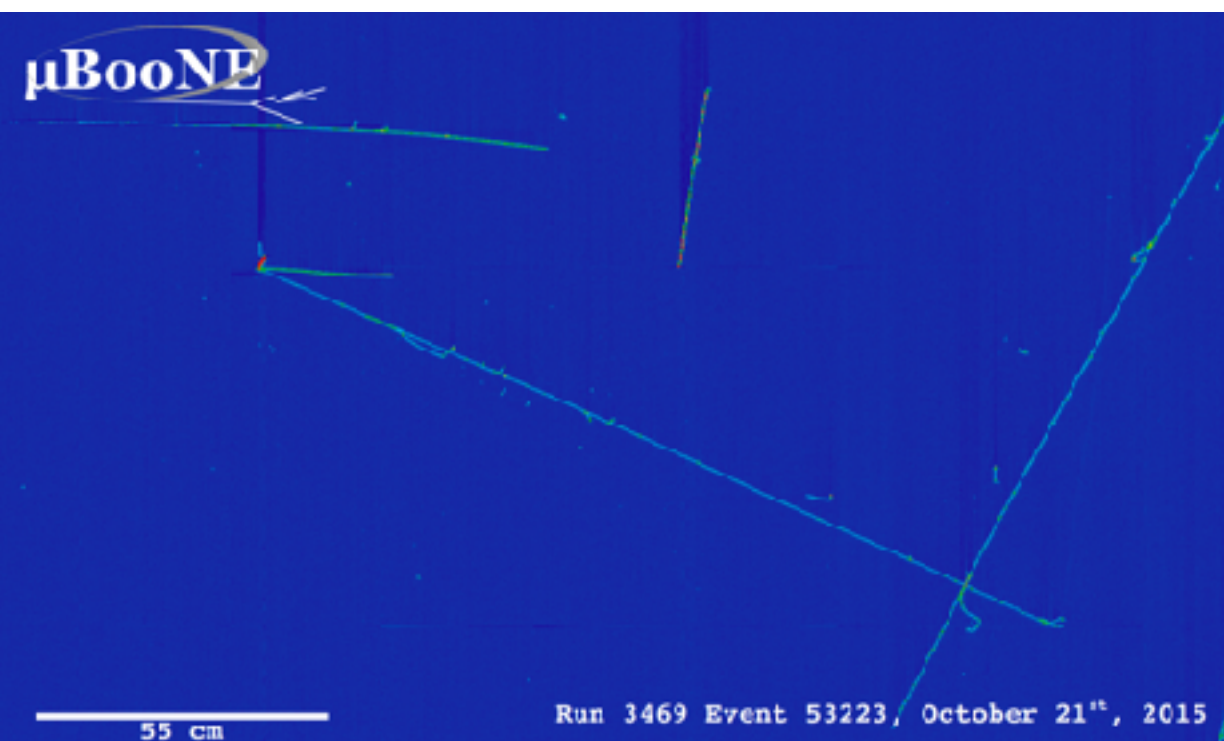
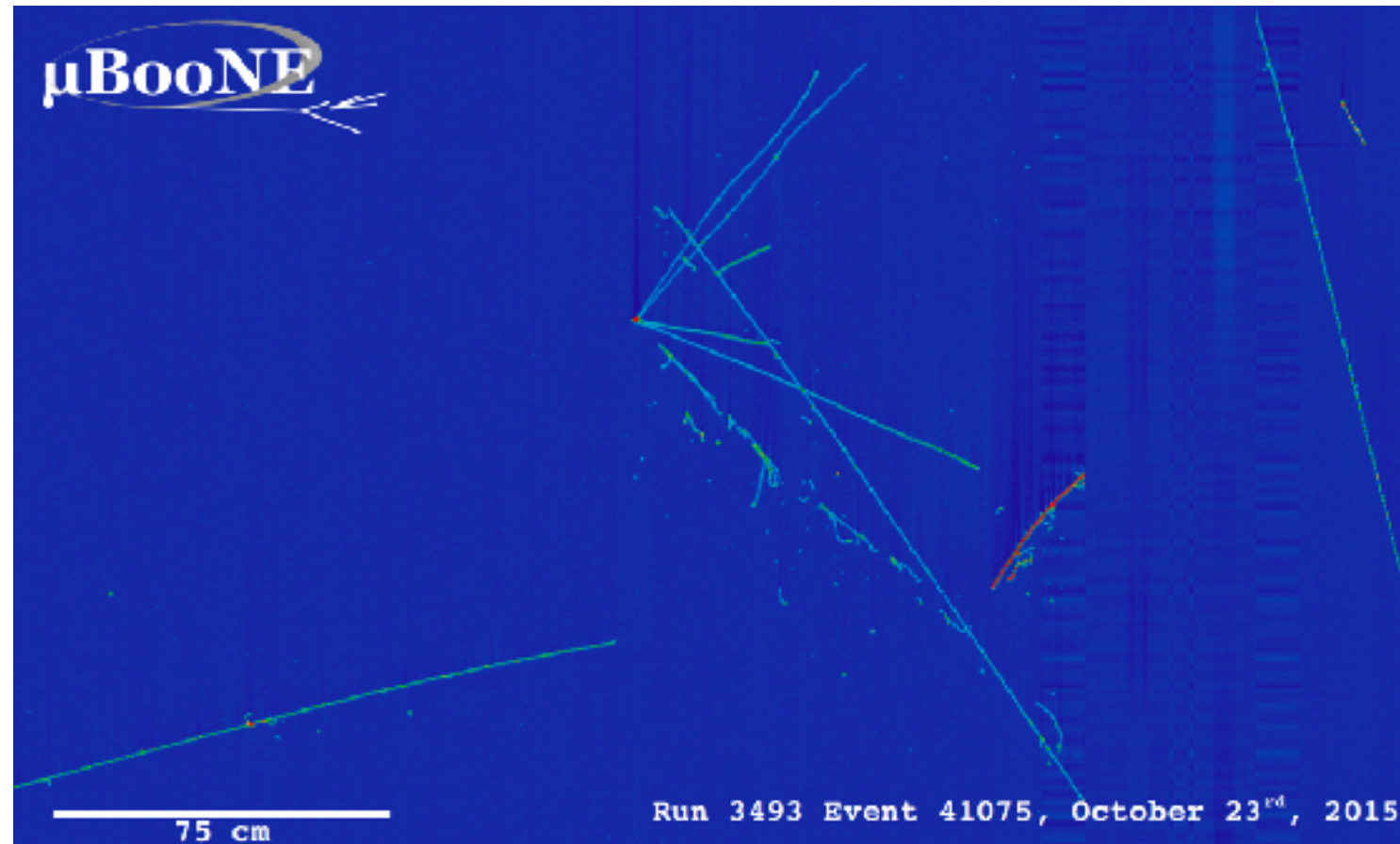
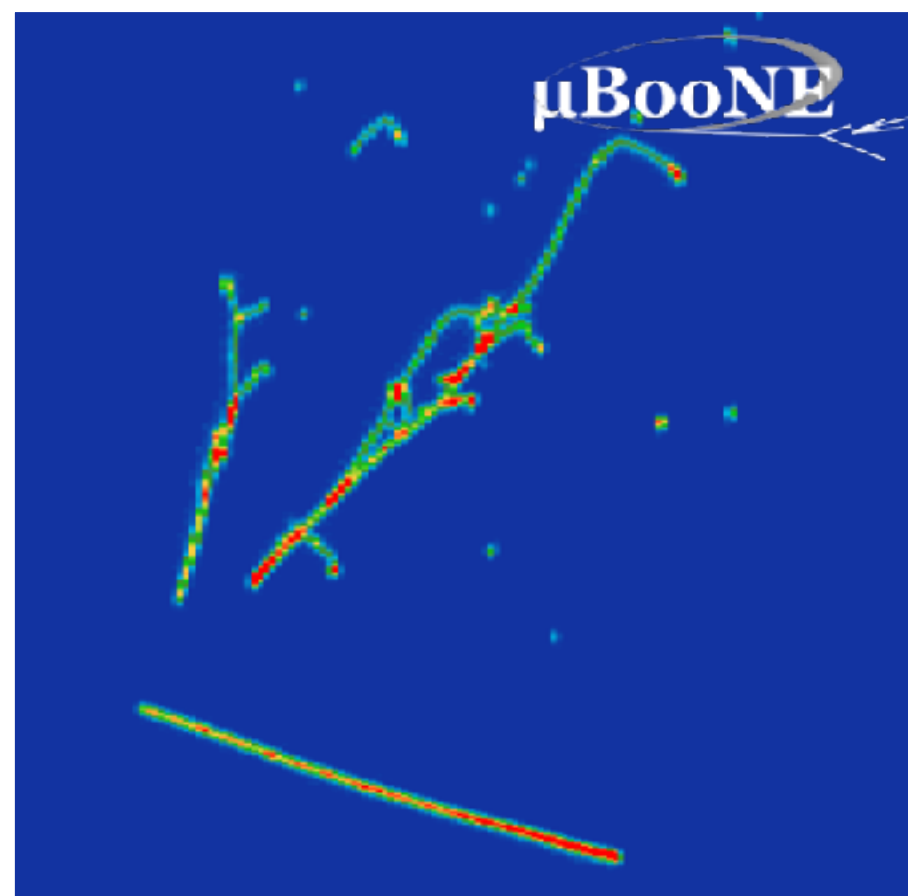
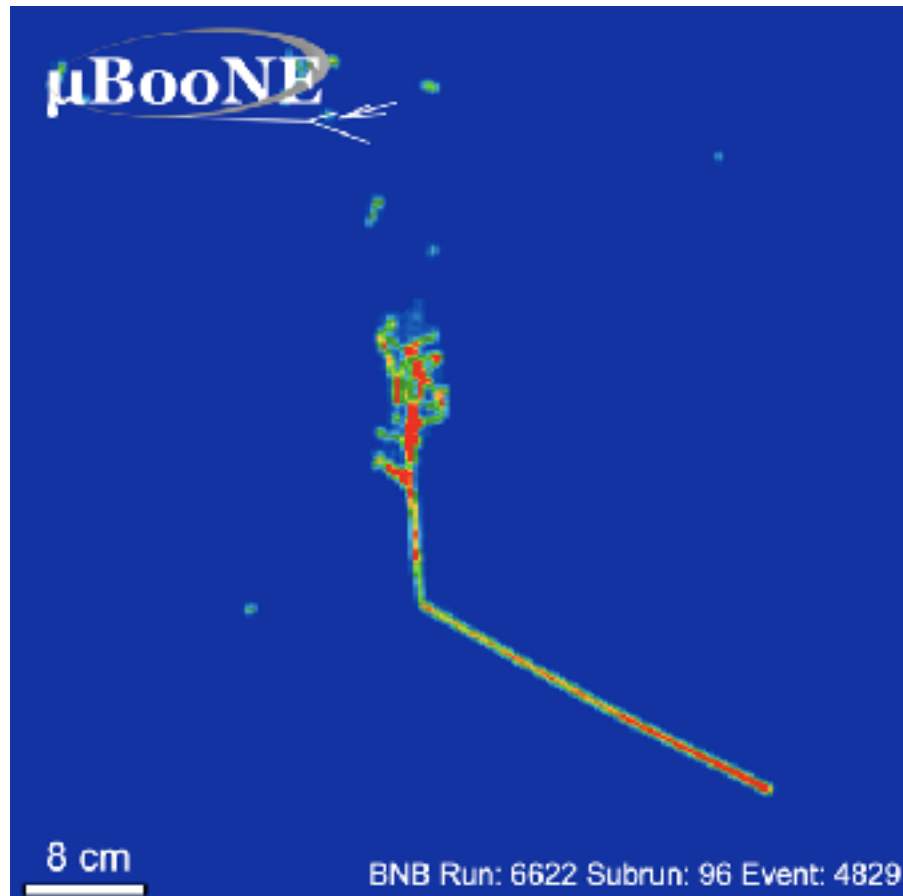
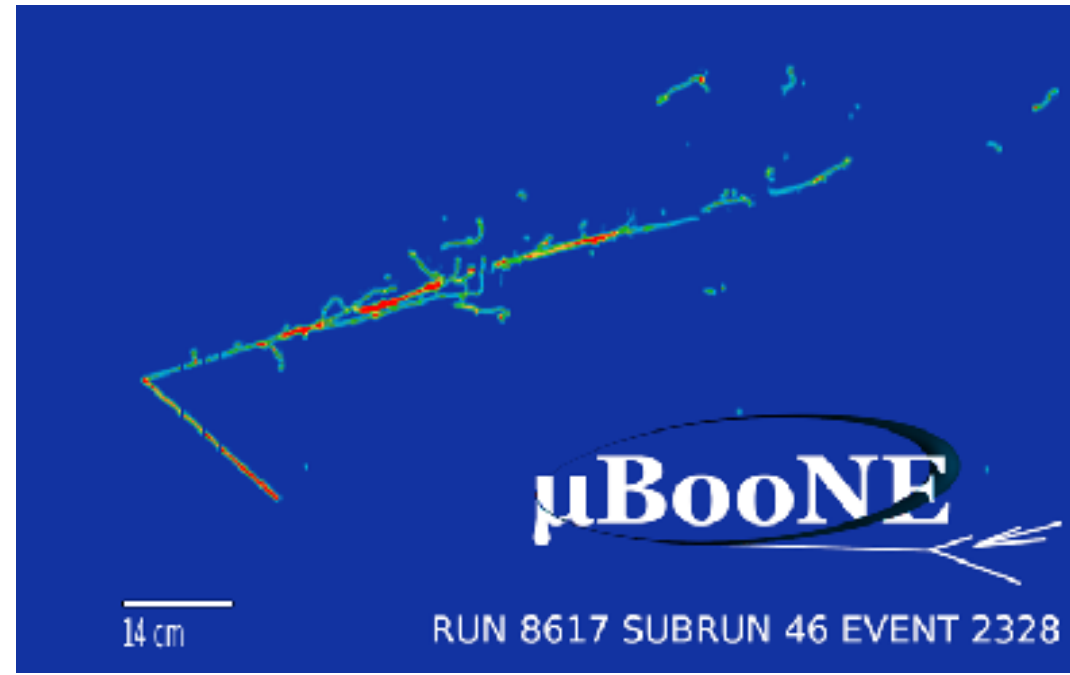
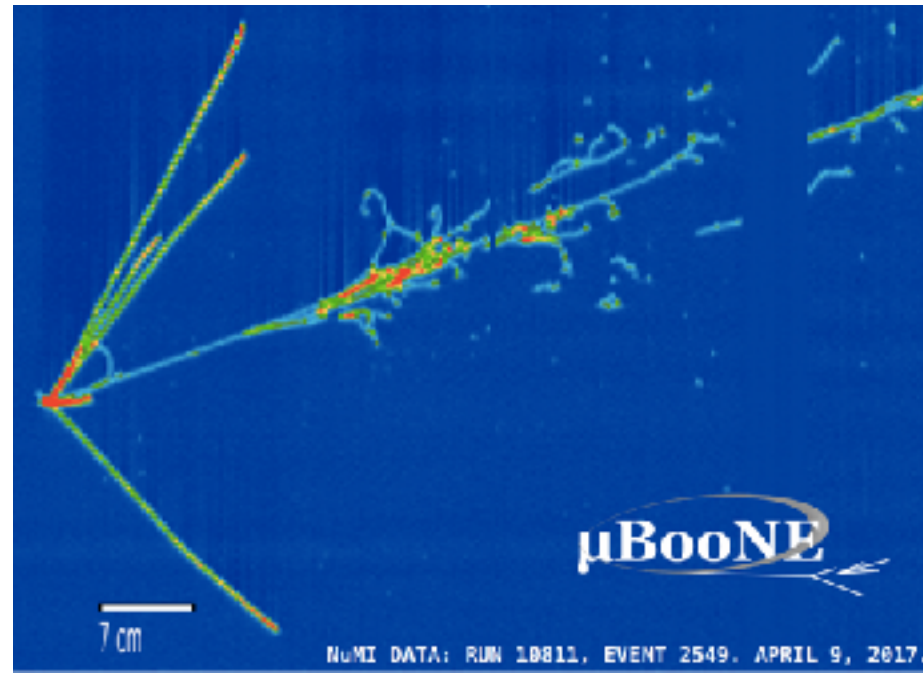
$\nu$  - Ar scattering

See Afroditi Papadopoulou's  
talk on Friday!

advancing LArTPC  
technology capabilities



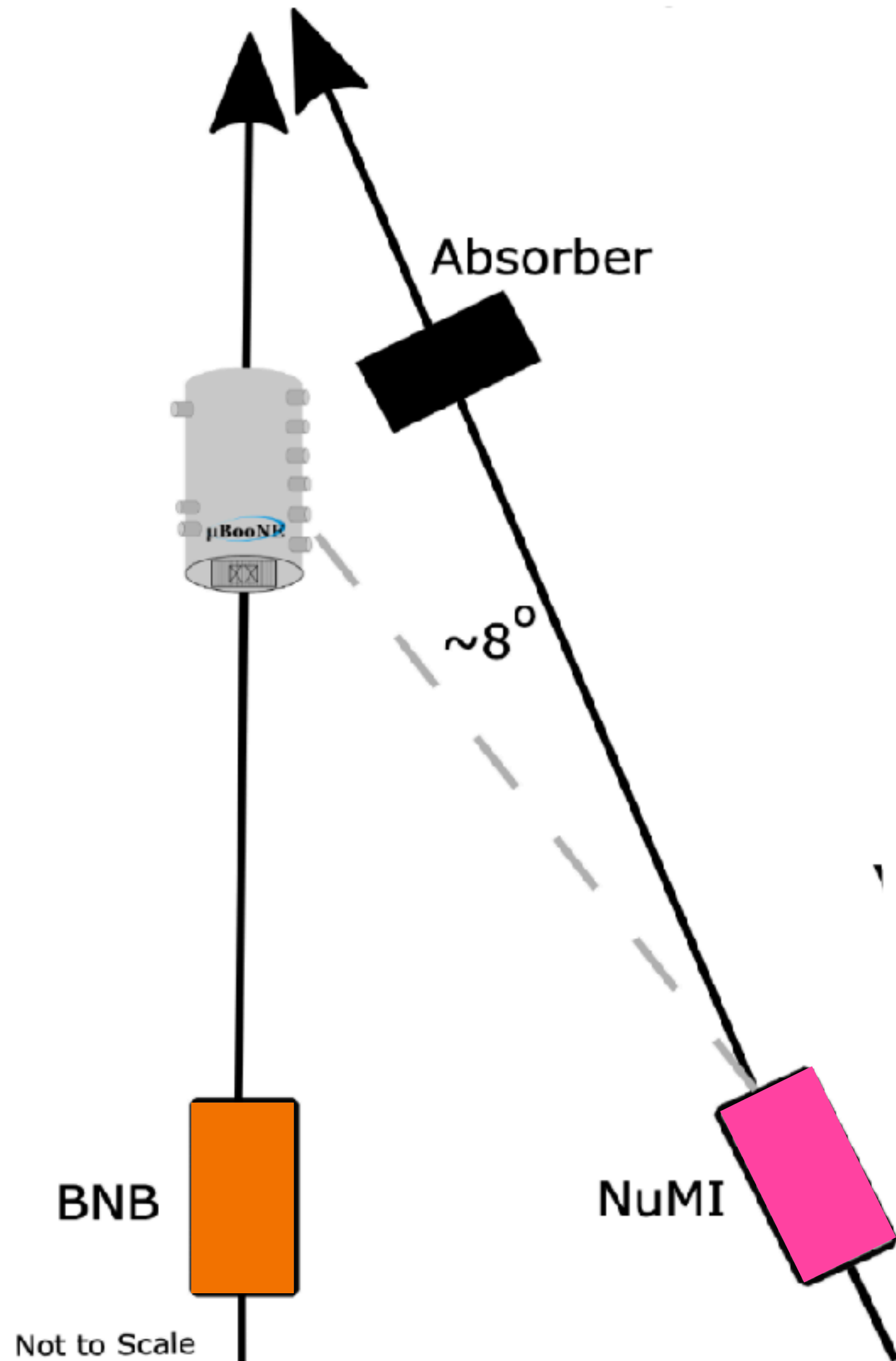
# MicroBooNE's LArTPC detector



Liquid Argon Time Projection Chamber

- millimeter spatial resolution
- excellent calorimetry & Particle ID

# MicroBooNE's neutrinos: BNB & NuMI



## Booster Neutrino Beamline:

- on-axis
- 99.5%  $\nu_\mu$  / 0.5%  $\nu_e$
- 0.1 - 1 GeV energy
- 470 meter baseline

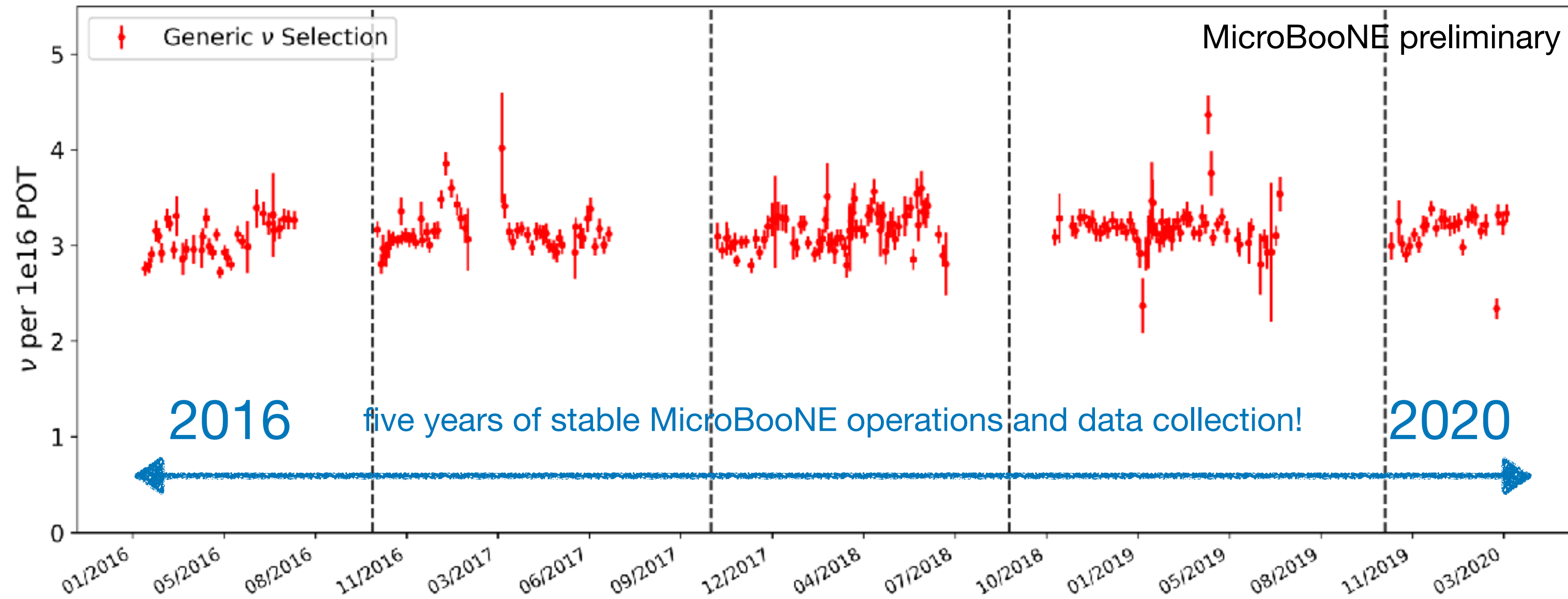
## NuMI:

- 8 degrees off-axis
- 95%  $\nu_\mu$  / 5%  $\nu_e$
- 50/50  $\nu/\bar{\nu}$
- Flux from target and absorber



O(500k) neutrino interactions collected

# Five years of neutrino data!



Longest continuously operating LArTPC

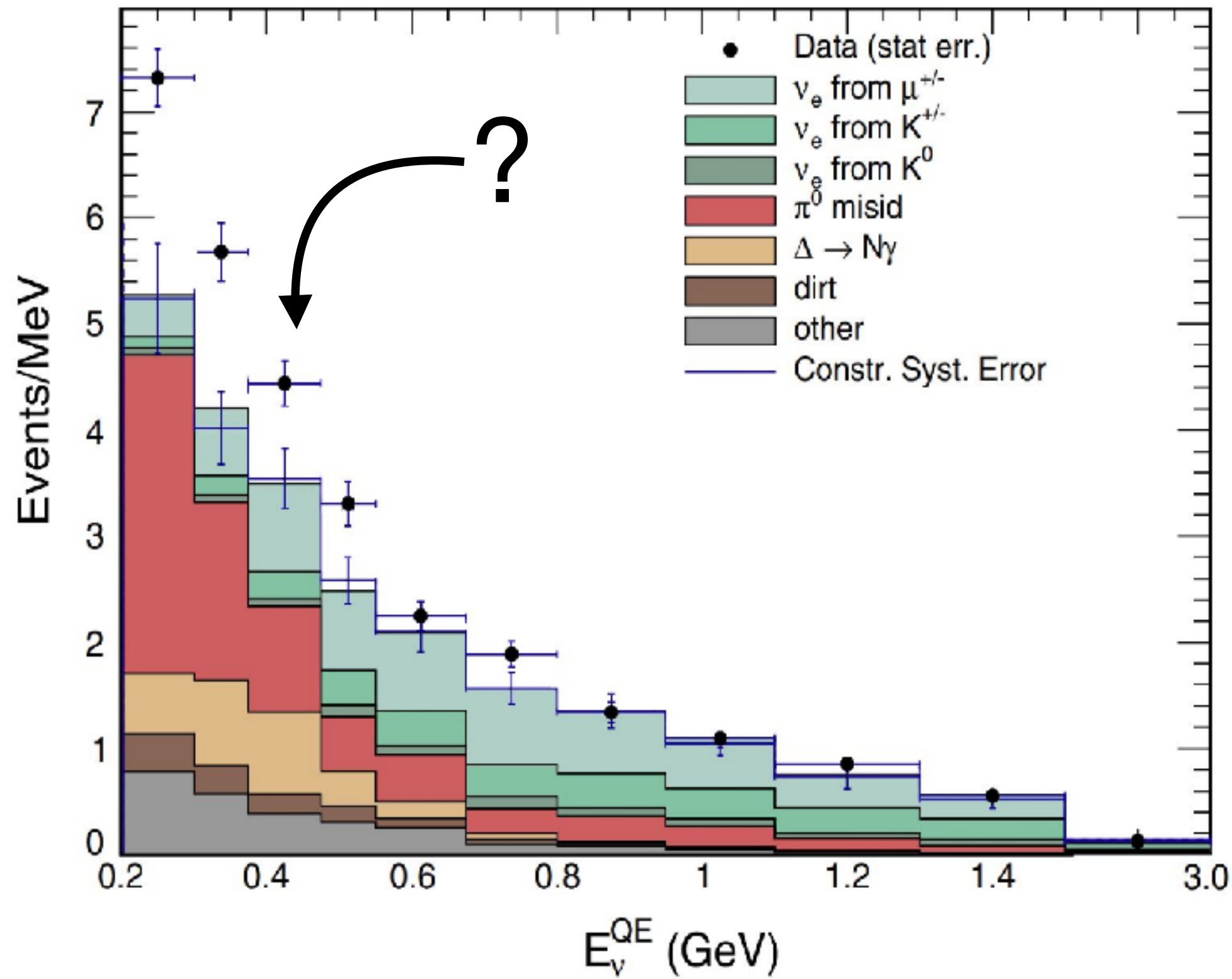
Five years of data @ Fermilab '15 - '20

195 collaborators from 38 institutions

[MicroBooNE papers on iNSPIRE](#)

# MicroBooNE's BSM physics program

Phys. Rev. D 103, 052002 MiniBooNE Collab.



Investigate the MiniBooNE “Low Energy Excess”

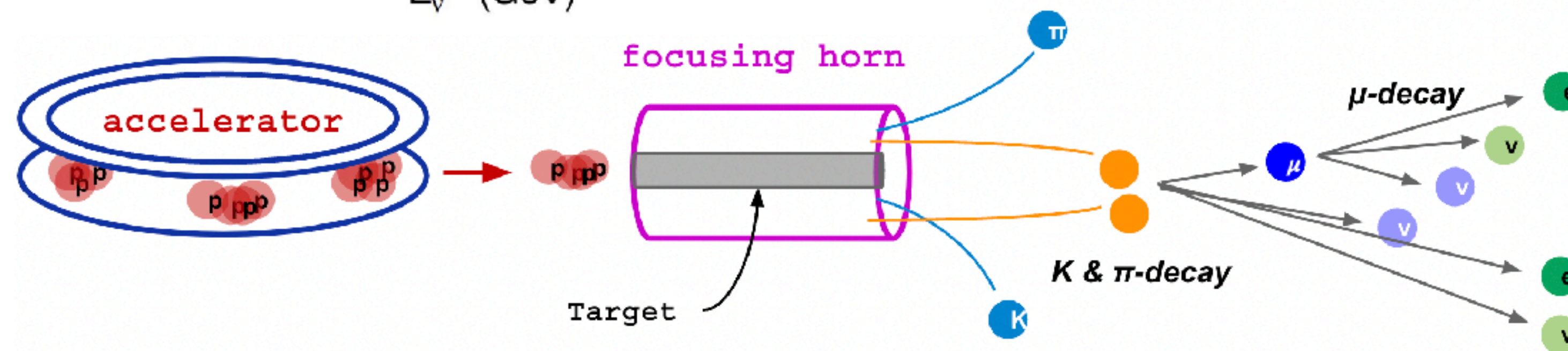
Outstanding anomaly for > 10 years

same BNB beam  
same baseline  
new detector!

broad physics program

Leverage BNB & NuMI beam lines

search for feebly interacting BSM particles



$\chi\bar{\chi}$  ----->

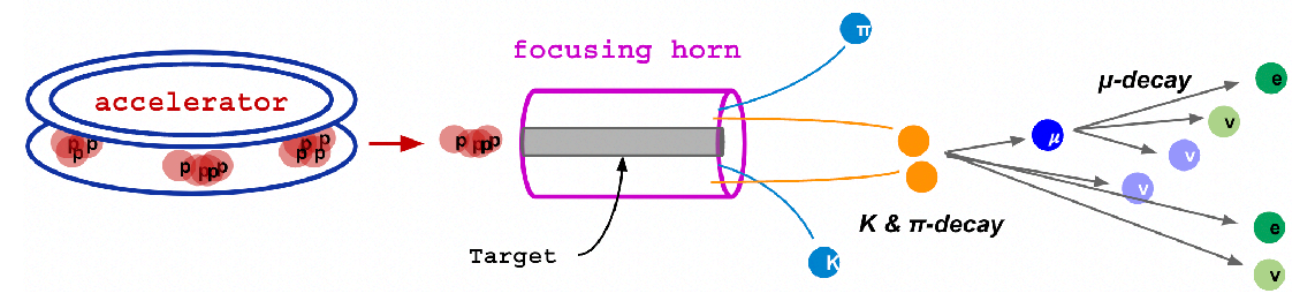
$\nu N$  ---->

$Z'$  ----->

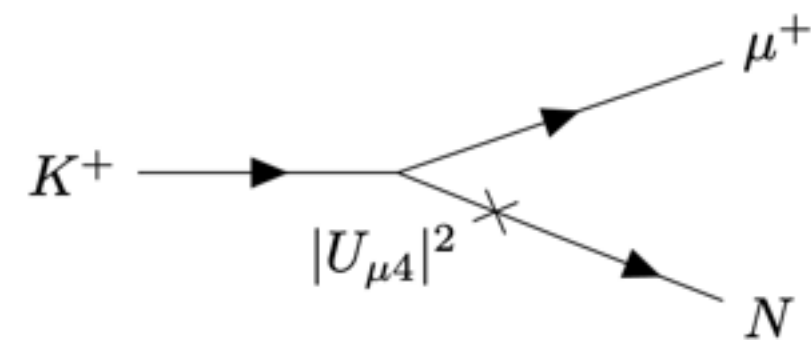


# Heavy Neutral Lepton searches

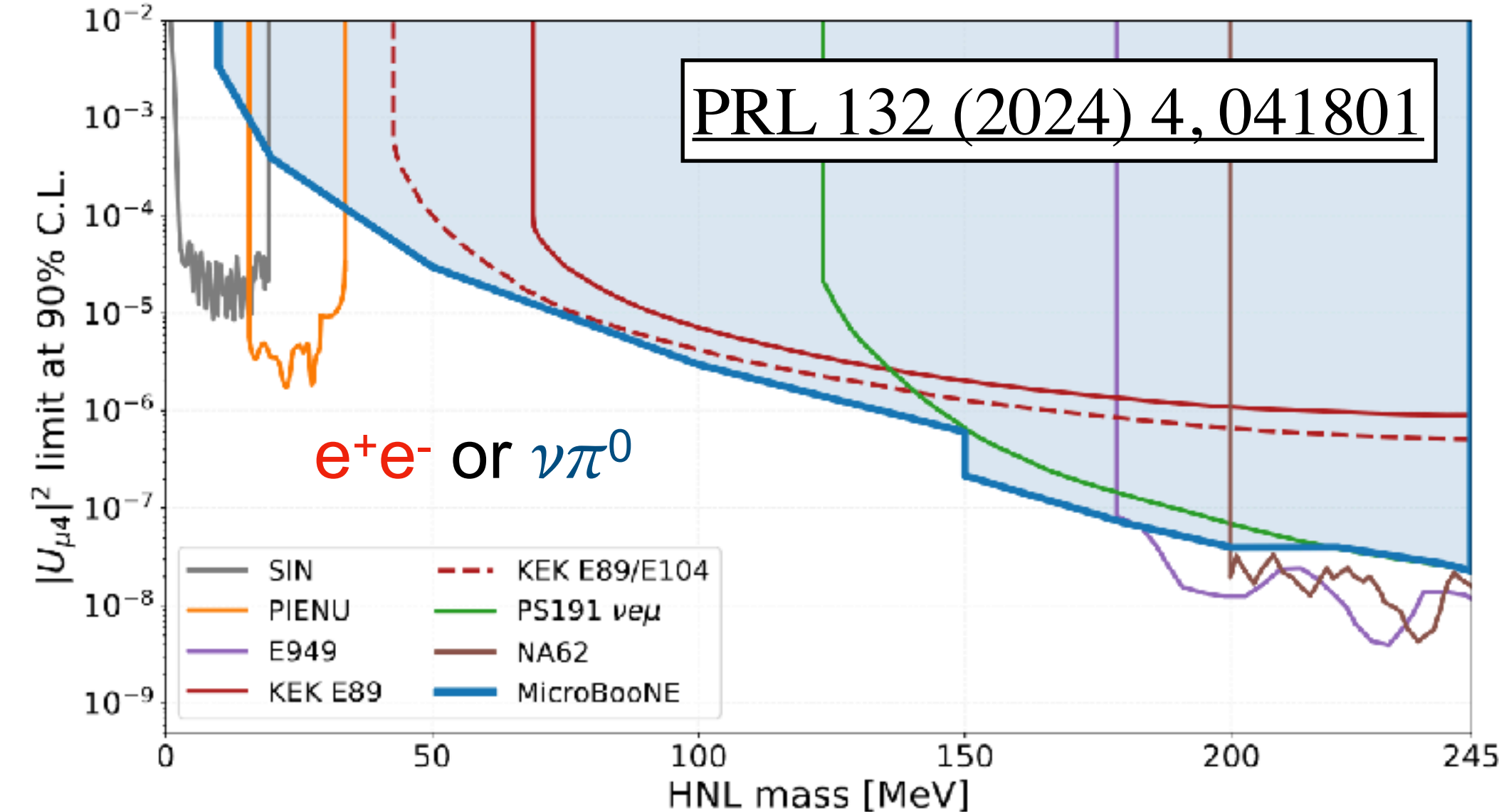
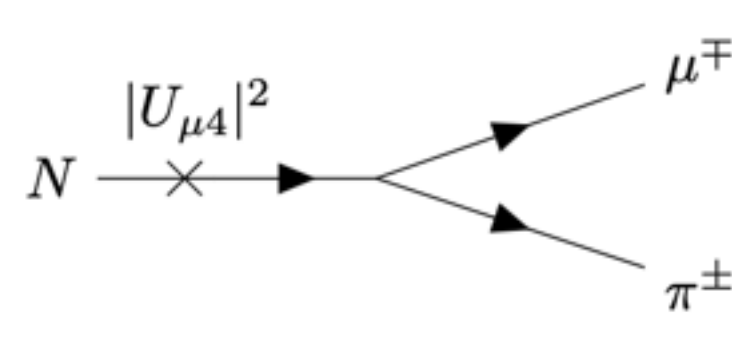
# New Results!



produced in beam via mixing



decay in the detector

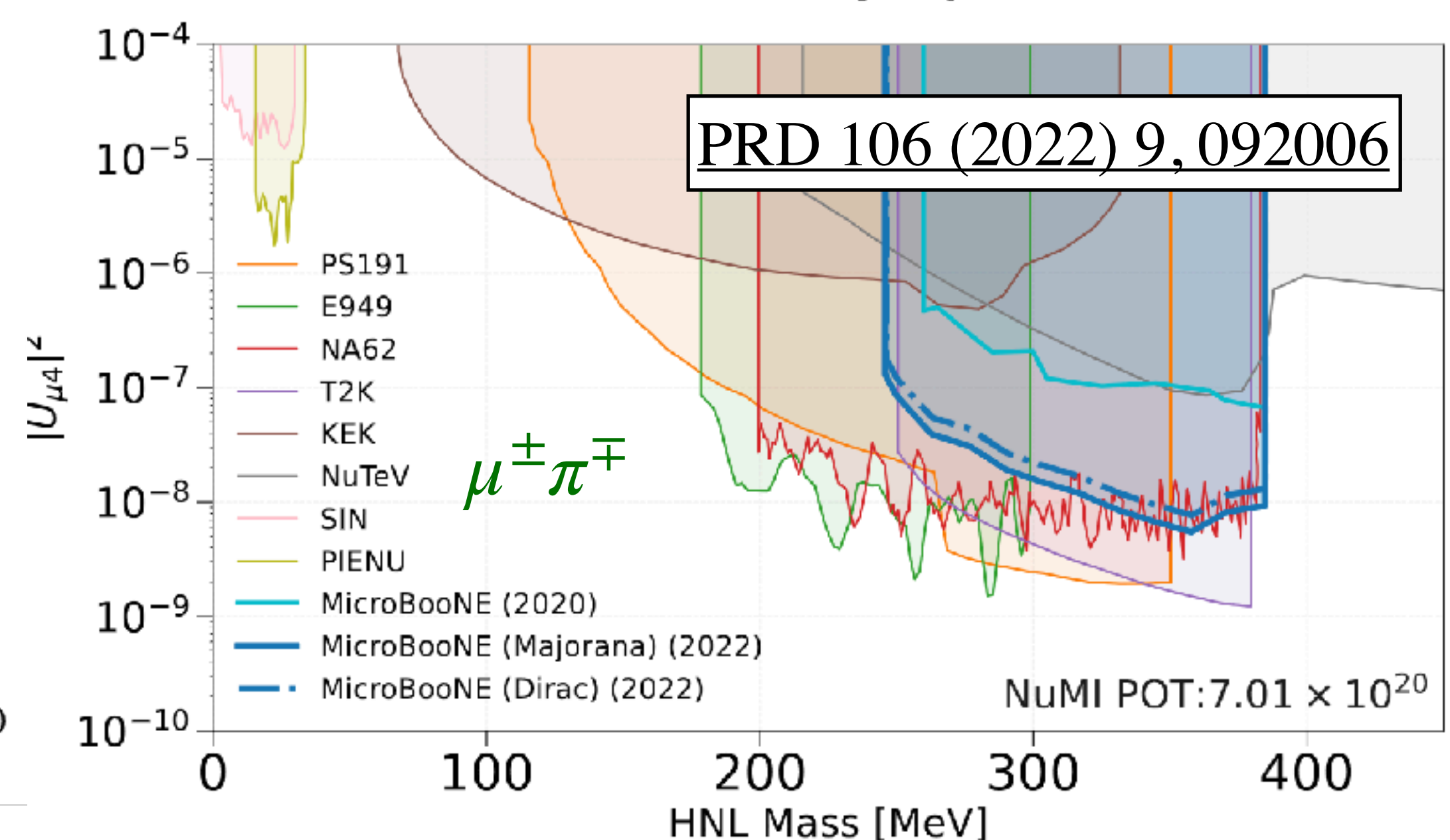
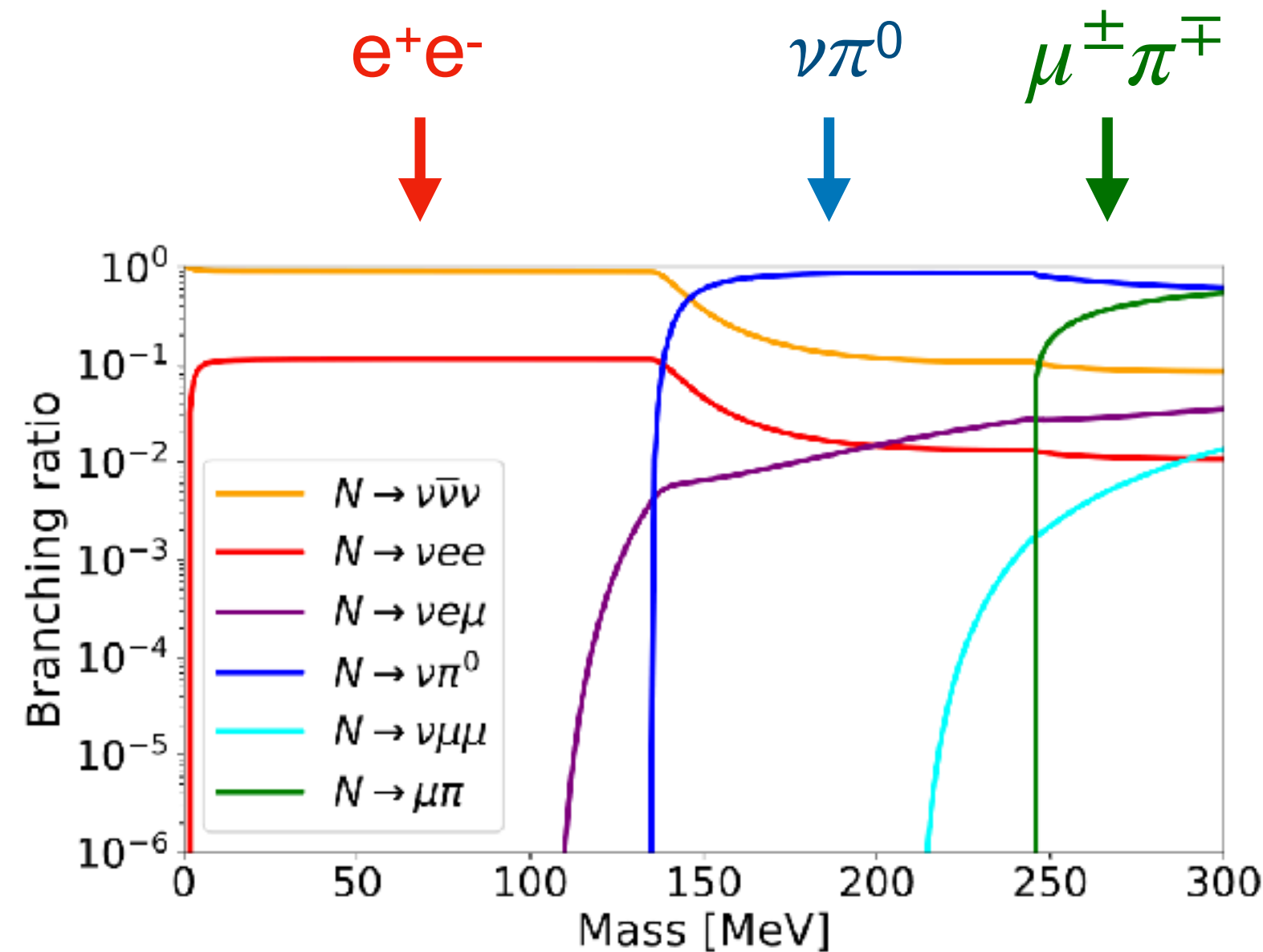


Heavy Neutral Leptons tied to:

- origin of neutrino mass
- Baryon asymmetry
- Dark Matter

Improve on past uB results:

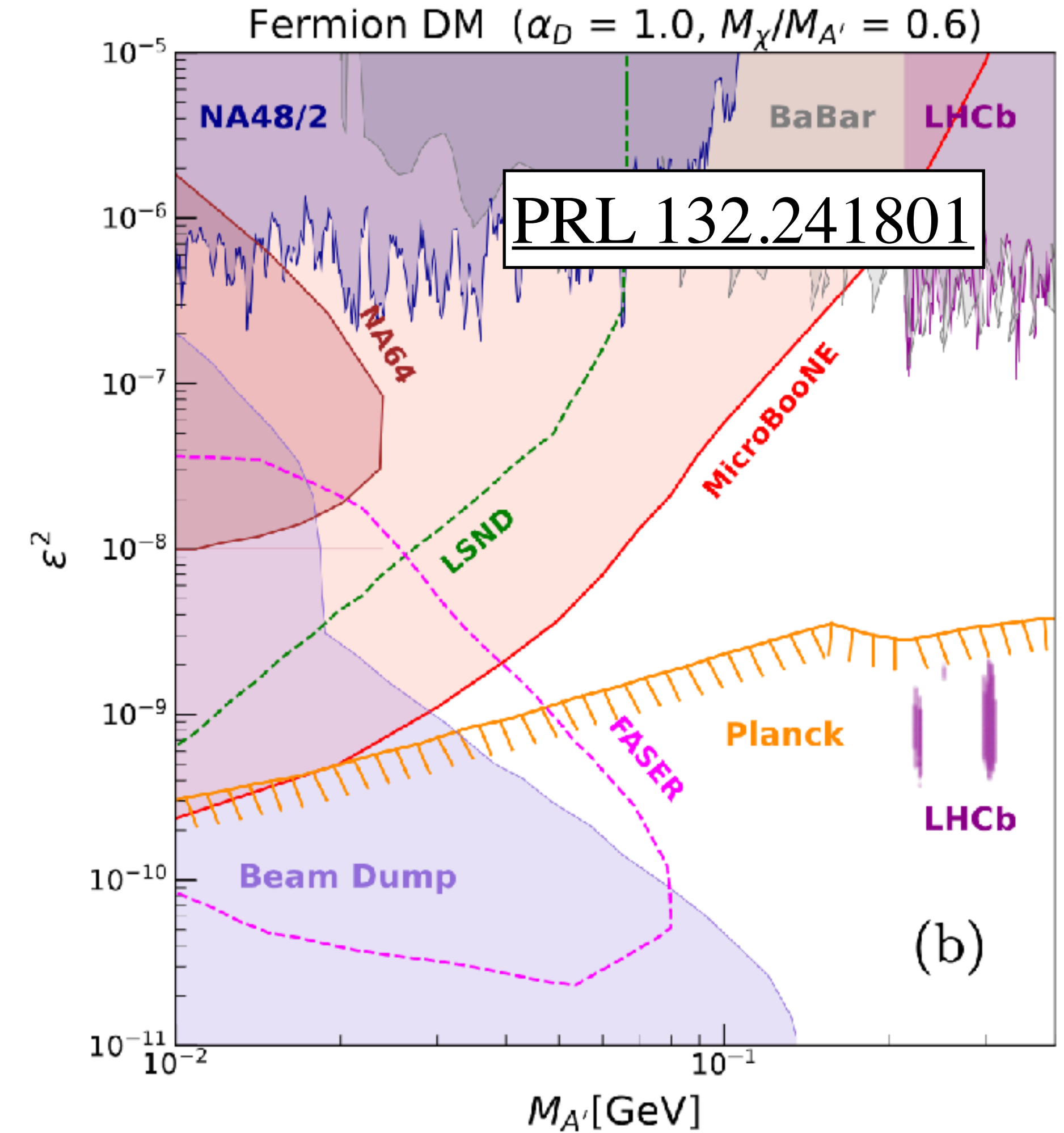
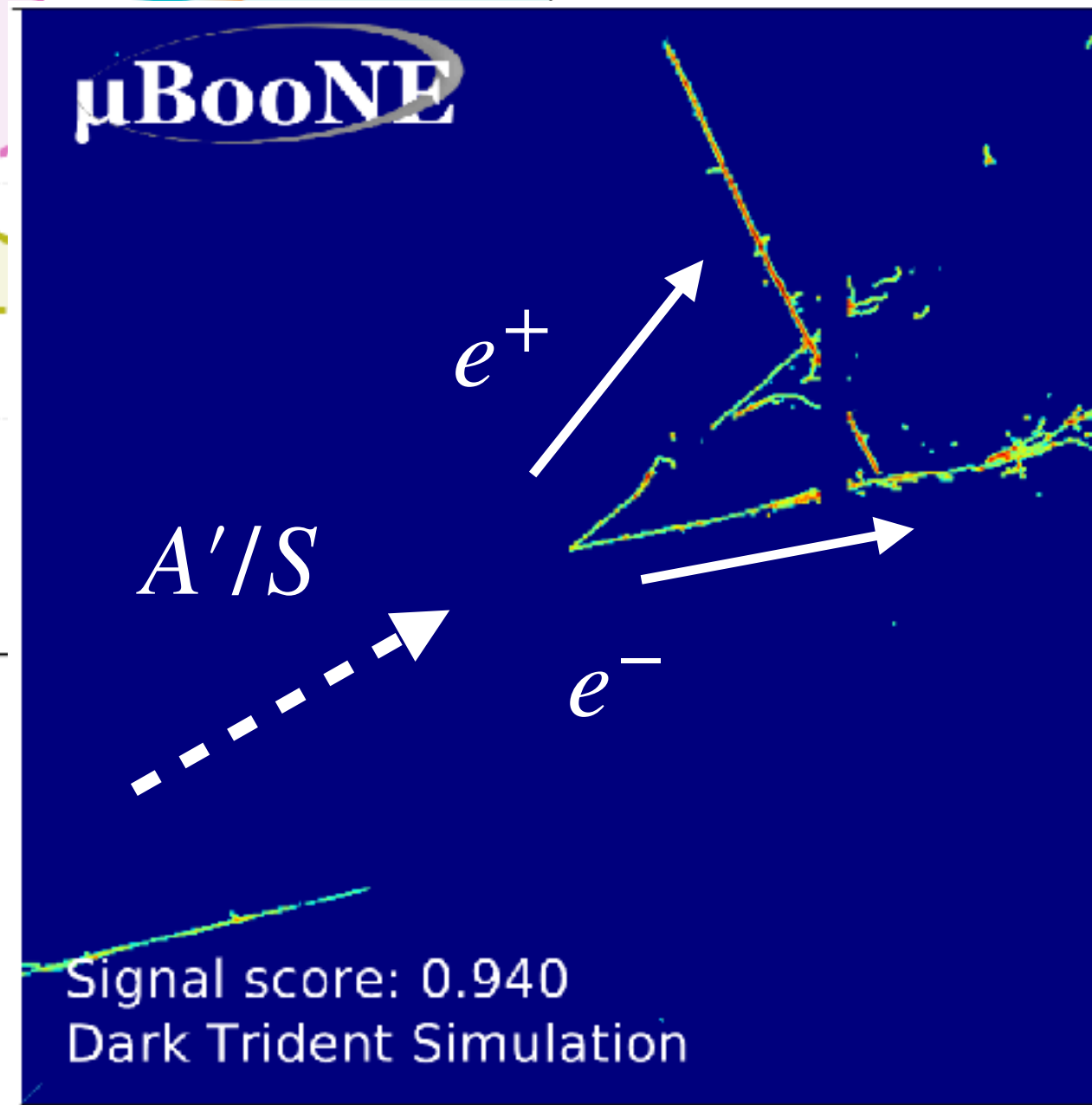
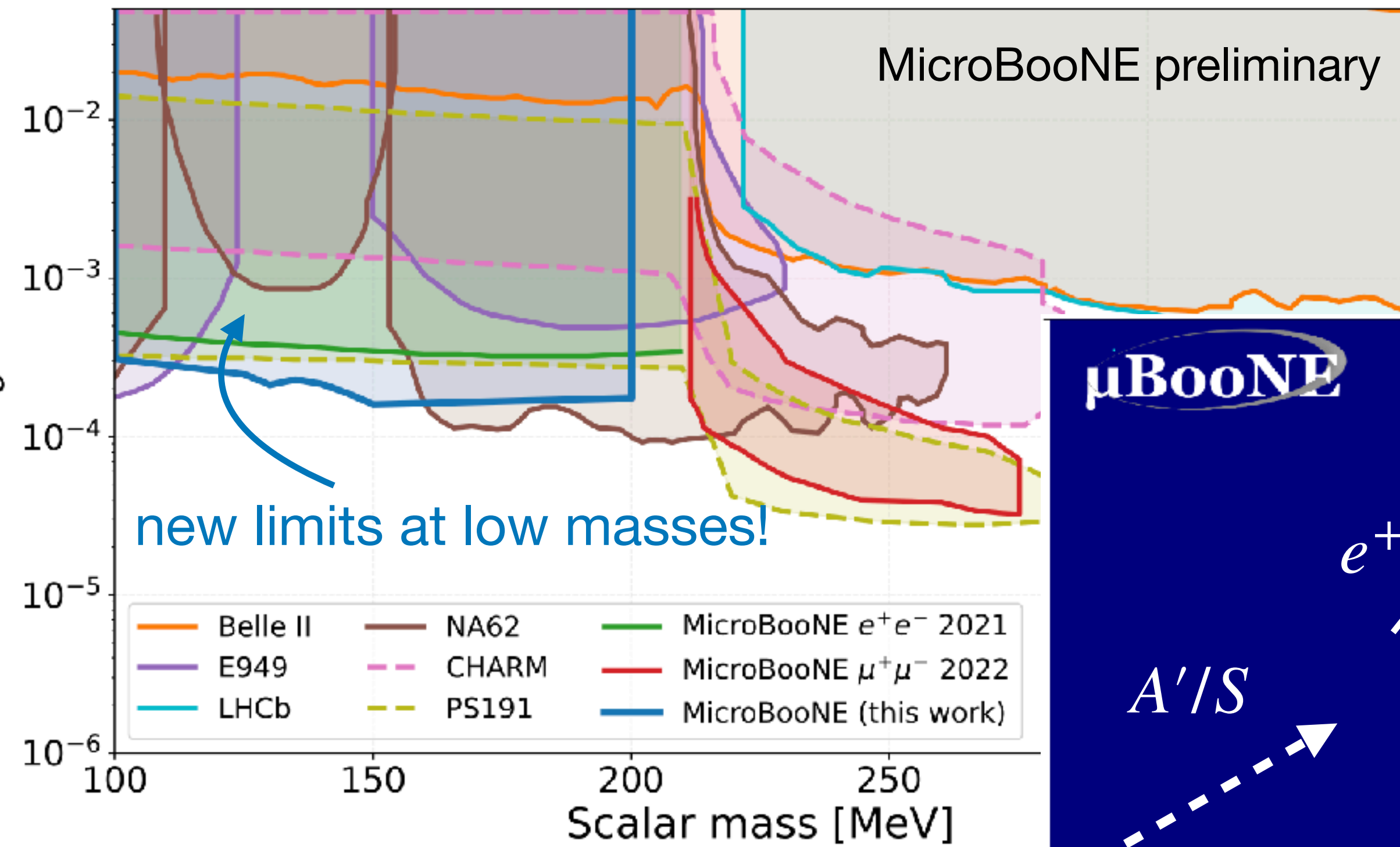
- NuMI absorber
- $e^+e^- / \pi^0$  sensitive to lower HNL masses.



leading limits at low mass



# Dark Tridents & Higgs Portal Scalars New Results!



sub-GeV **Dark Sector** searches:

Dark Tridents: “vector portal”

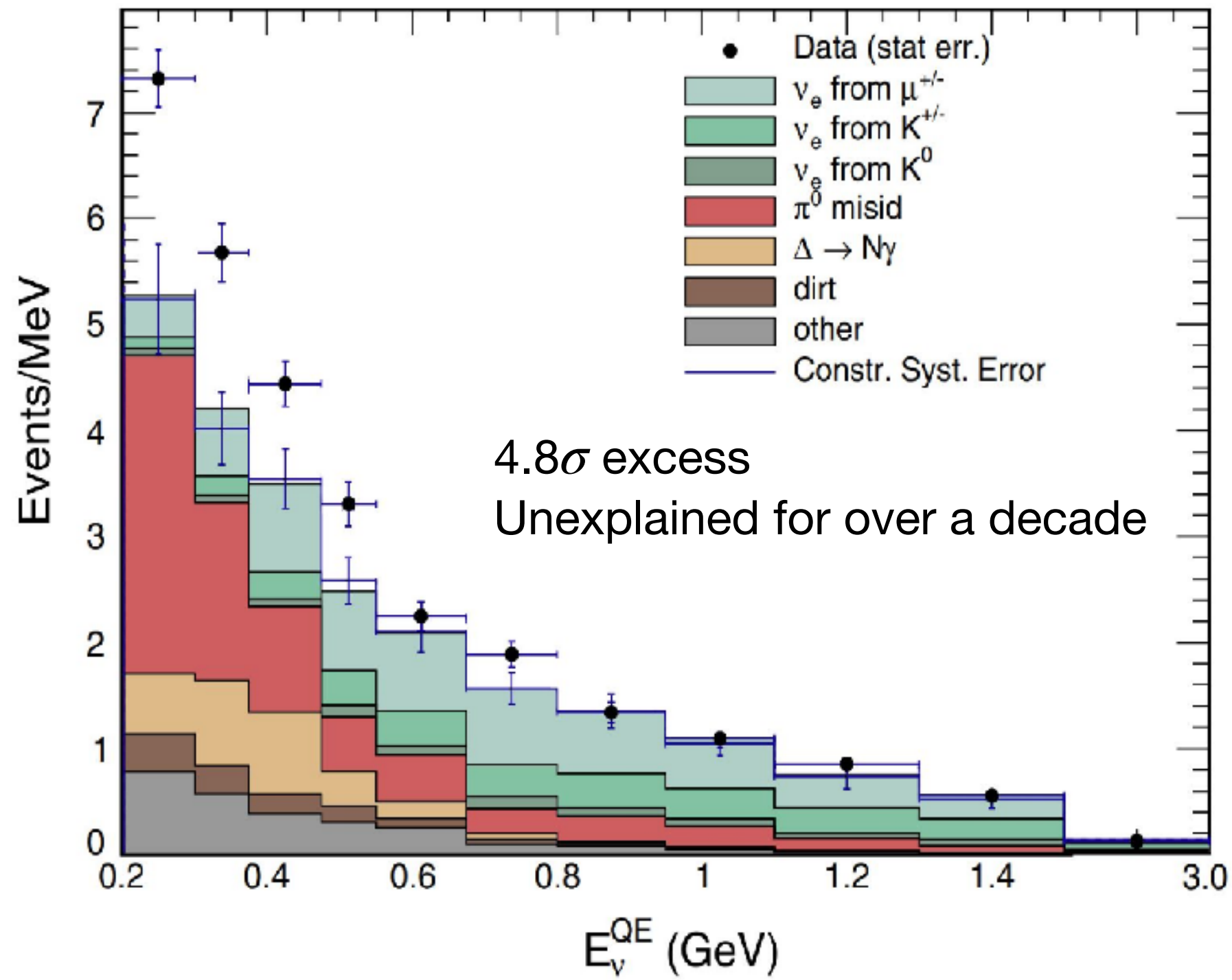
Higgs Portal Scalar: “Higgs portal”

Can decay to  $e^+e^-$  final-state in TPC

“Dark Sector Searches with MicroBooNE”  
POSTER #634 [Friday]

# “Low Energy Excess” search

Phys. Rev. D 103, 052002 MiniBooNE Collab.



Expanding on MicroBooNE’s ‘21 results:

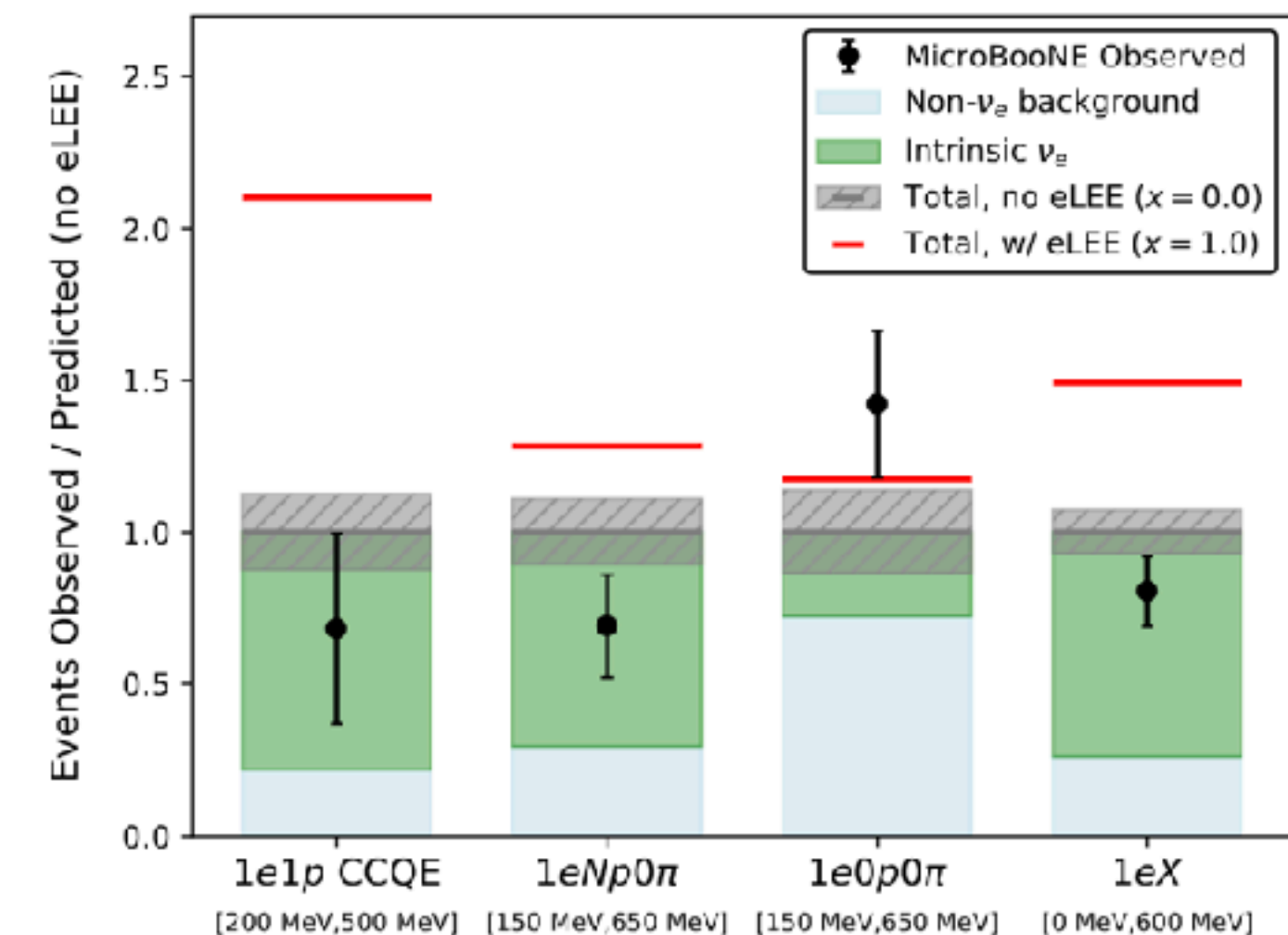
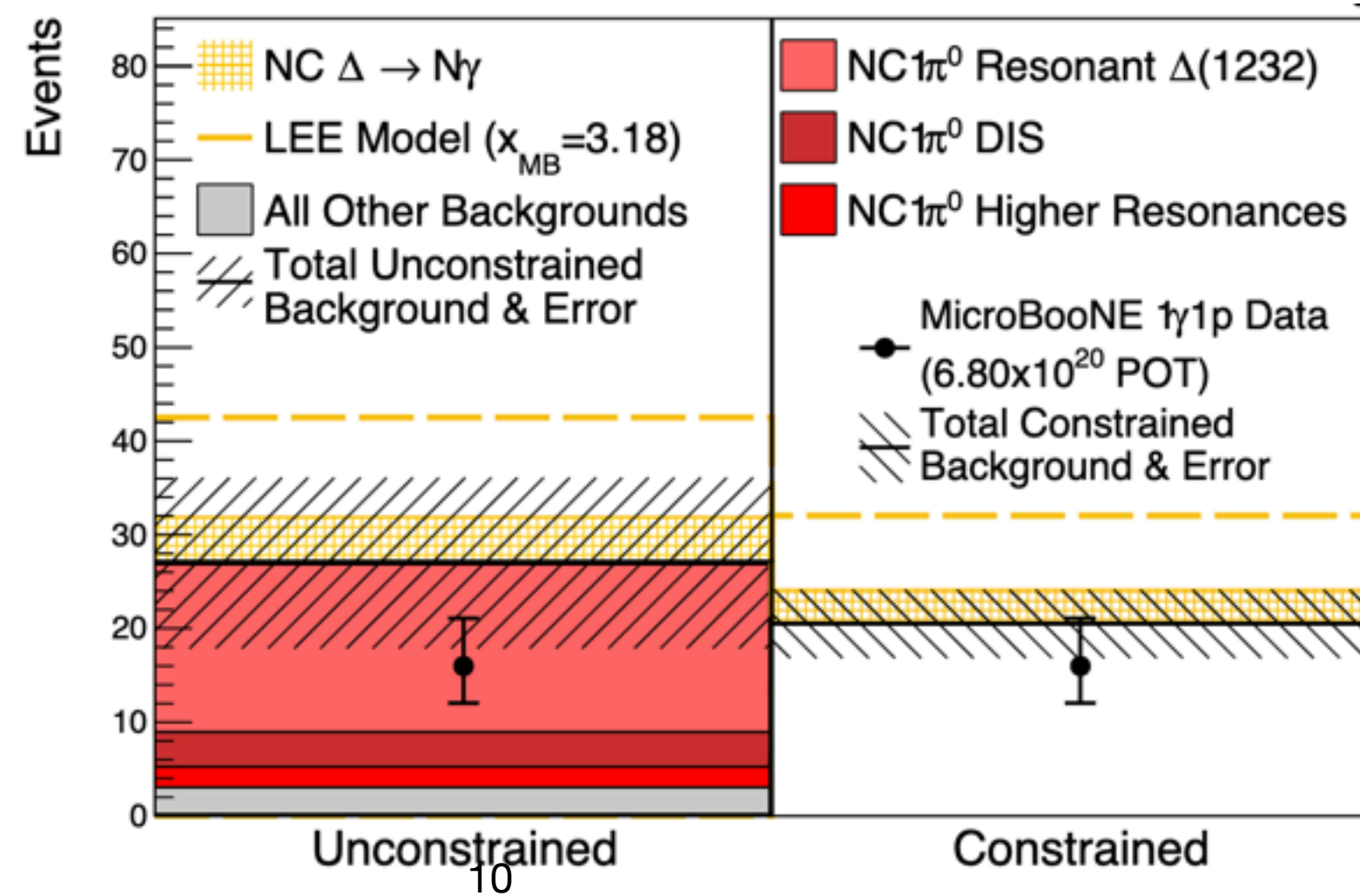
- new  $e^+e^-$  BSM-focused analyses
- comprehensive **single- $\gamma$**  searches
- expanded  $\nu_e$  excess analysis

$\nu_e$  ?  $\nu_s$  ? **single- $\gamma$  ?**  
 $e^+e^-$  ?

“Low Energy Excess Searches” [POSTER #628 \[Tuesday\]](#)

PRL 128 (2022) 111801

PRL 128 (2022) 24, 241801



# LEE Search: BSM $e^+e^-$

Dark Neutrinos decaying to  $e^+e^-$  pairs.

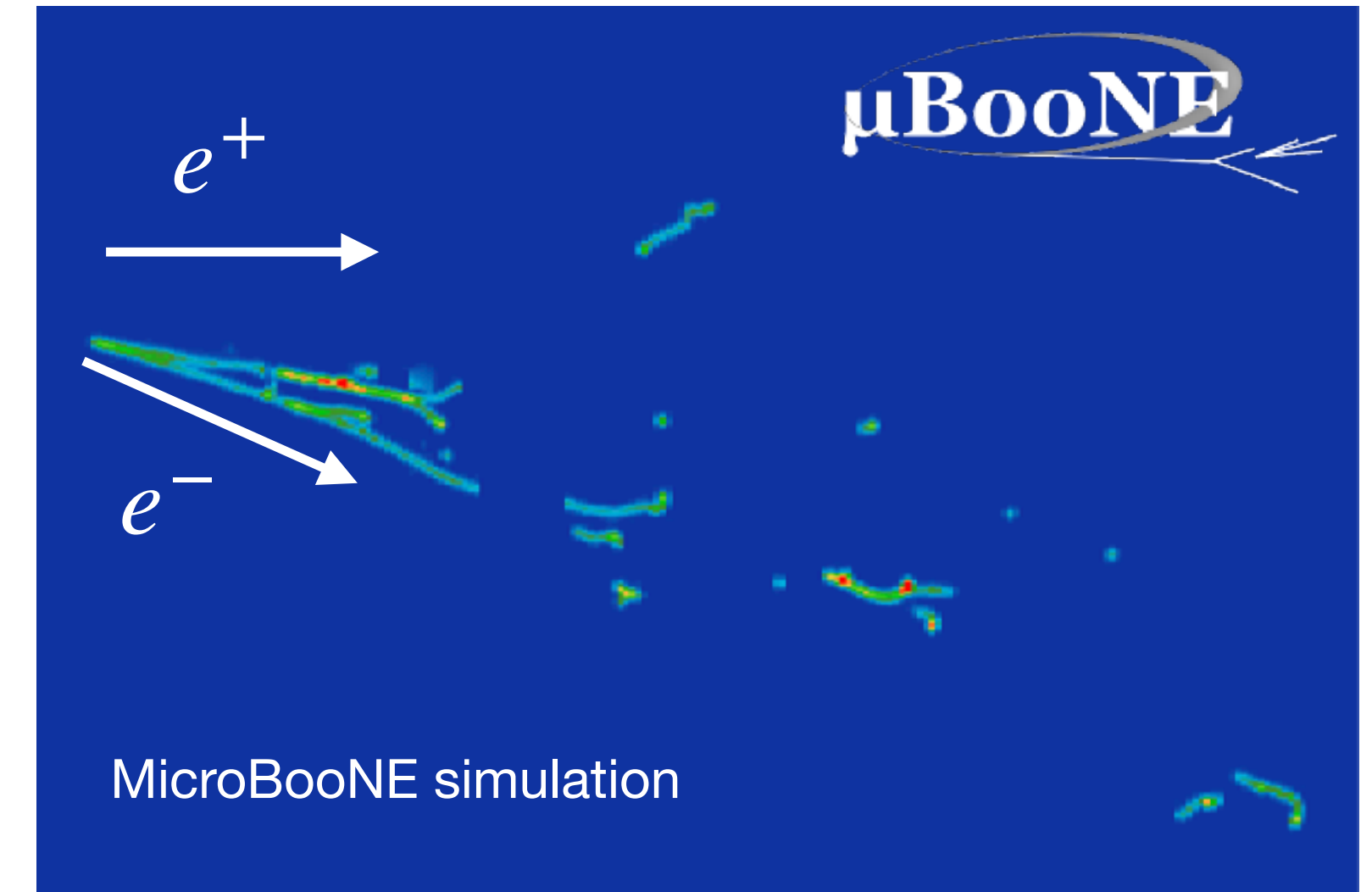
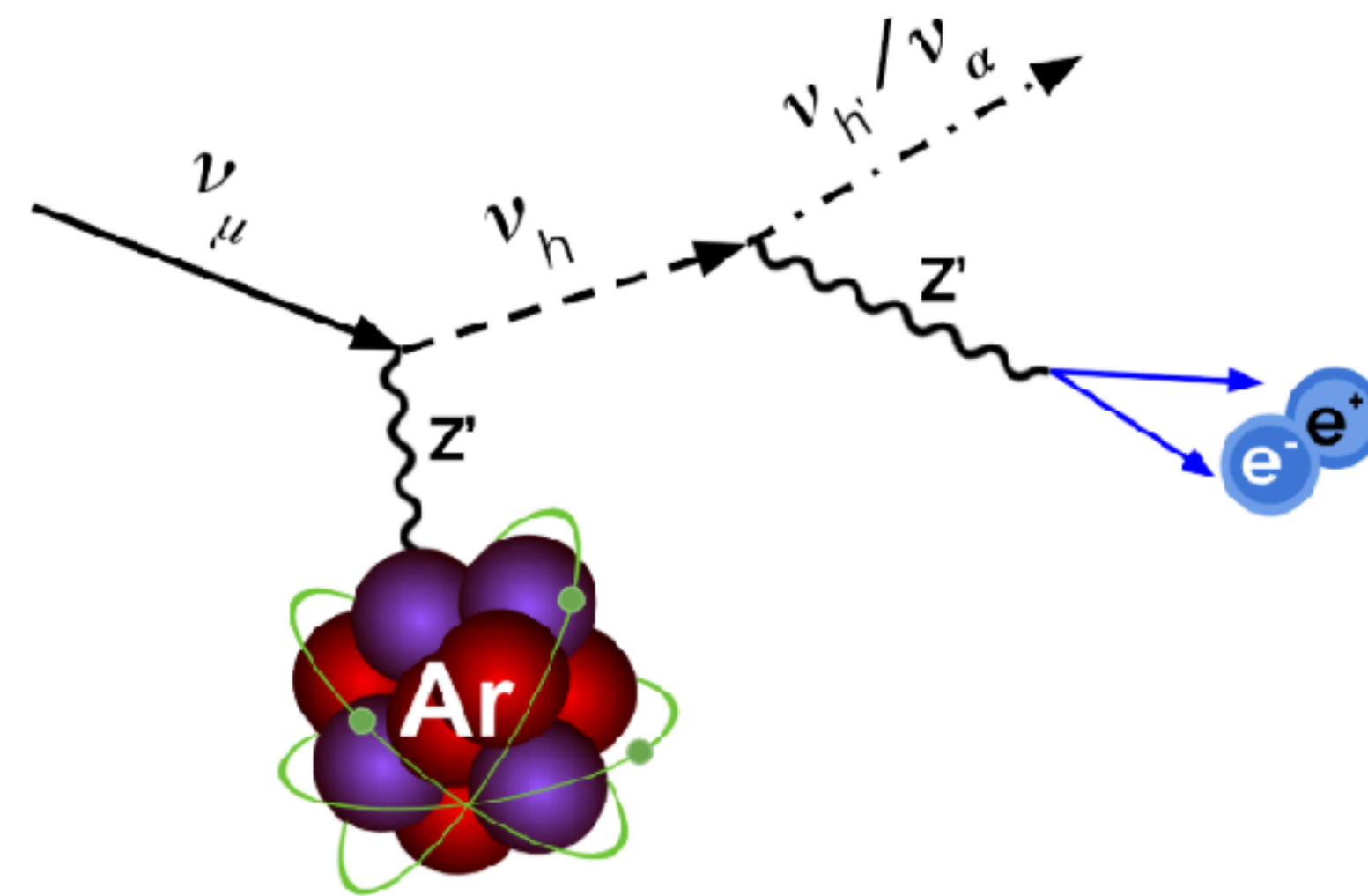
Based on:

Ballet, Pascoli, Ross-Lonergan  
[PRD 99 \(2019\) 071701](#)

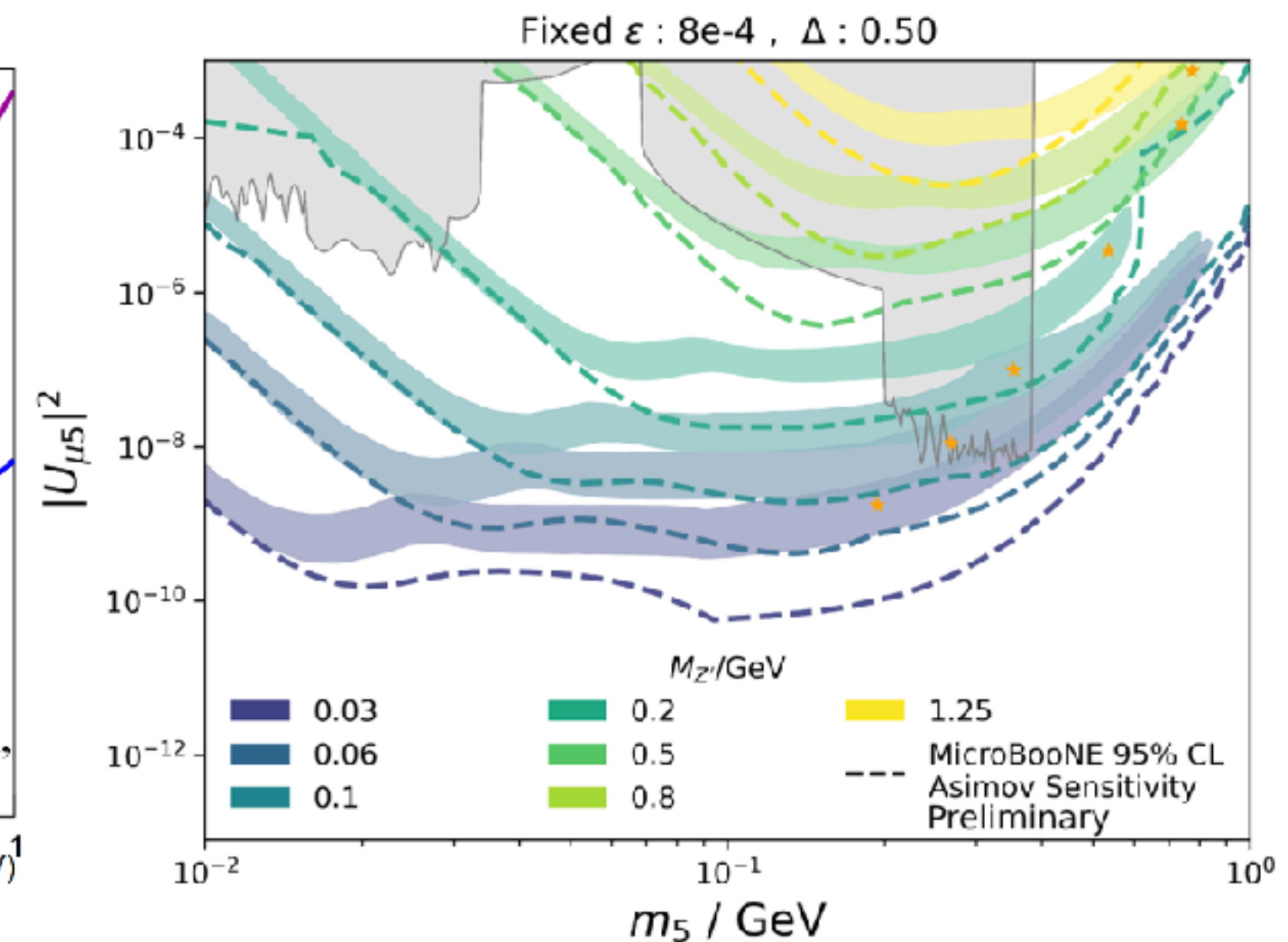
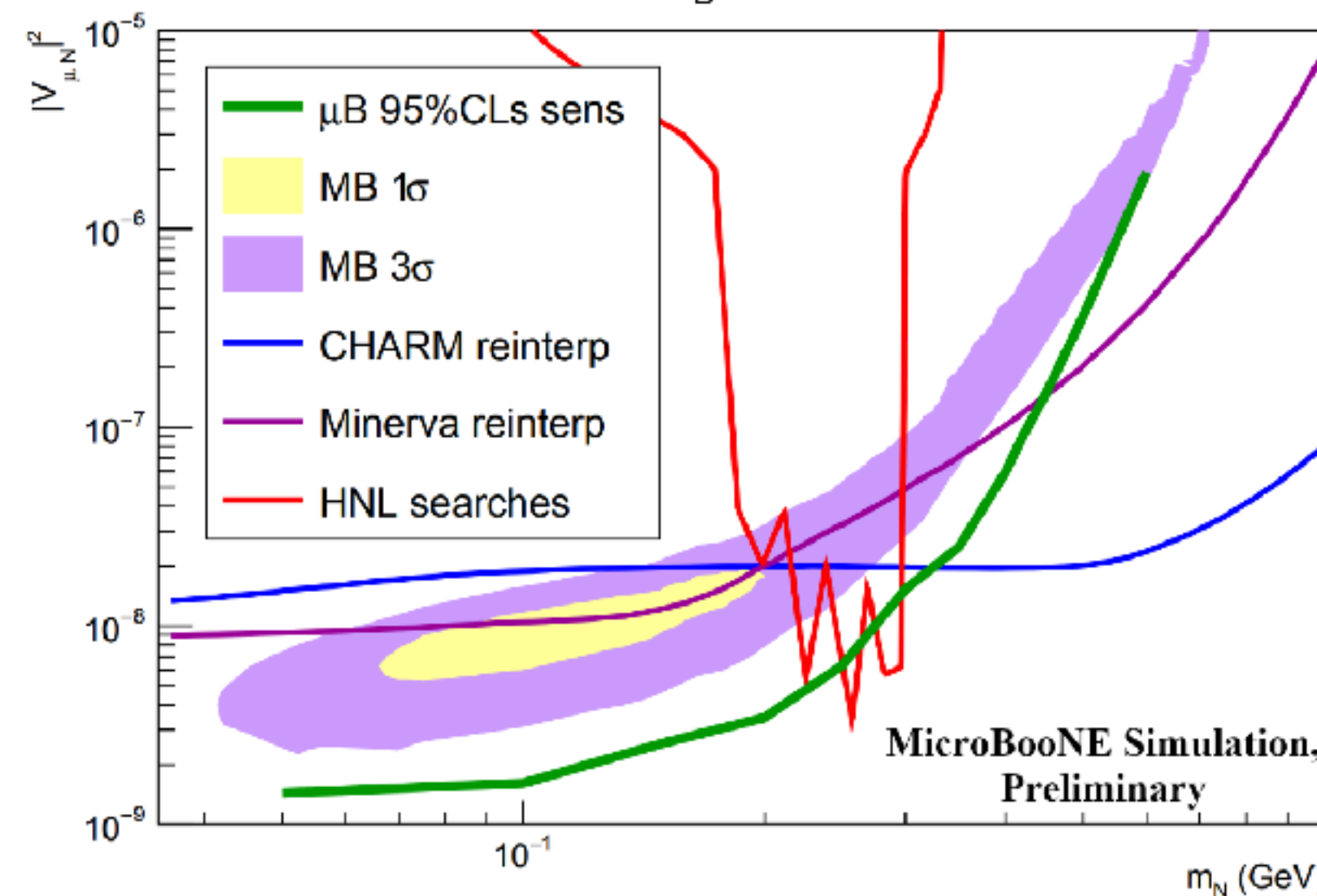
Bertuzzo, Jana, Machado, Zukanovich  
 Funchal  
[PRL 121 \(2018\) 24, 241801](#)

Sensitive to MiniBooNE allowed  
 region for these models at  $> 95\%$  CL

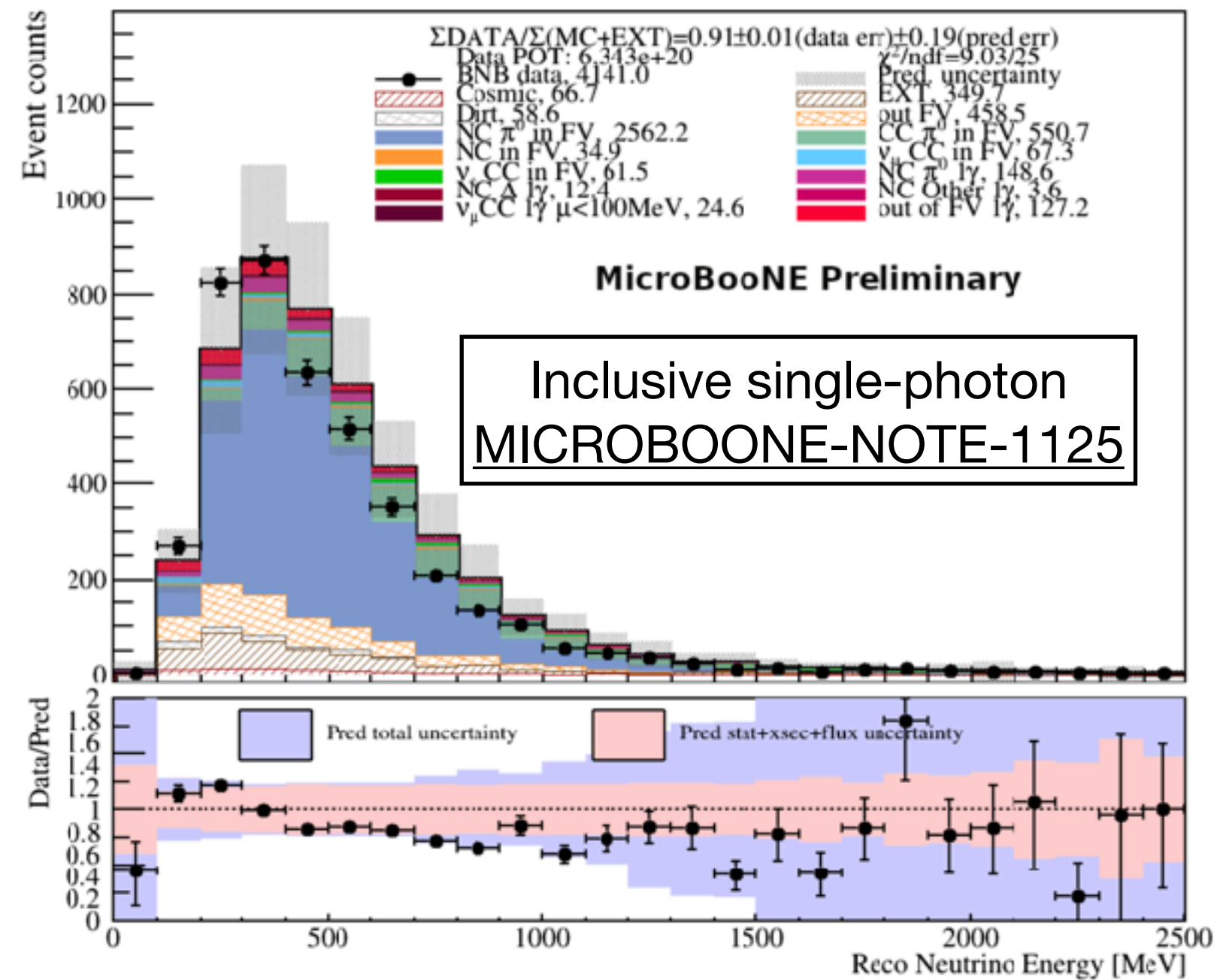
More details at:  
[MICROBOONE-NOTE-1124-PUB](#)



$m_{Z'}=30 \text{ MeV}, \alpha_D=0.25, \alpha\epsilon^2=2\times 10^{-10}$



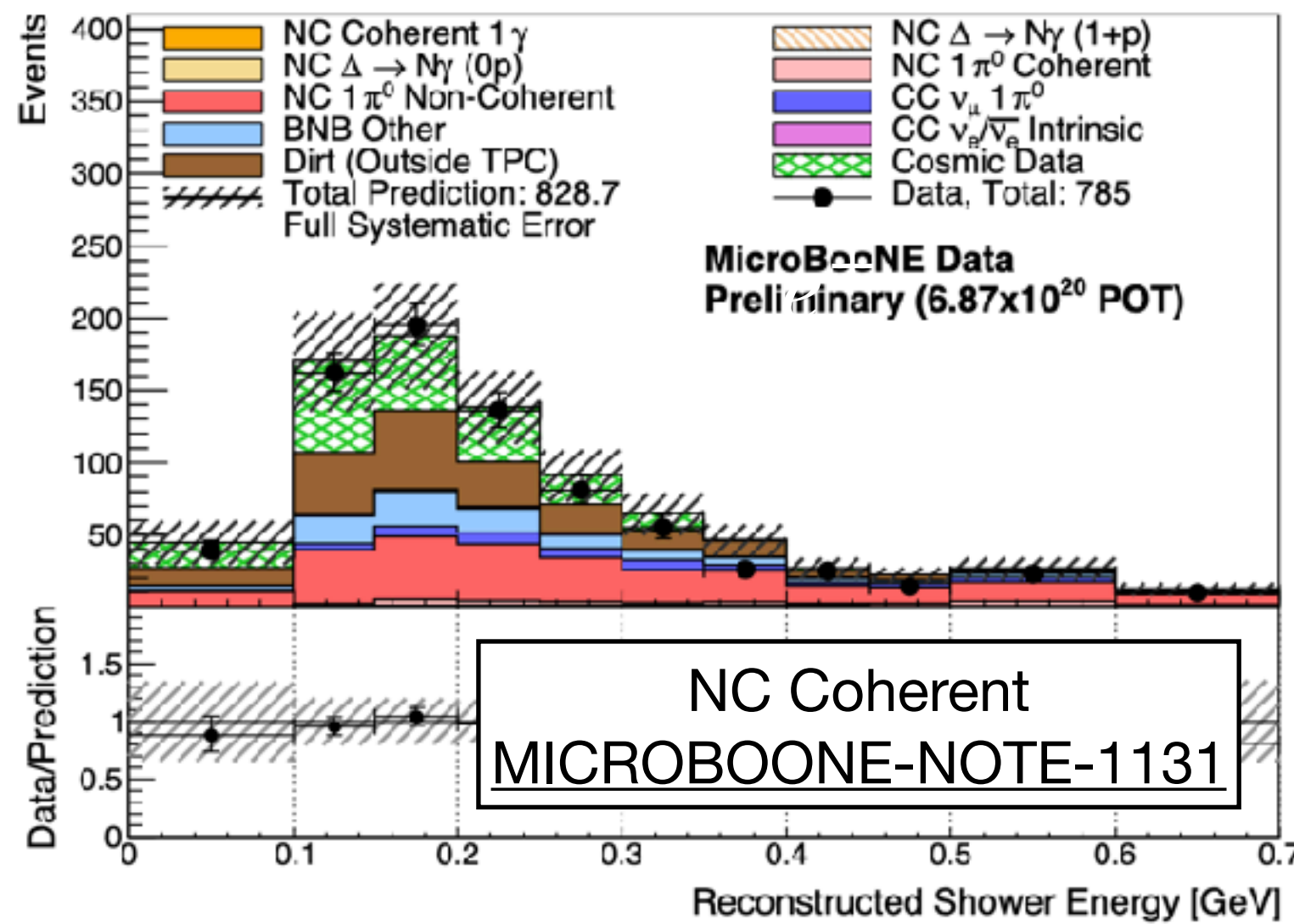
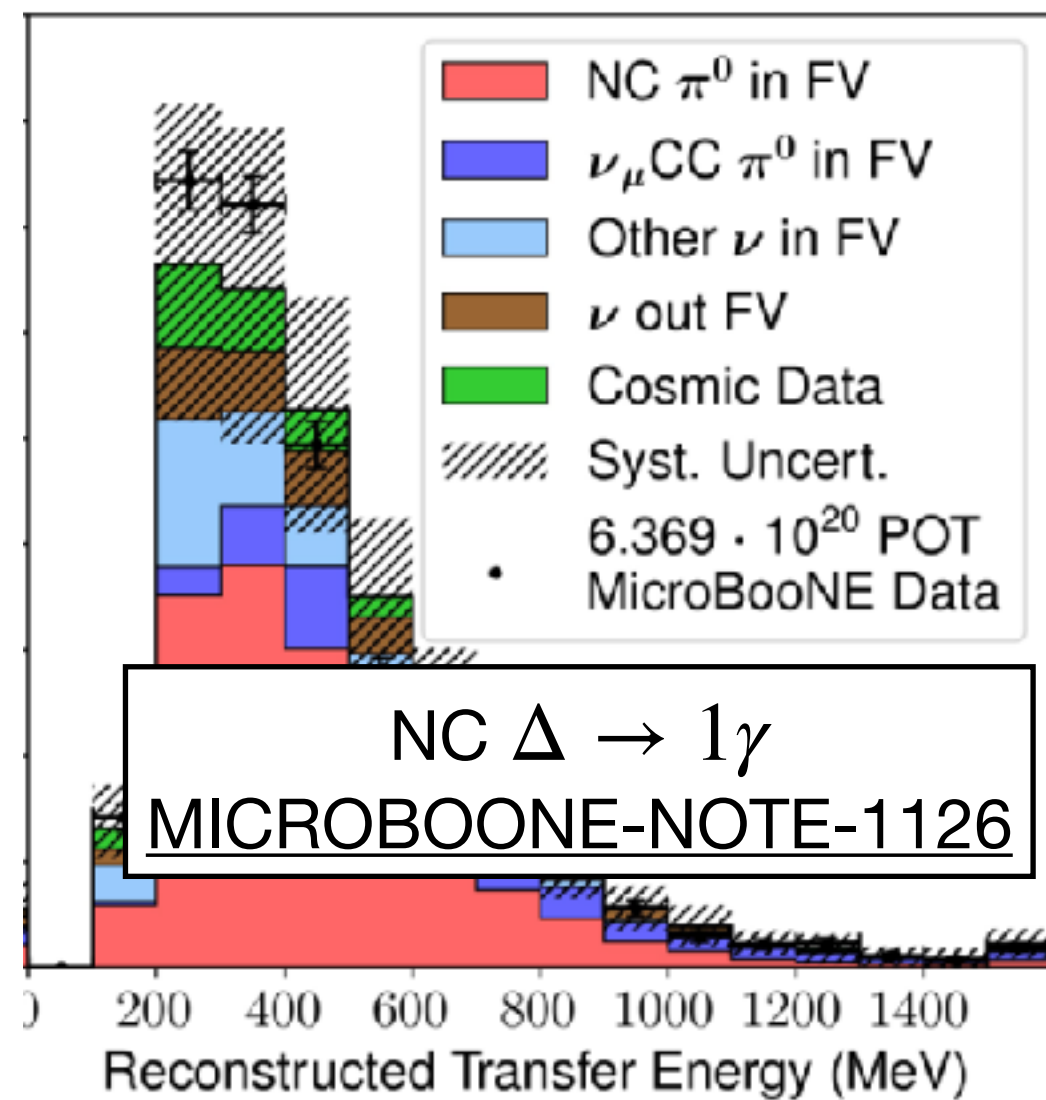
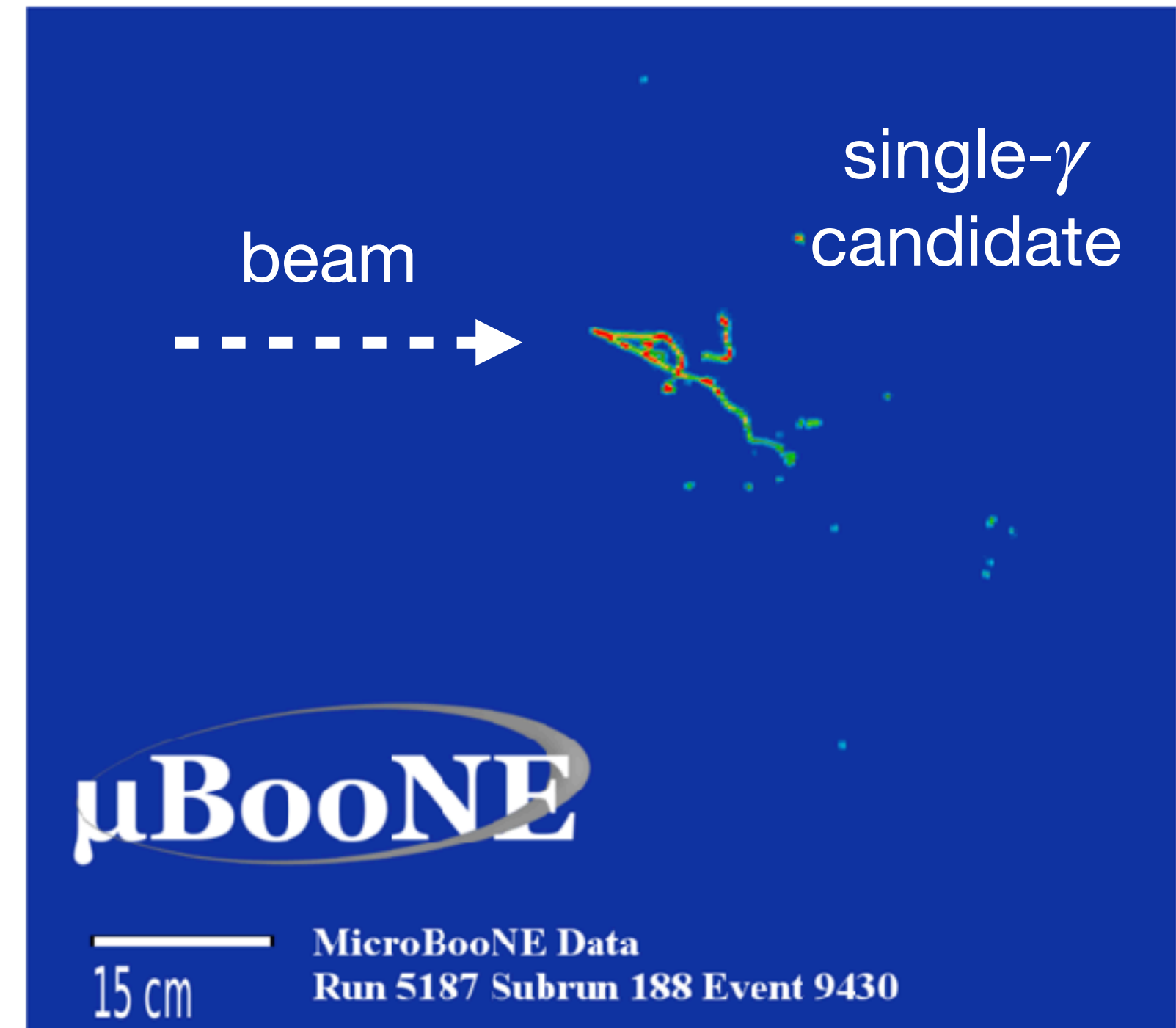
# LEE Search: single photons



Past MicroBooNE results focused on NC  $\Delta \rightarrow 1\gamma$  SM background

Three new analyses:

- NC coherent
- inclusive single- $\gamma$
- updated NC  $\Delta \rightarrow 1\gamma$ .

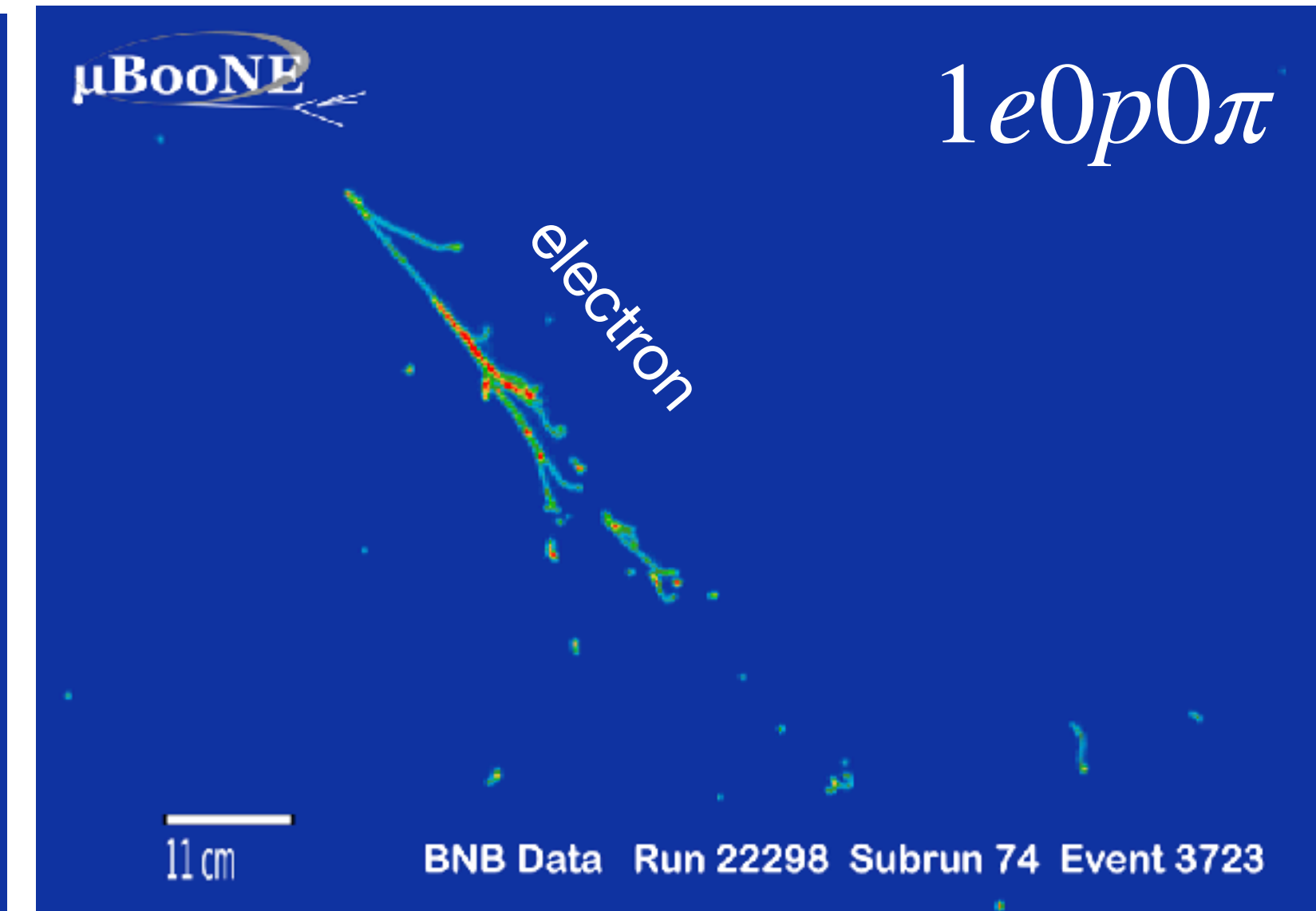
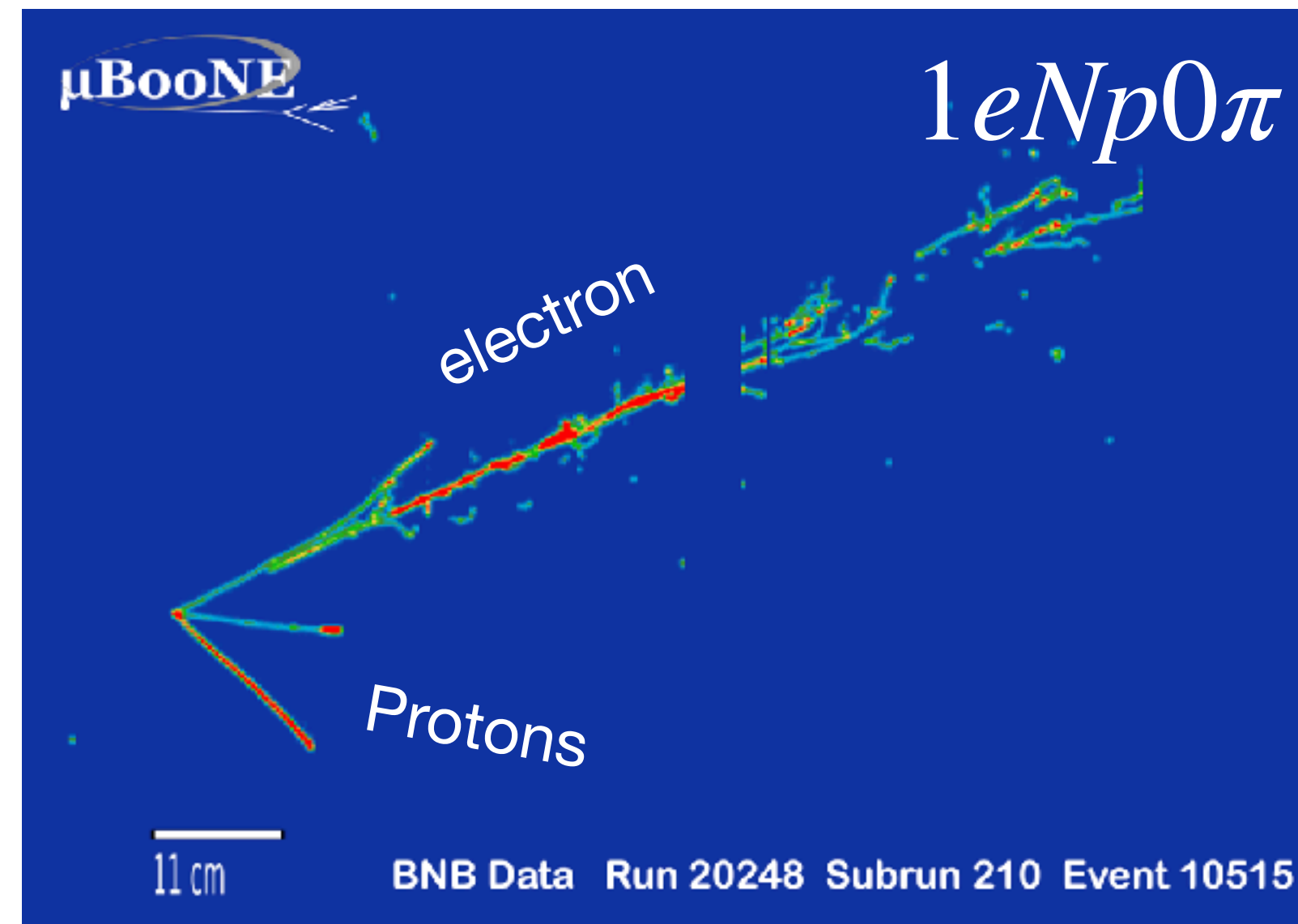


Now casting a wide net on  $\gamma$ -channel no matter the origin.

← NC  $\pi^0$  rich sidebands for these analyses

pionless  $\nu_e$  LEE analysis

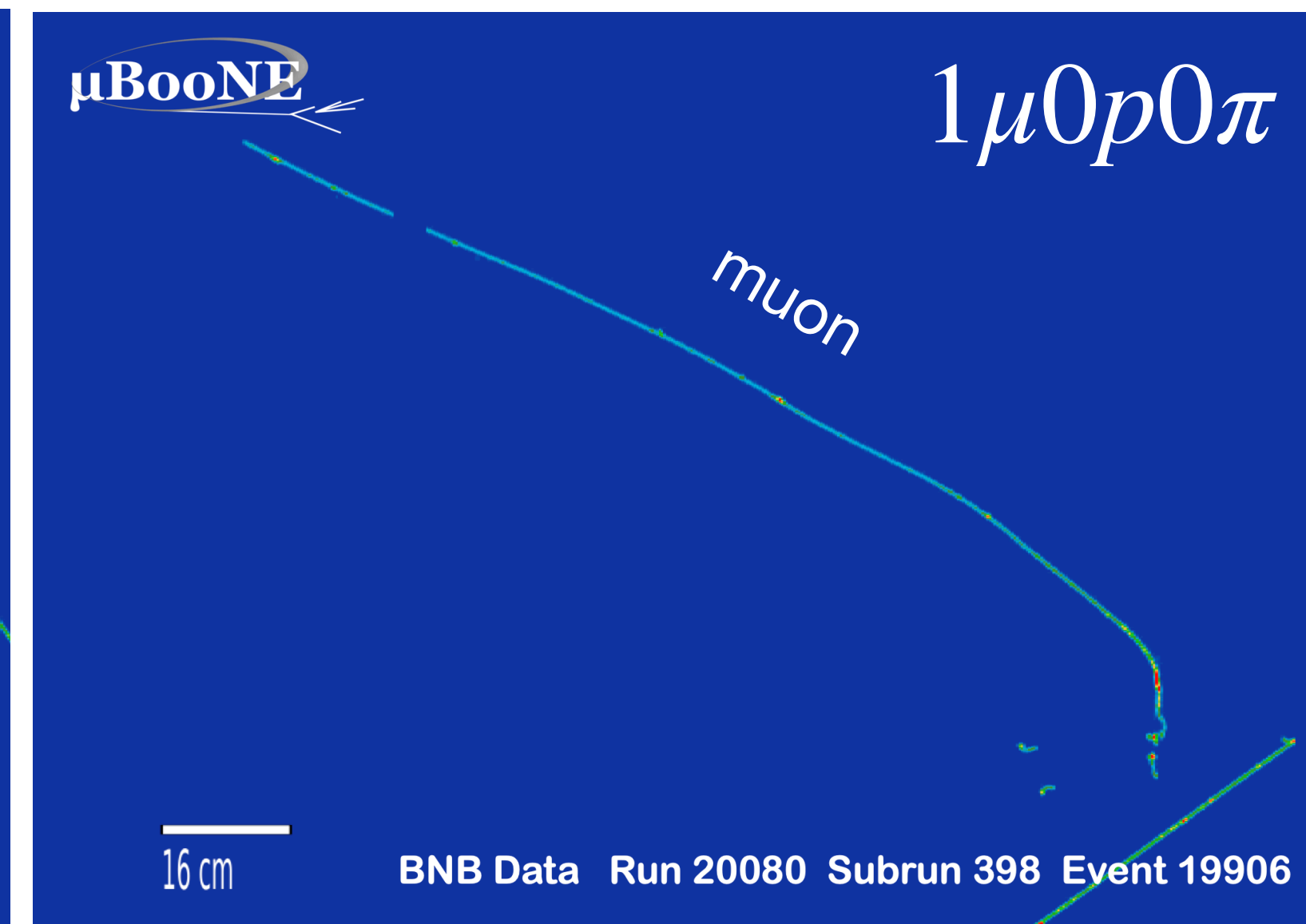
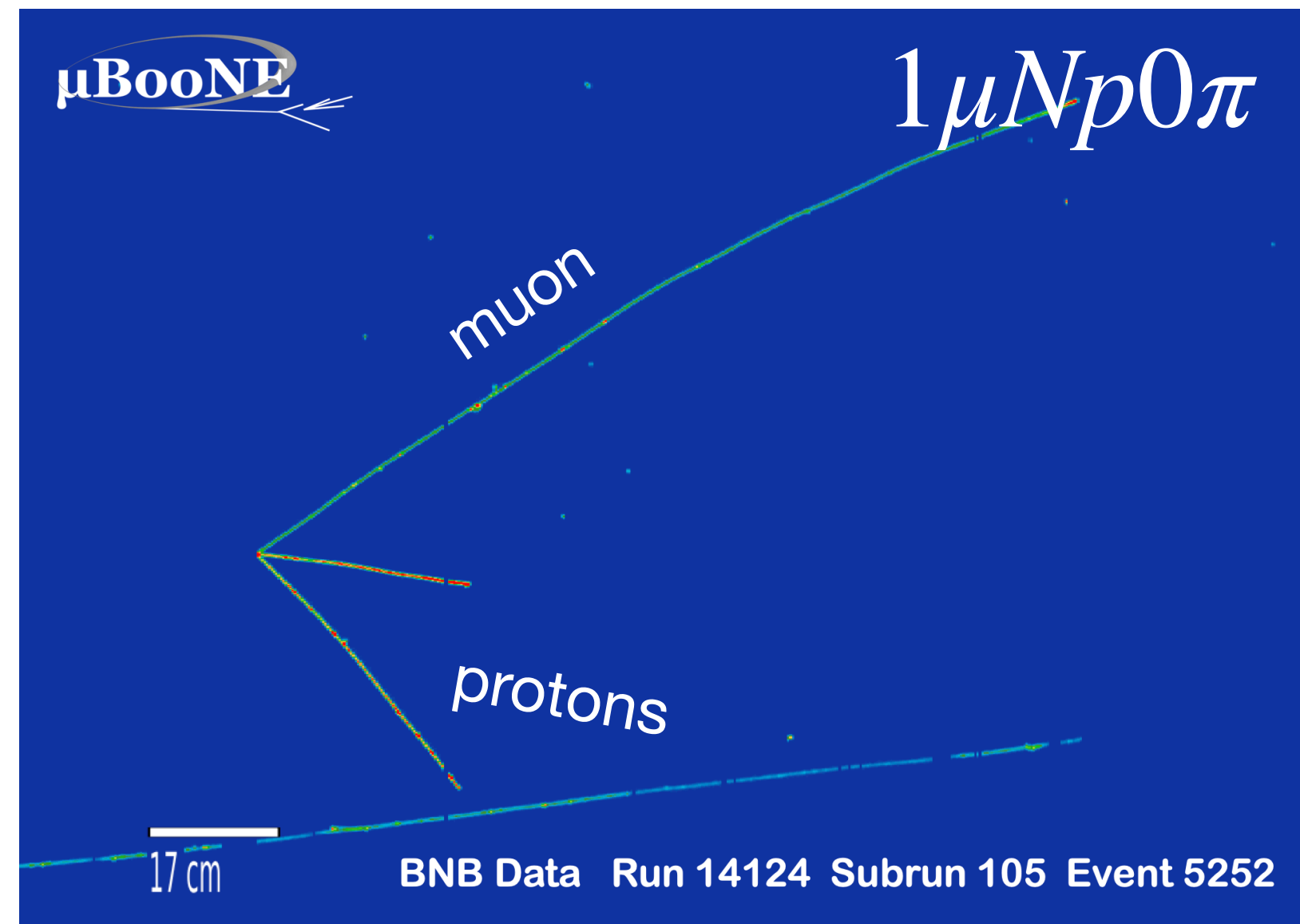
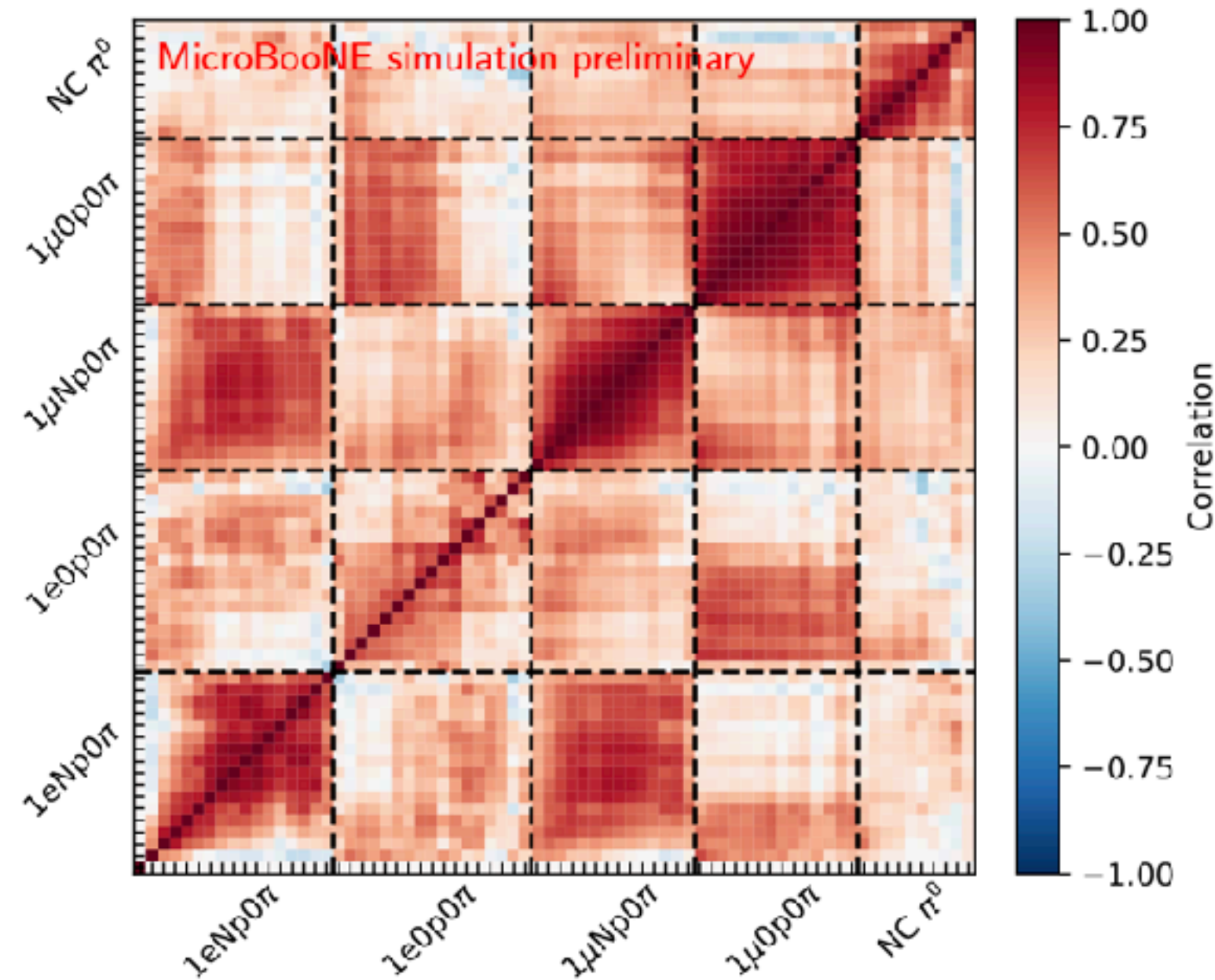
- same topology as MiniBooNE LEE
- update of [PRD 105 \(2022\) 11, 112004](#)



First analysis using data from all five runs of MicroBooNE (2016-2020)

$$6.8 \times 10^{20} \rightarrow 11.1 \times 10^{20} \text{ POT of BNB data}$$

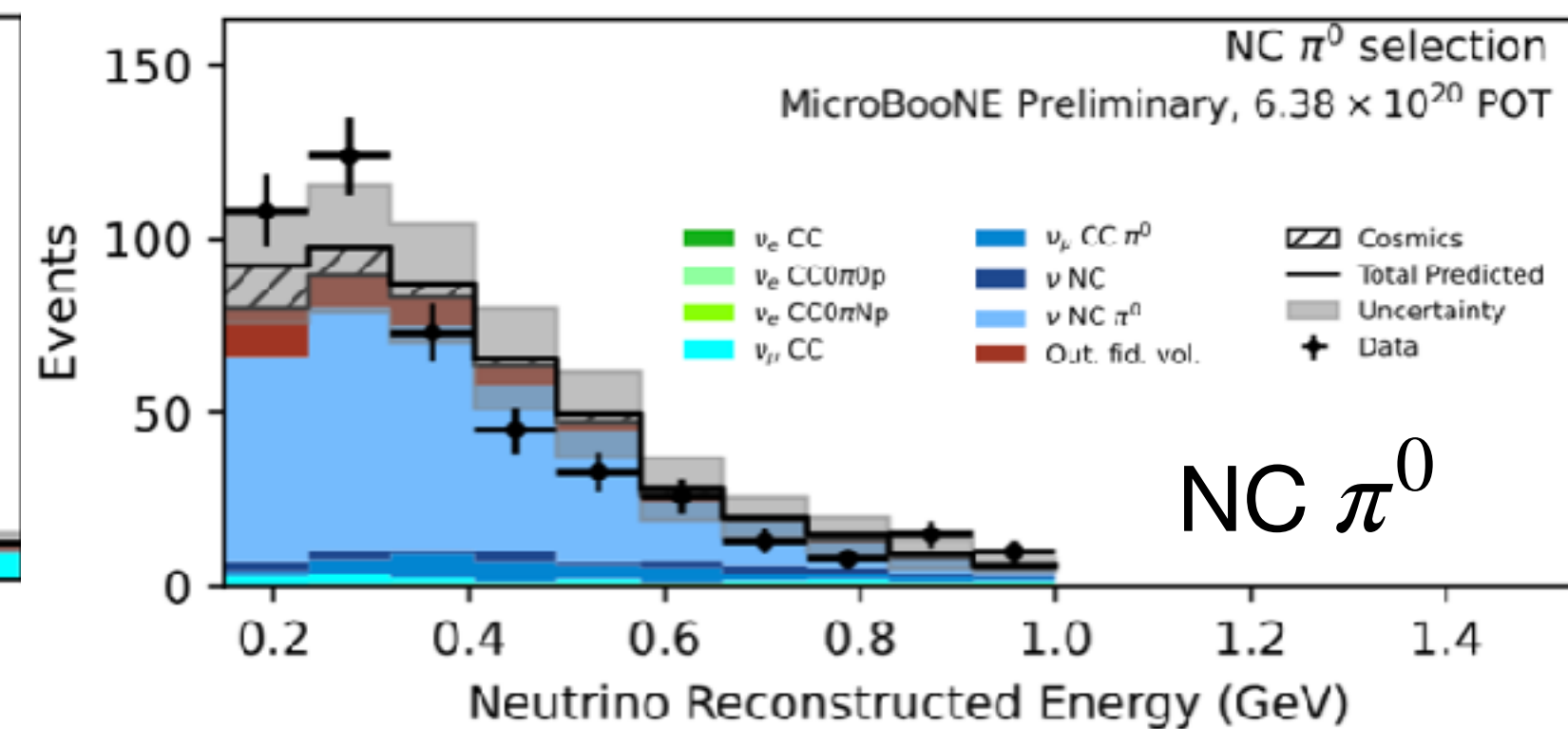
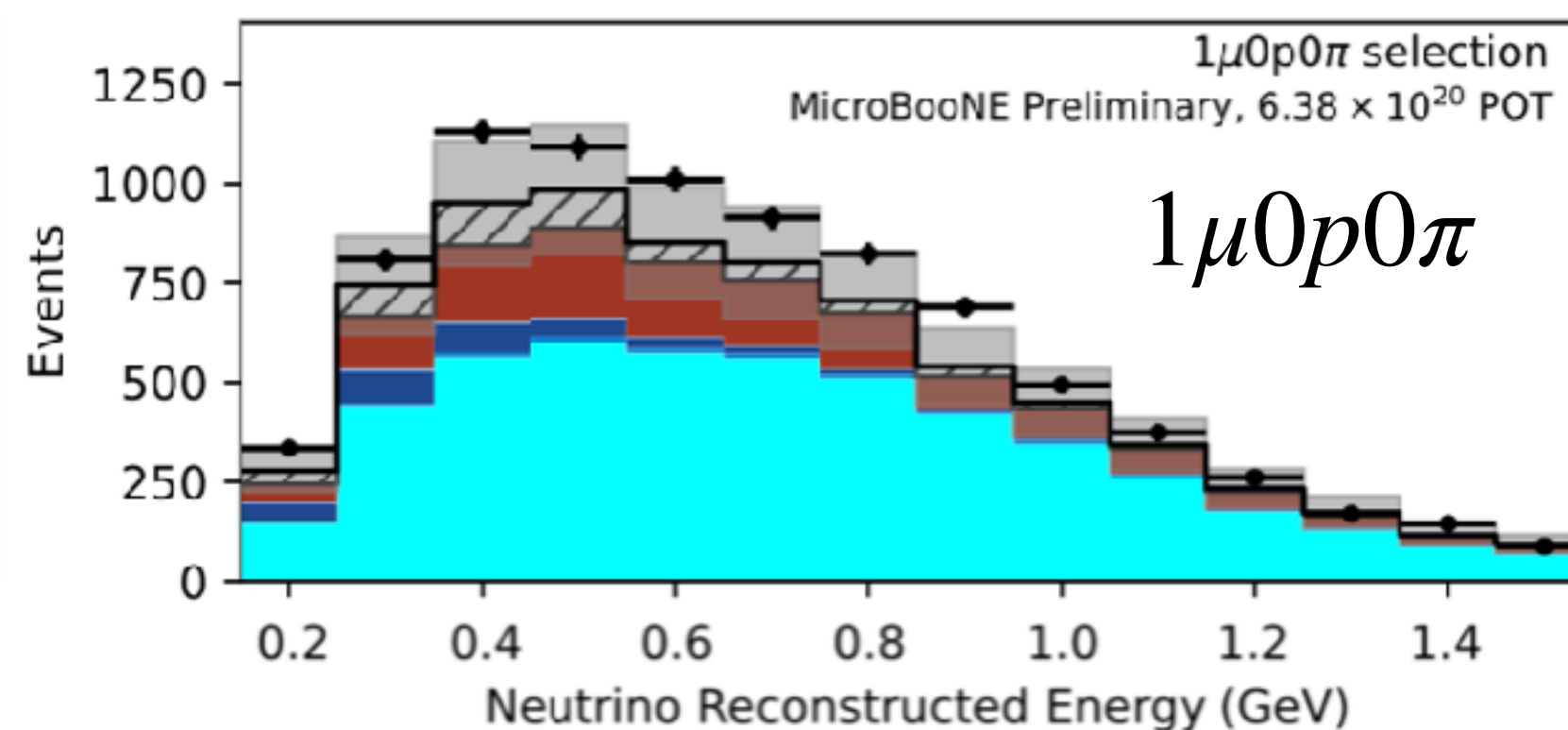
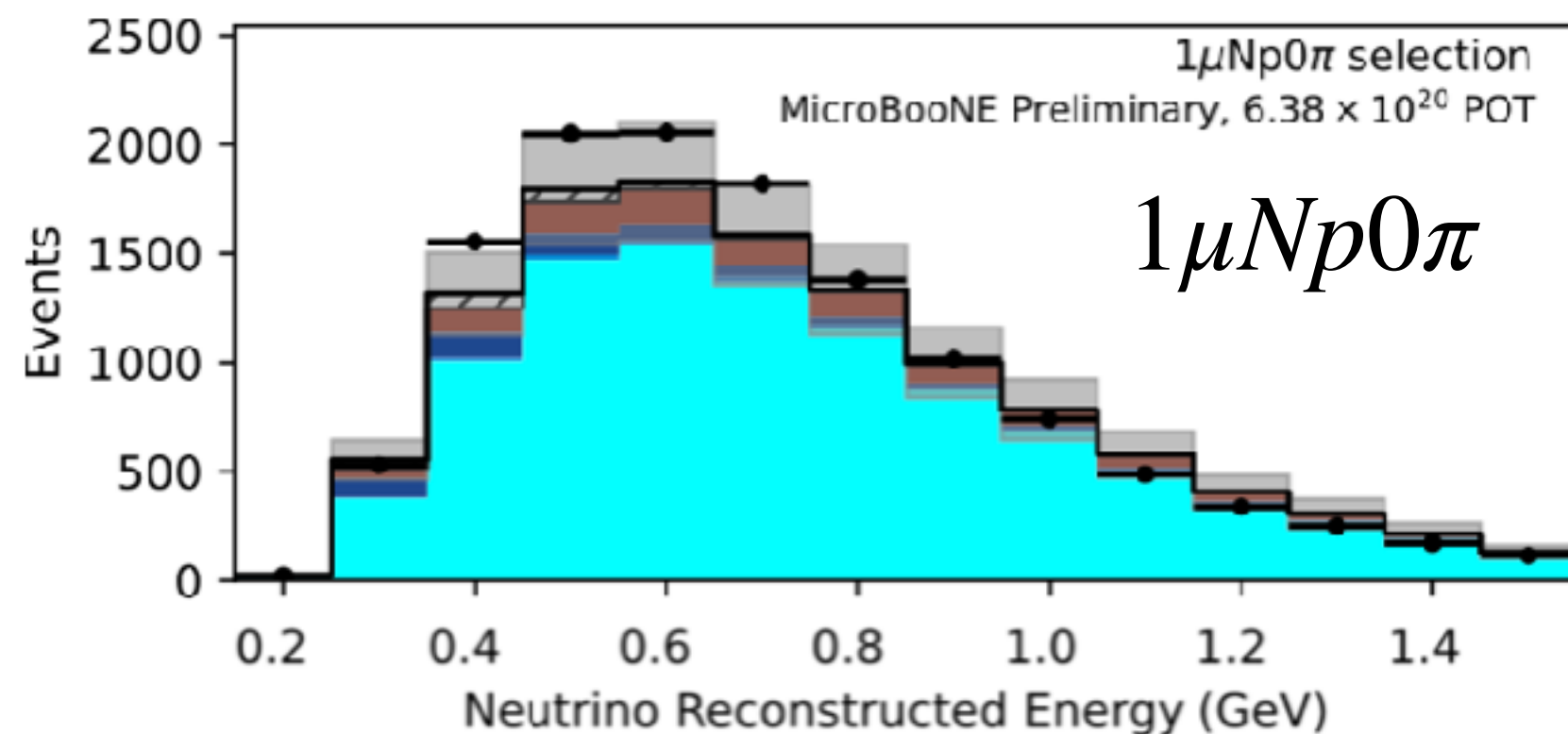
# LEE Search: $\nu_e$ sideband constraint



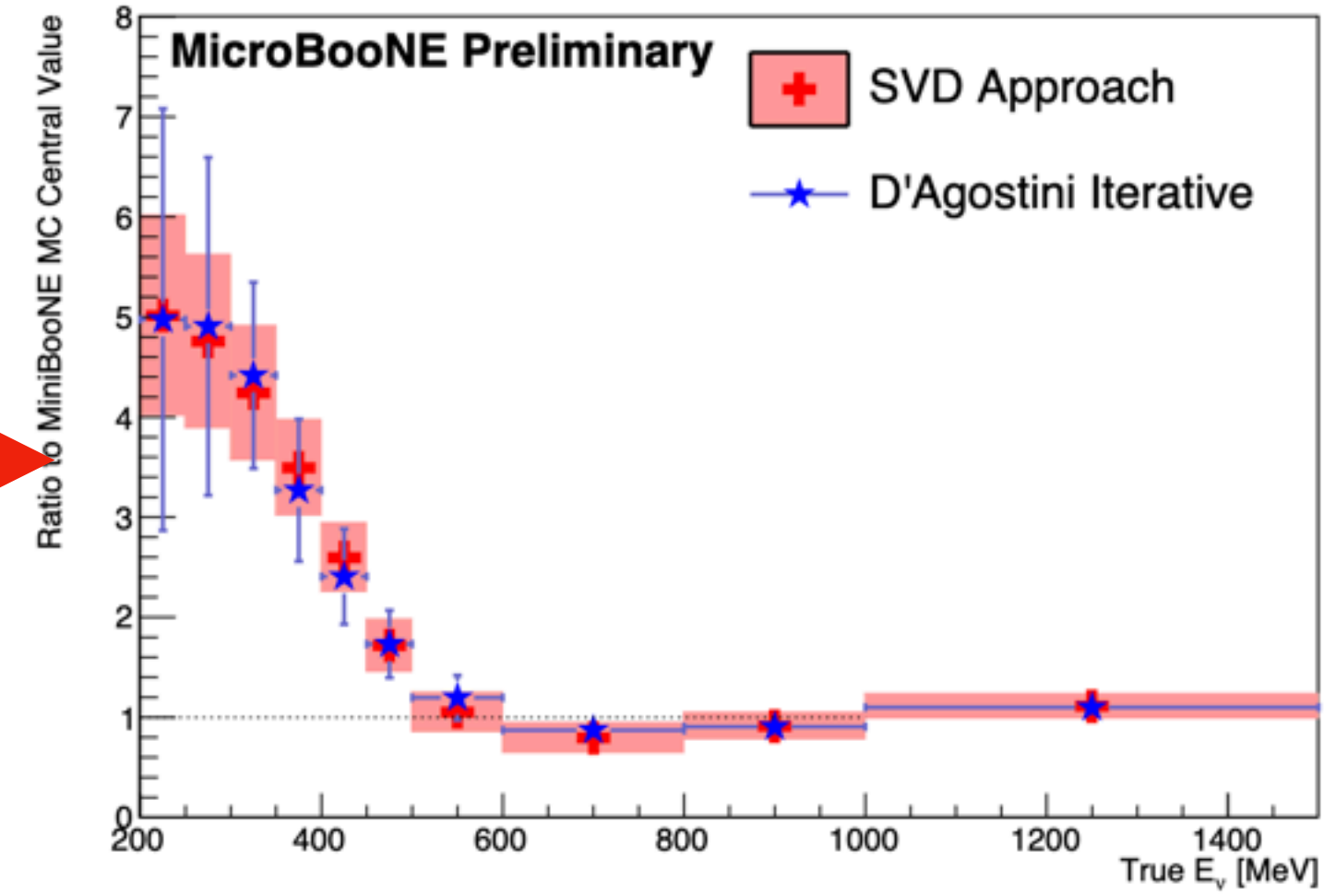
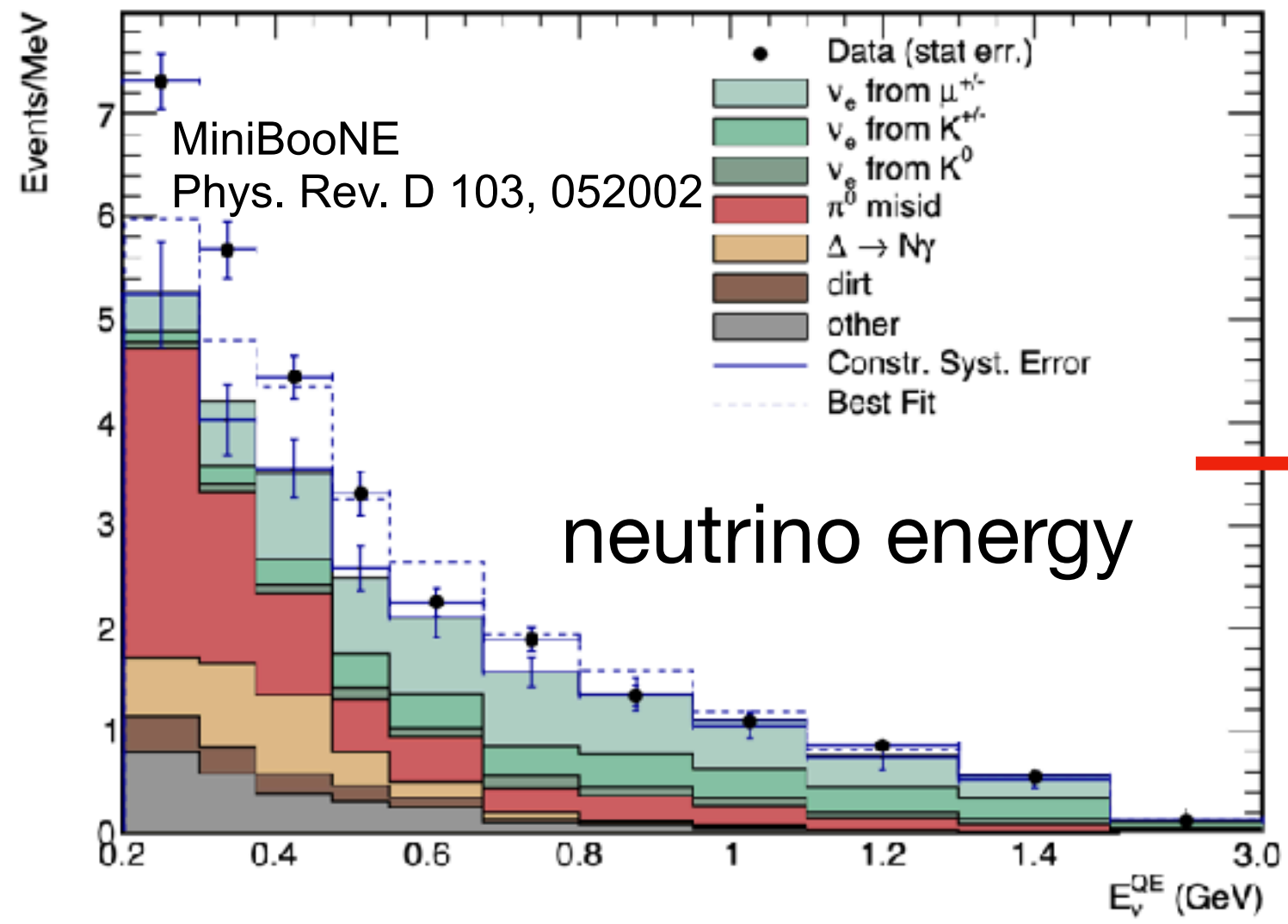
Updated  $\nu_\mu$  sidebands to better constrain intrinsic  $\nu_e$  and background  $\pi^0$

match hadronic final states of  $\nu_e$  signal channel

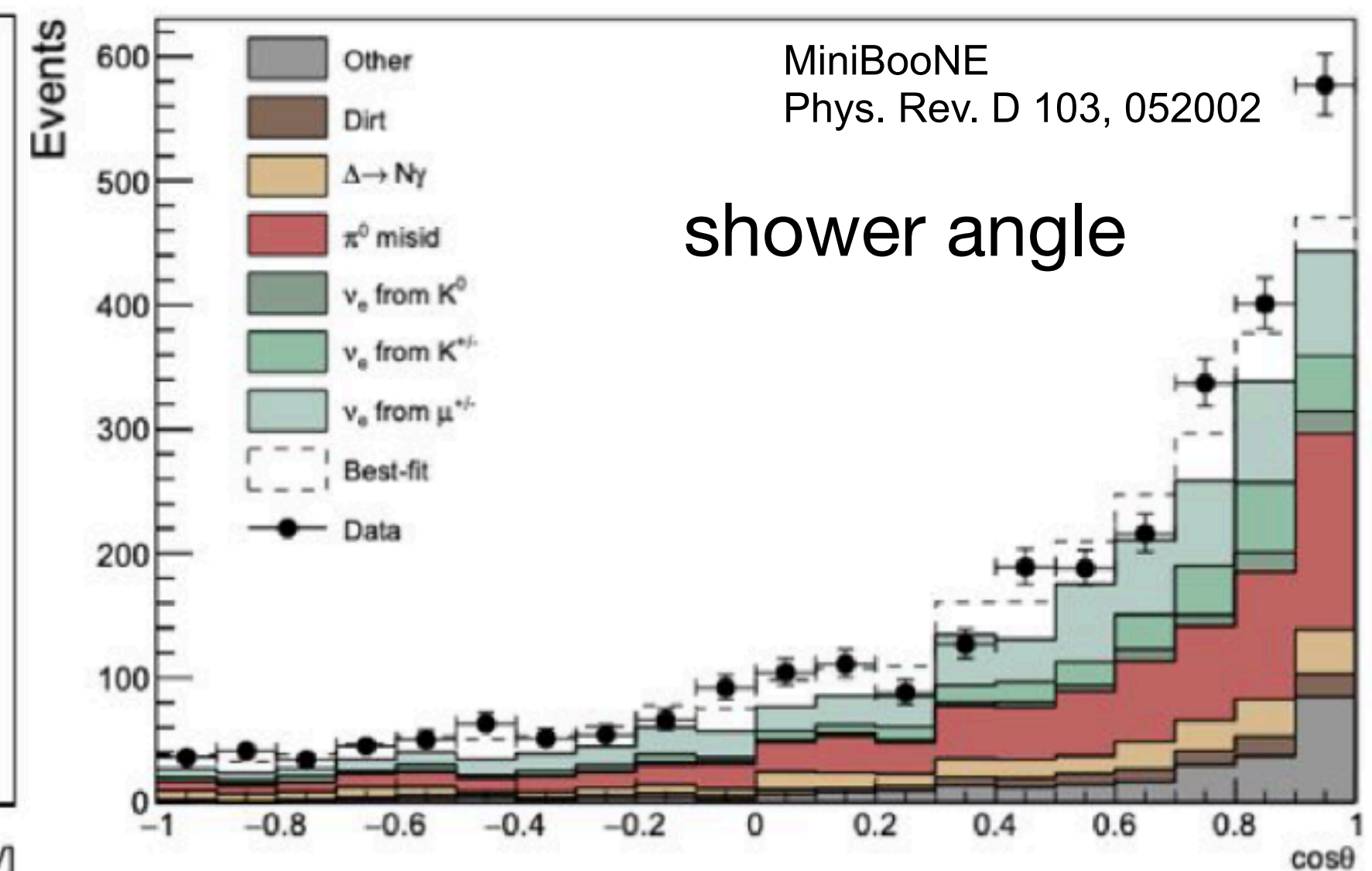
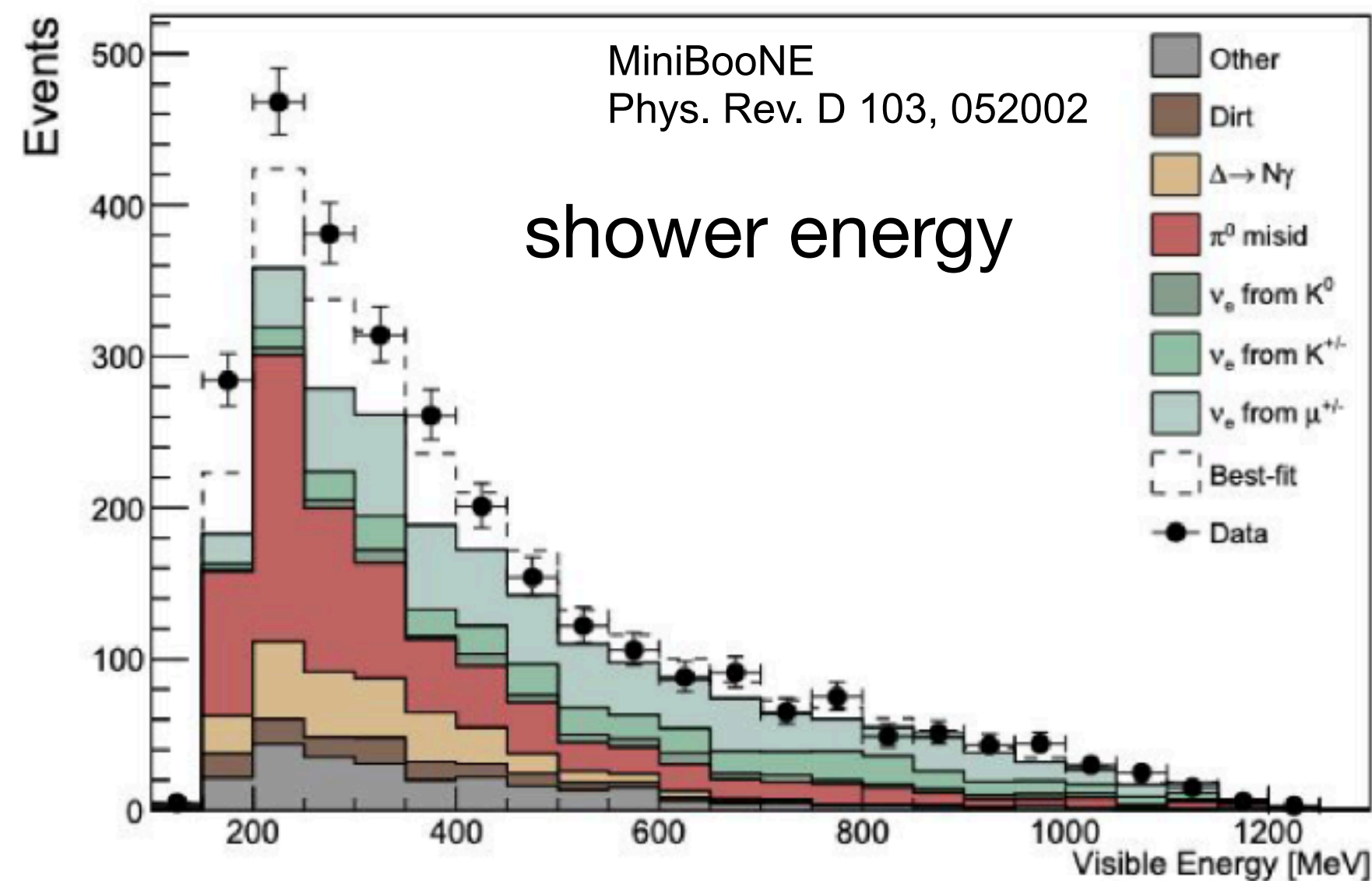
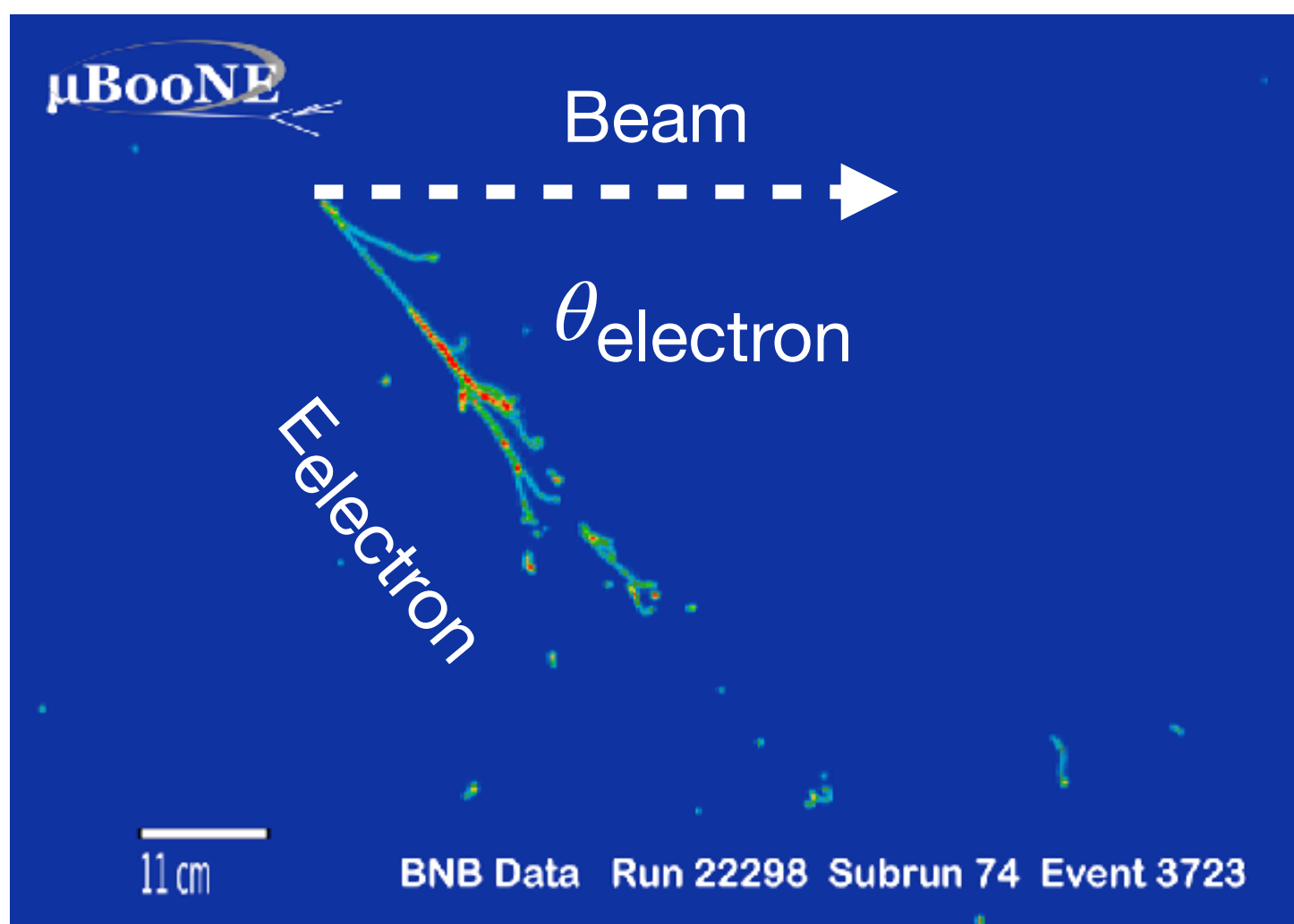
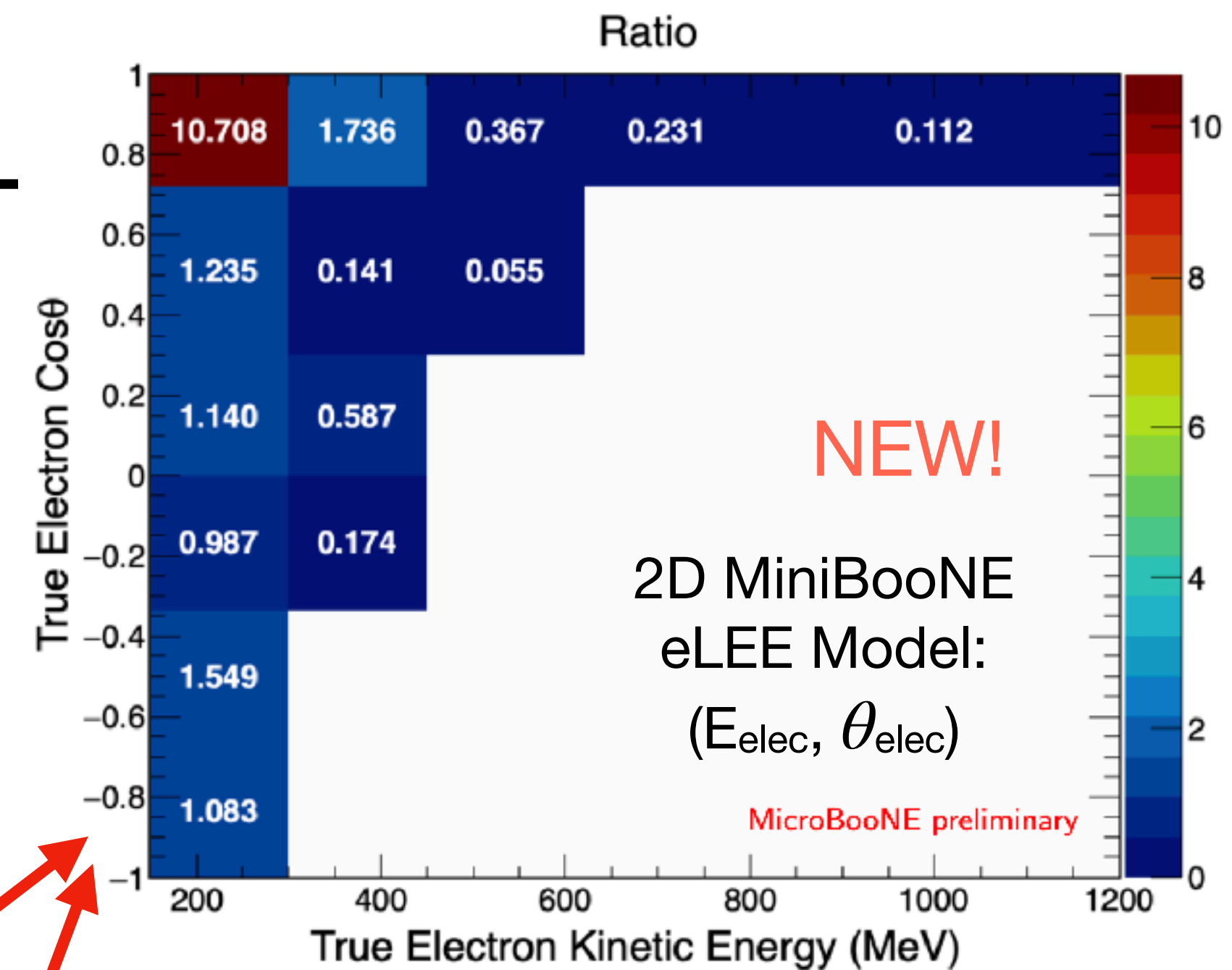
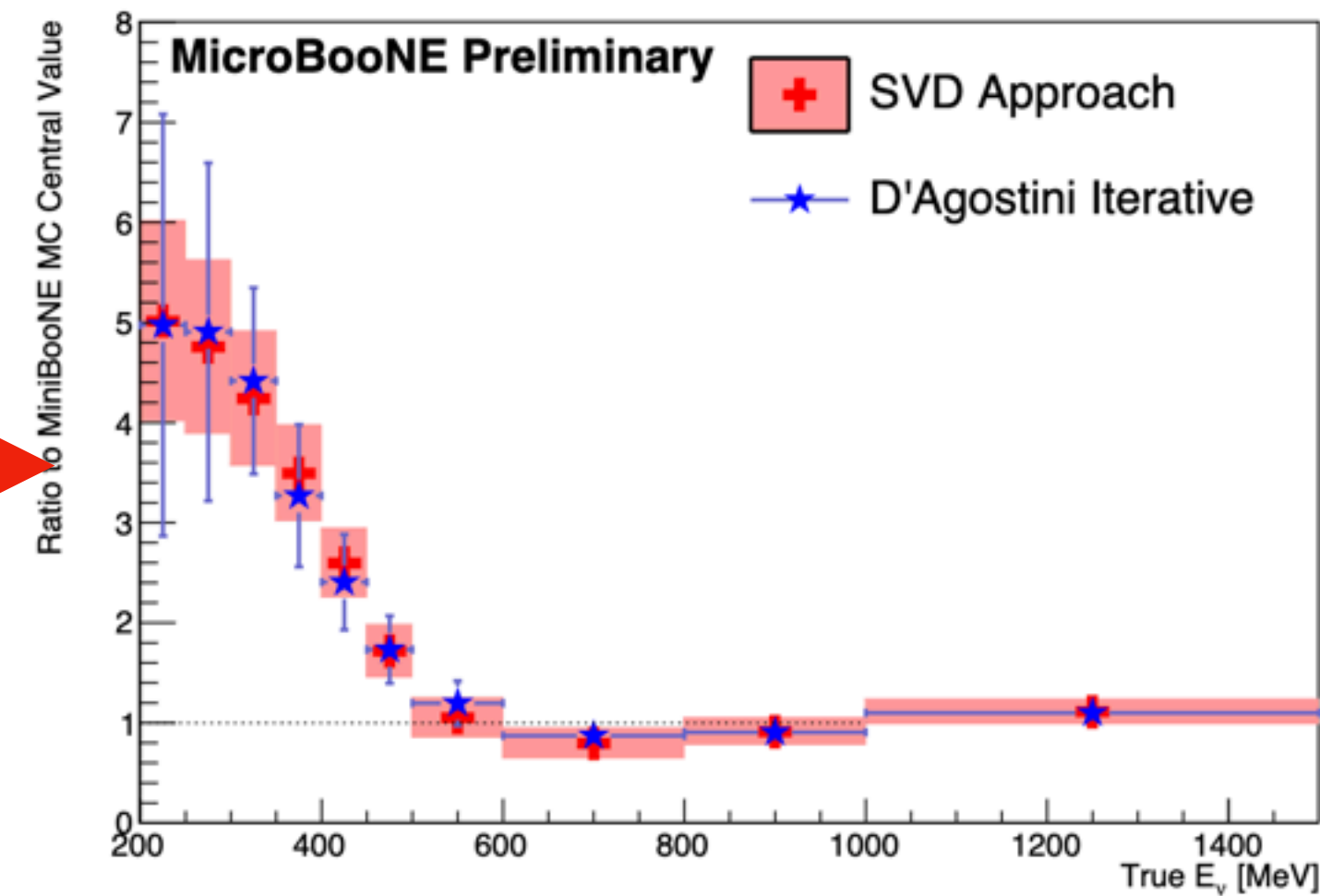
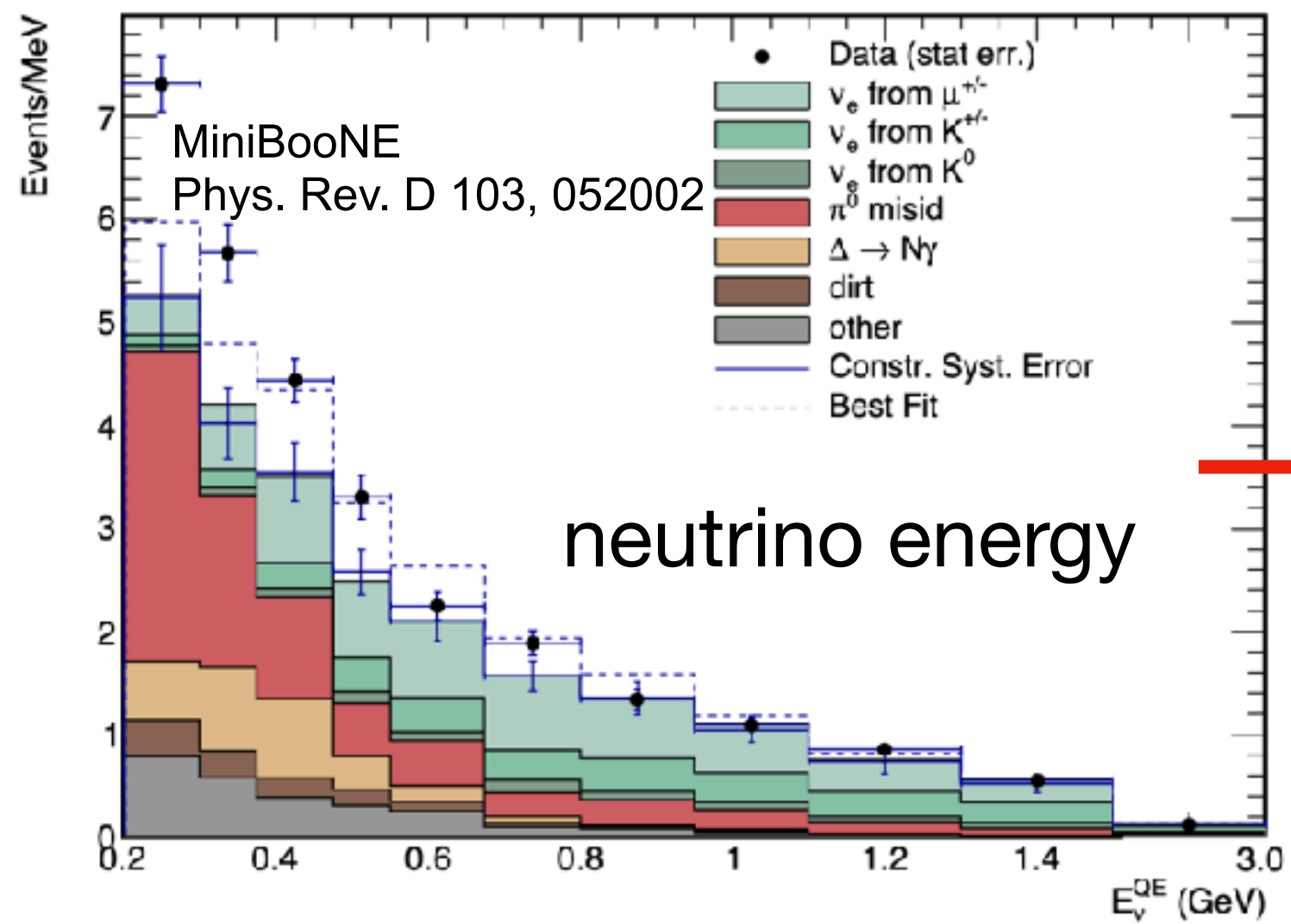
constrain dominant  $\pi^0$  background



# LEE Search: $\nu_e$ signal model(s)



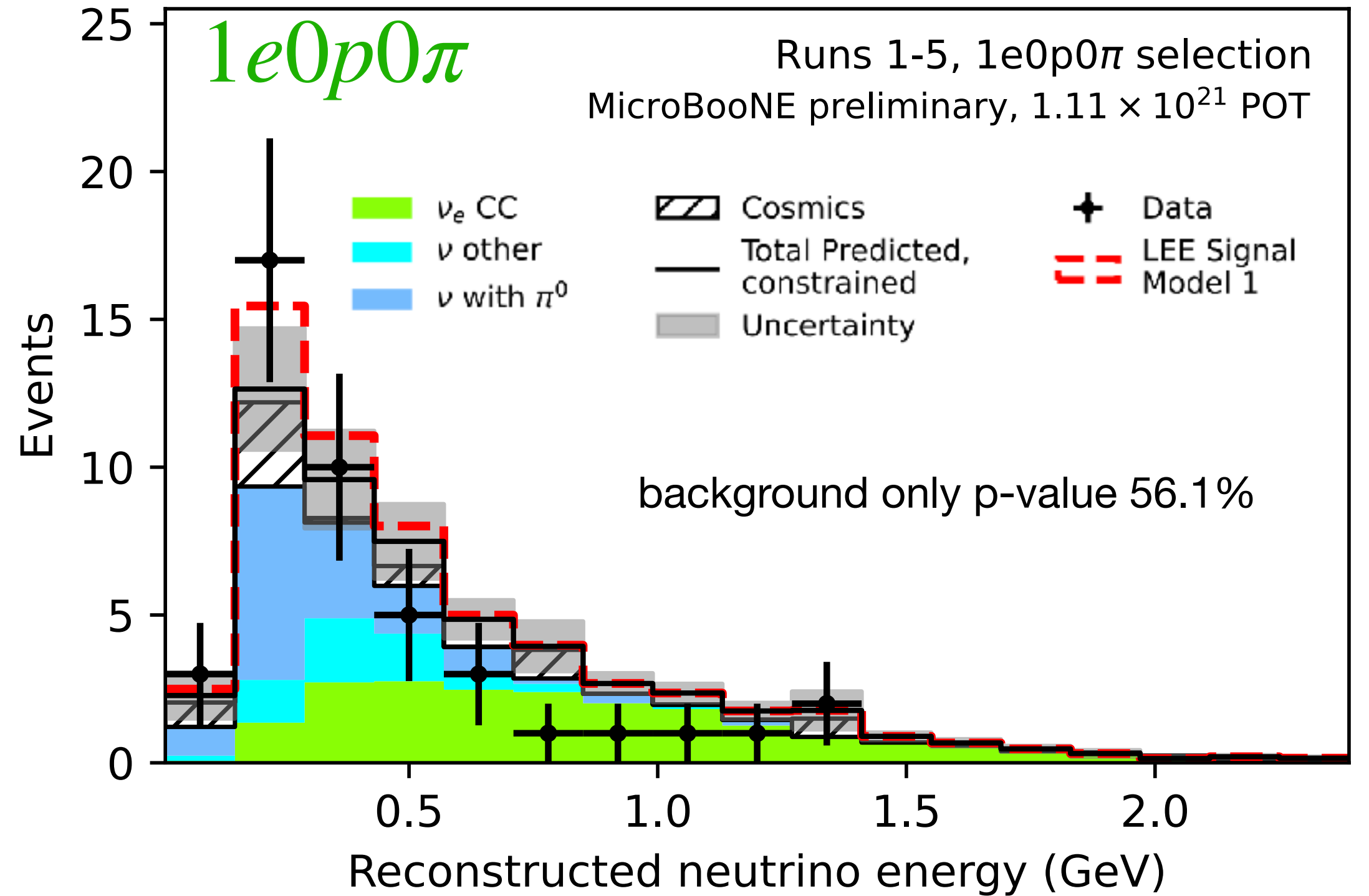
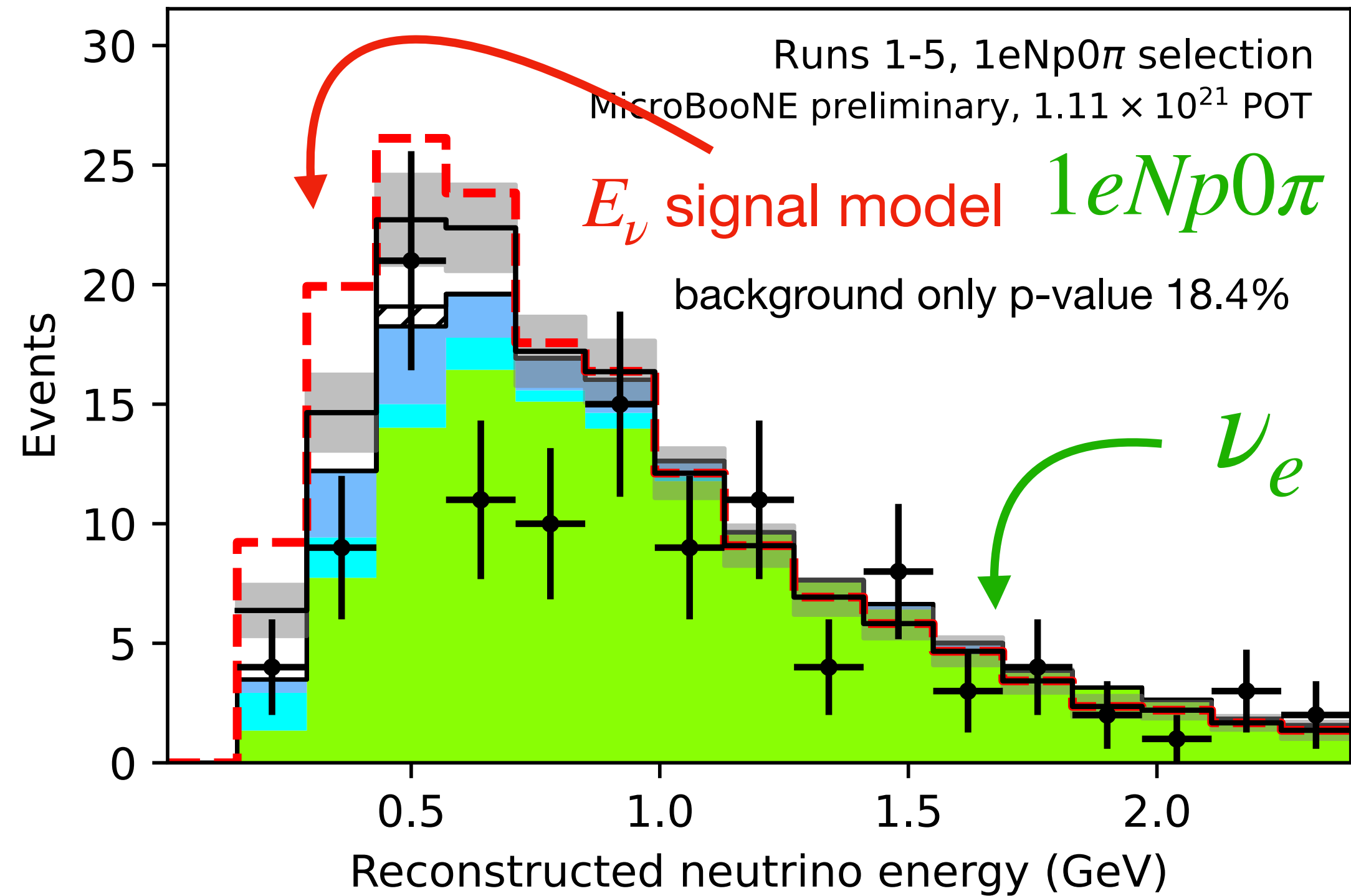
# LEE Search: $\nu_e$ signal model(s)



Complementary excess hypotheses expand analysis reach and help solidify conclusions.



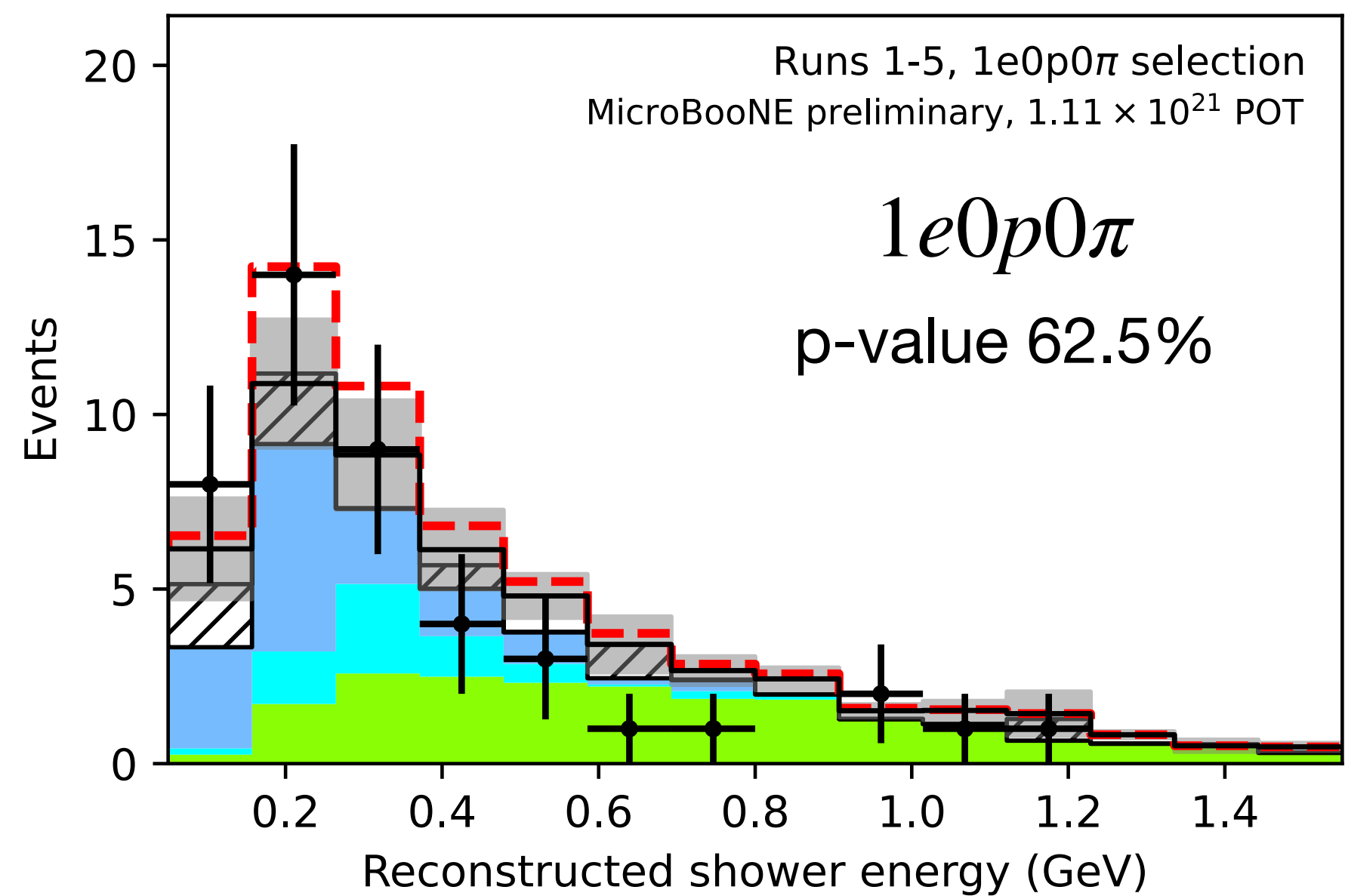
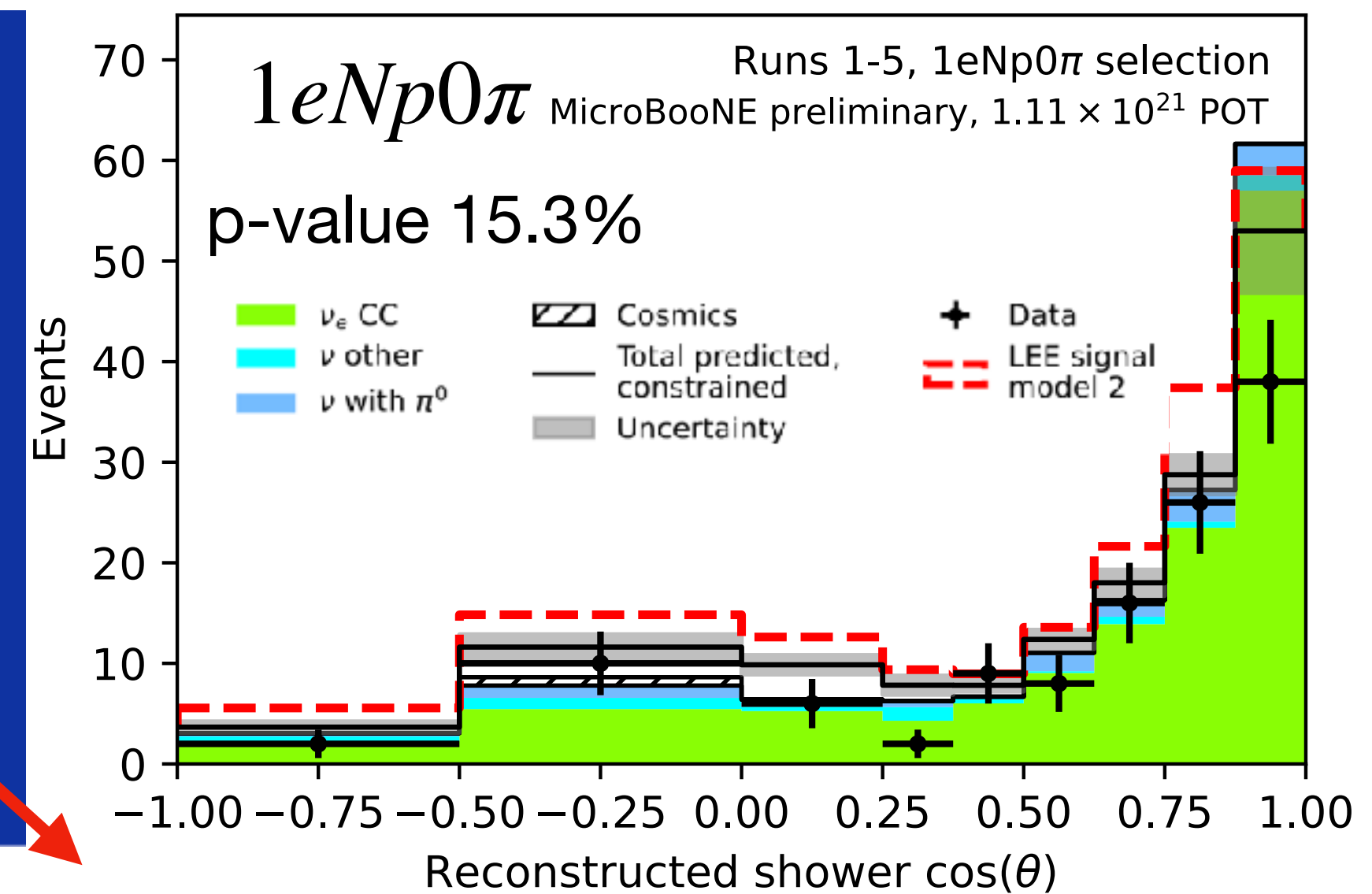
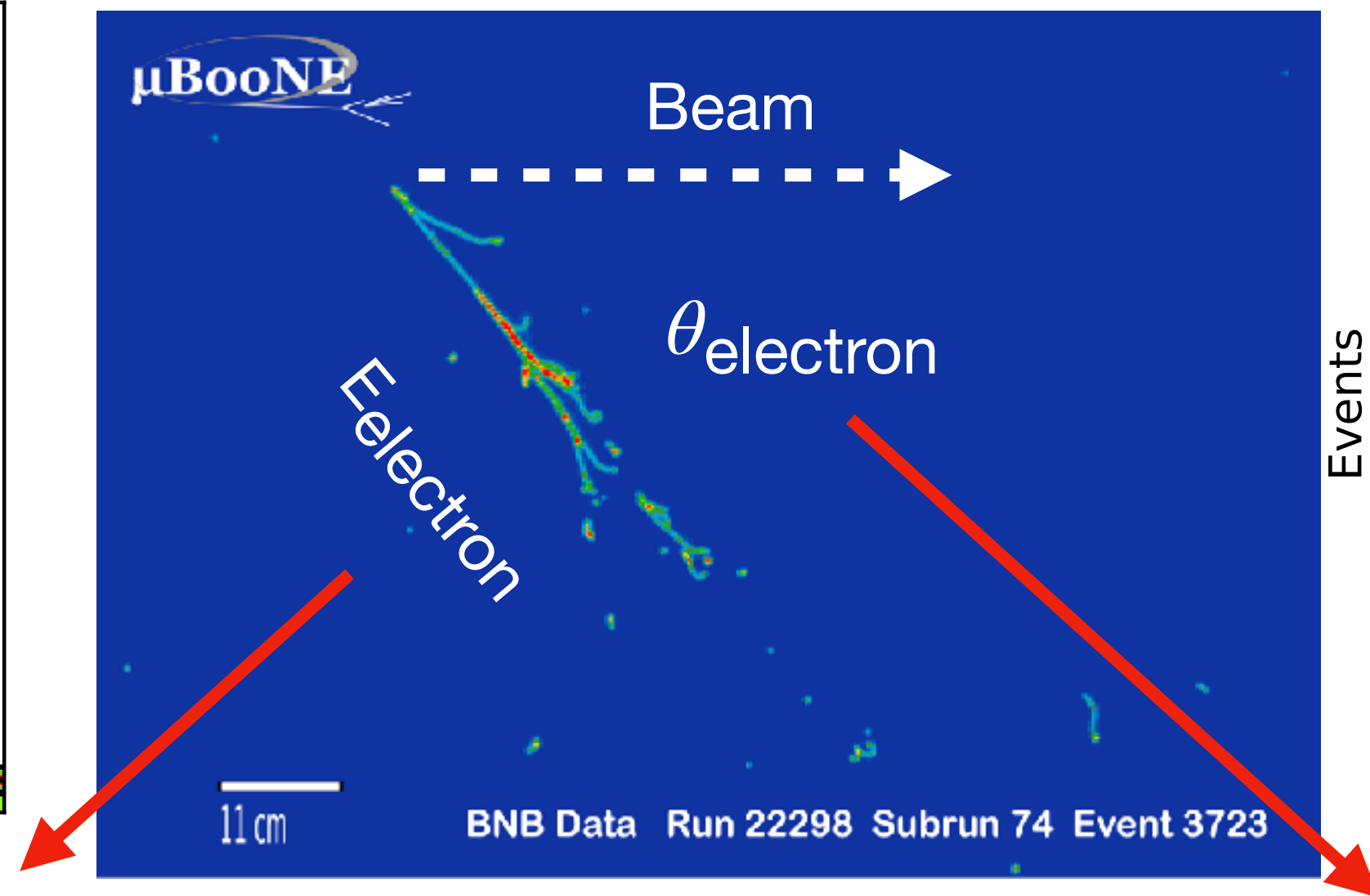
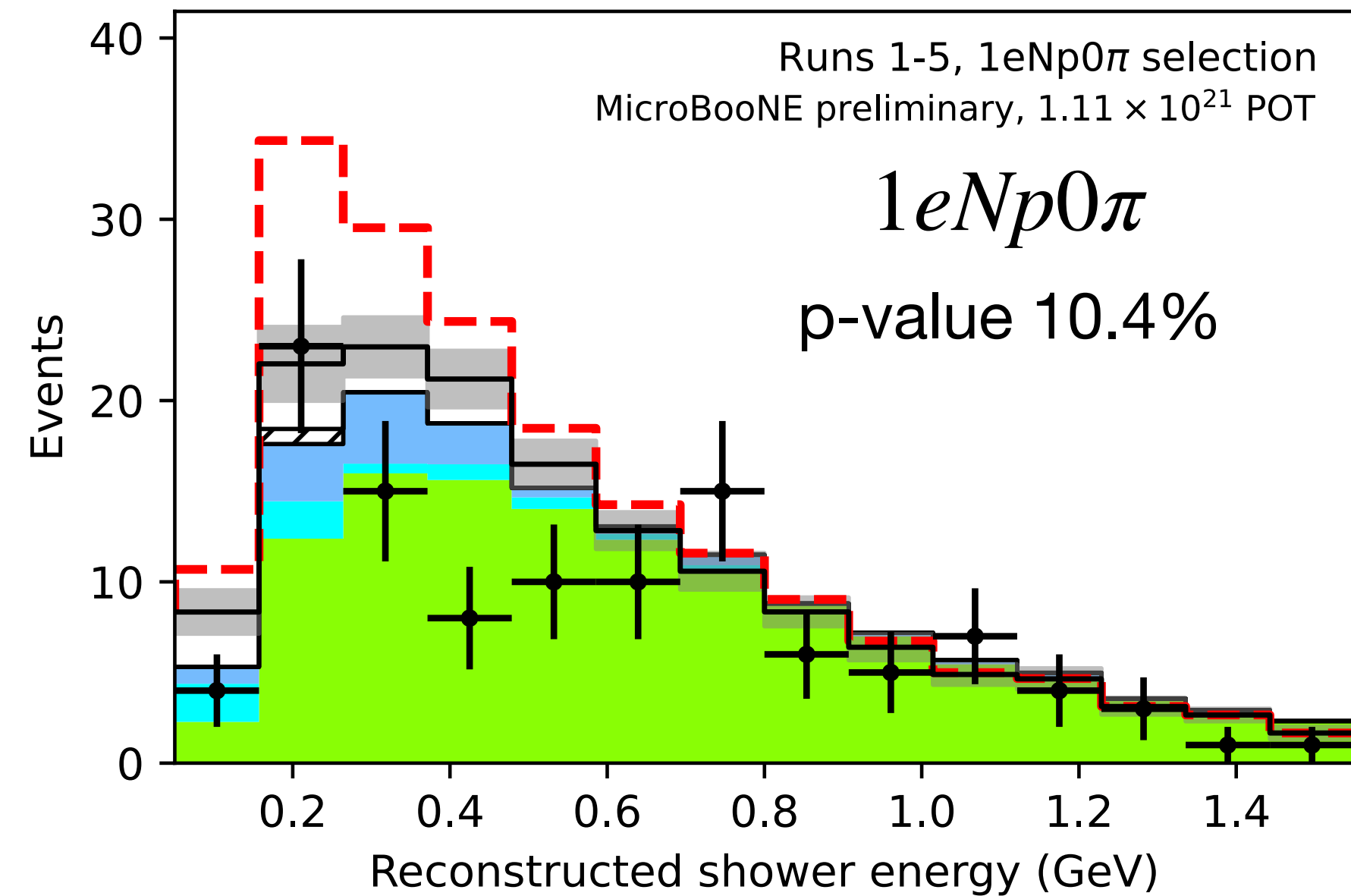
# LEE Search: $\nu_e$ results



Test MB excess under hypothesis of a **neutrino energy dependent  $\nu_e$  rate scaling**.

- Same model tested in first round of analysis.
- Data in overall agreement with intrinsic  $\nu_e$  flux prediction.
- Rule out  $\nu_e$  excess model @ 99.5% CL in Np & 0p combined channels.

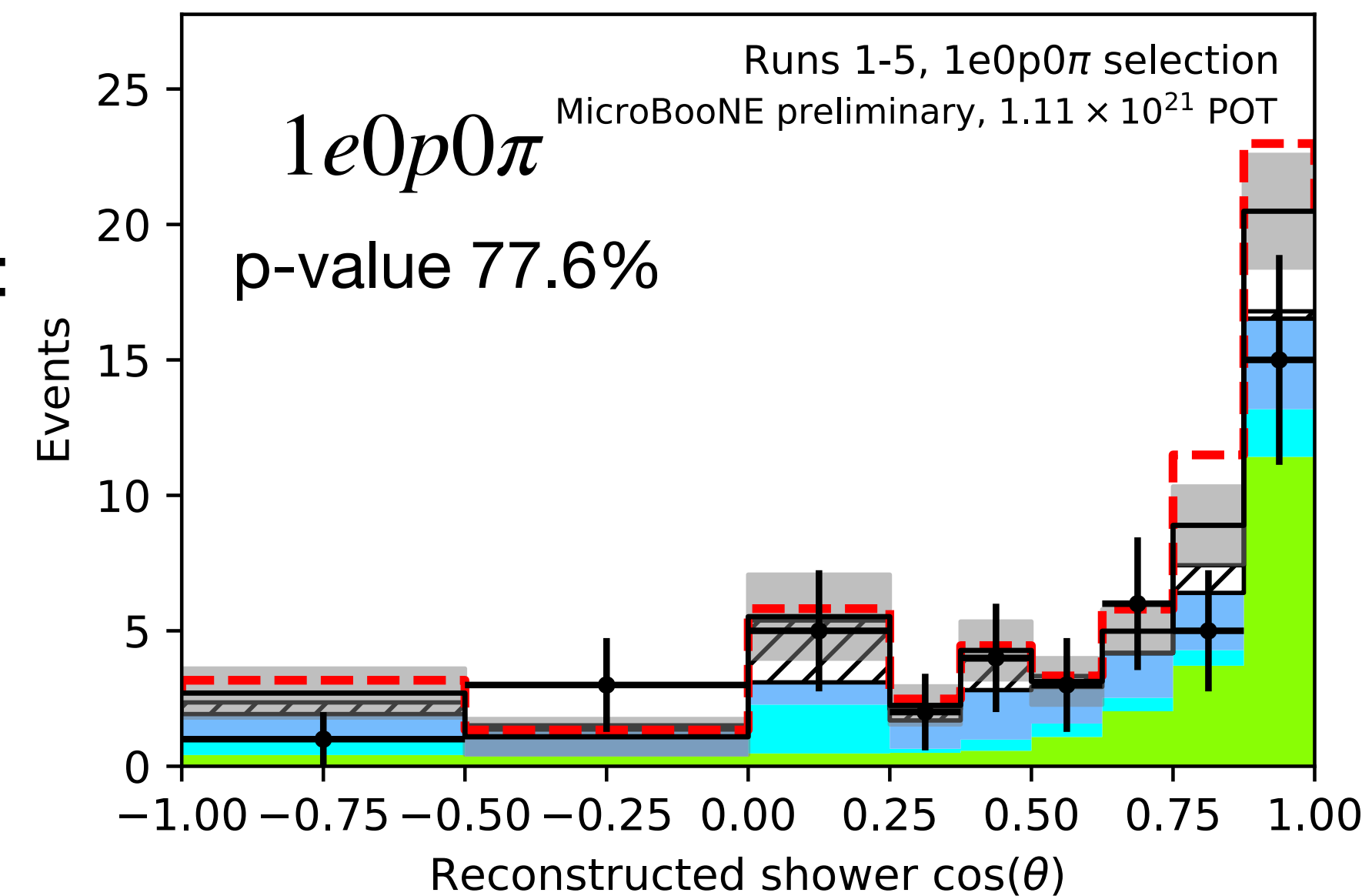
# LEE Search: $\nu_e$ results



Shower kinematics-based model:

combined Np & 0p channels:

exclude model at  $> 99.9\%$  CL



# LEE Search: $\nu_e$

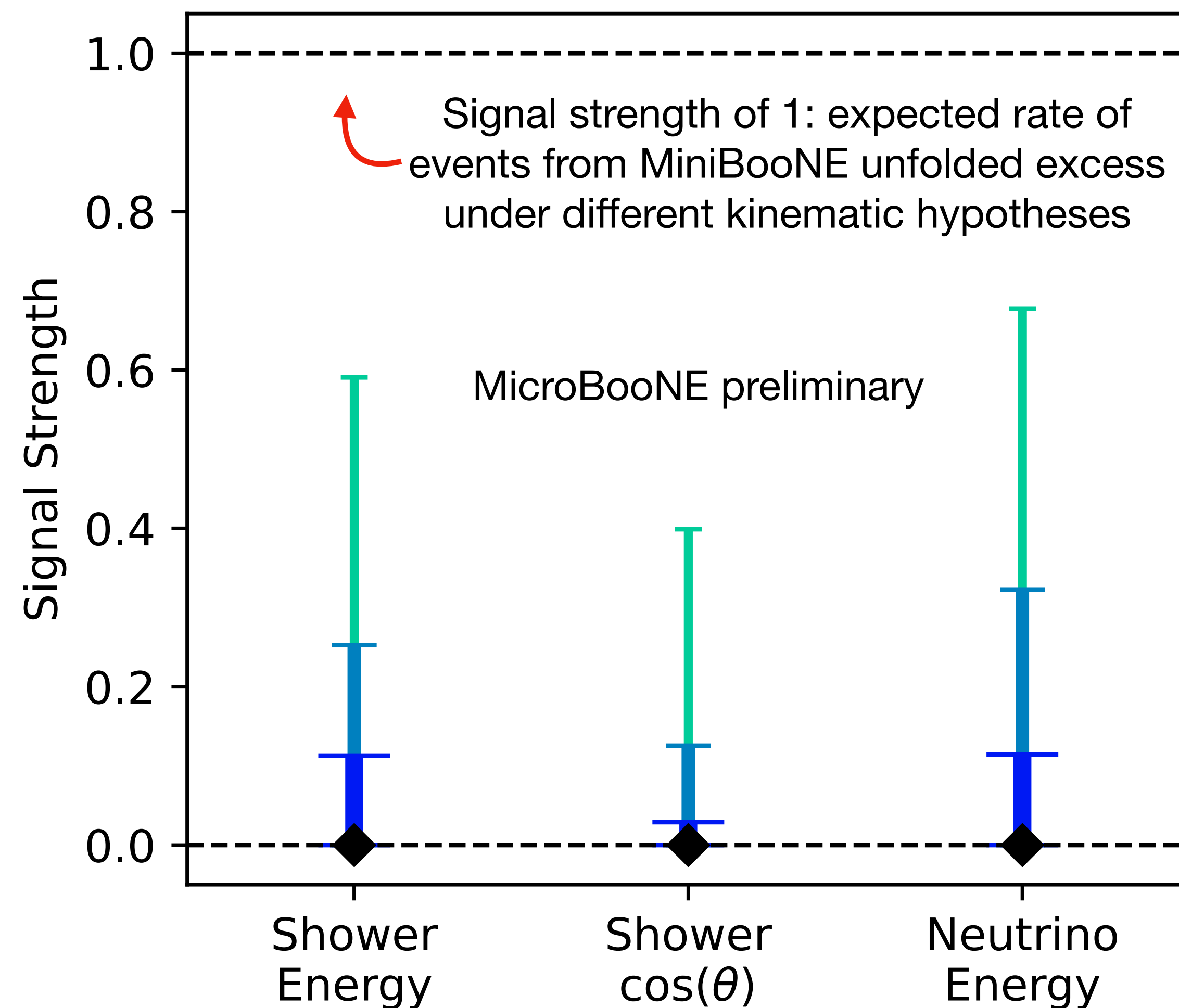
Expanded investigation of electron excess hypothesis:

- 6.86e20  $\rightarrow$  11.1e20 POT of data
- new constraint of intrinsic  $\nu_e$  and  $\pi^0$  backgrounds
- complementary signal hypotheses:  $E_\nu$ ,  $E_{\text{elec}}$ , and  $\theta_{\text{elec}}$

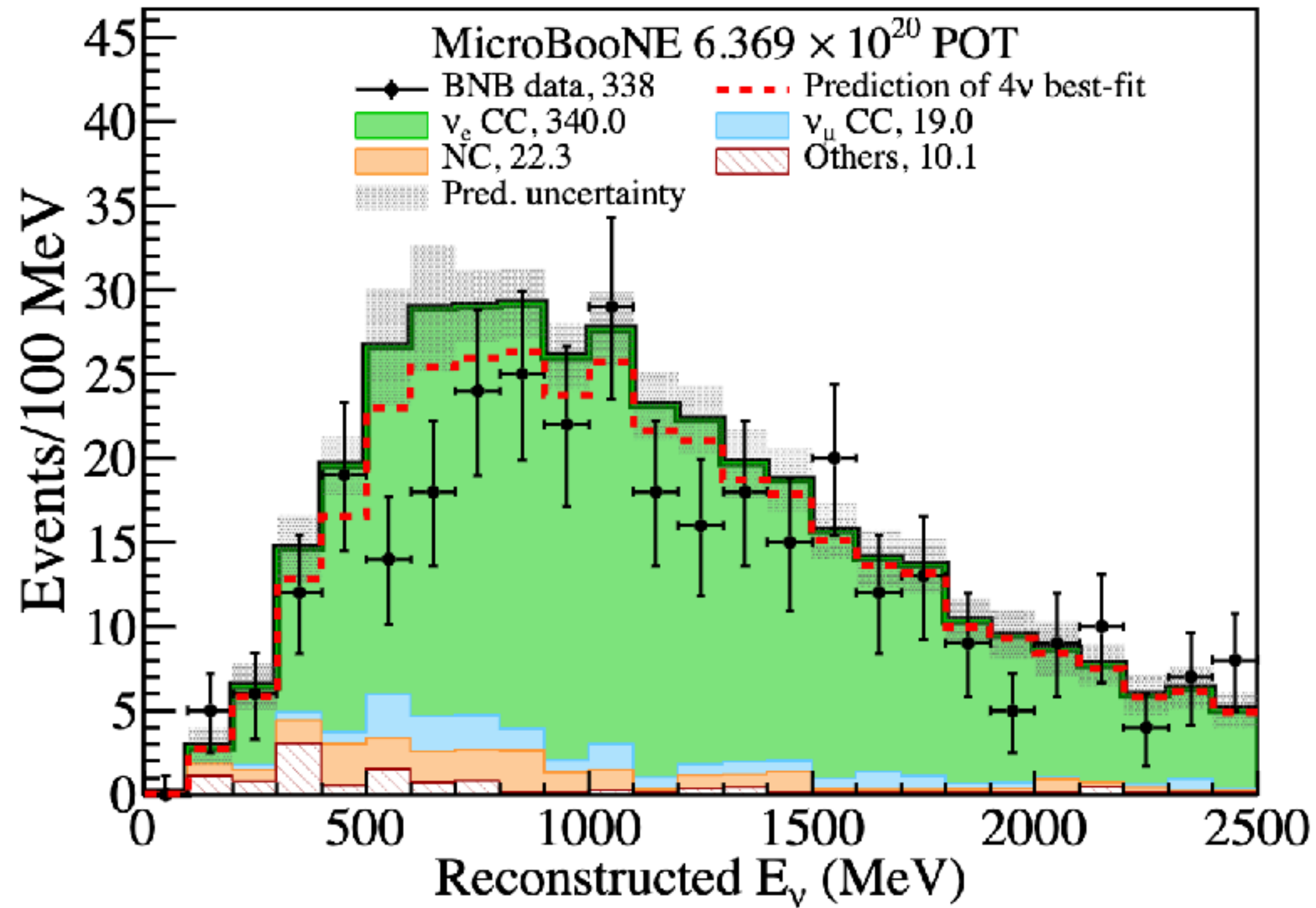
## Results:

- data compatible with background-only prediction
- **data inconsistent with  $\nu_e$ -like excess at  $> 99\%$  CL**
- results consistent across kinematic variables tested.

More details in [MICROBOONE-NOTE-1127-PUB](#)

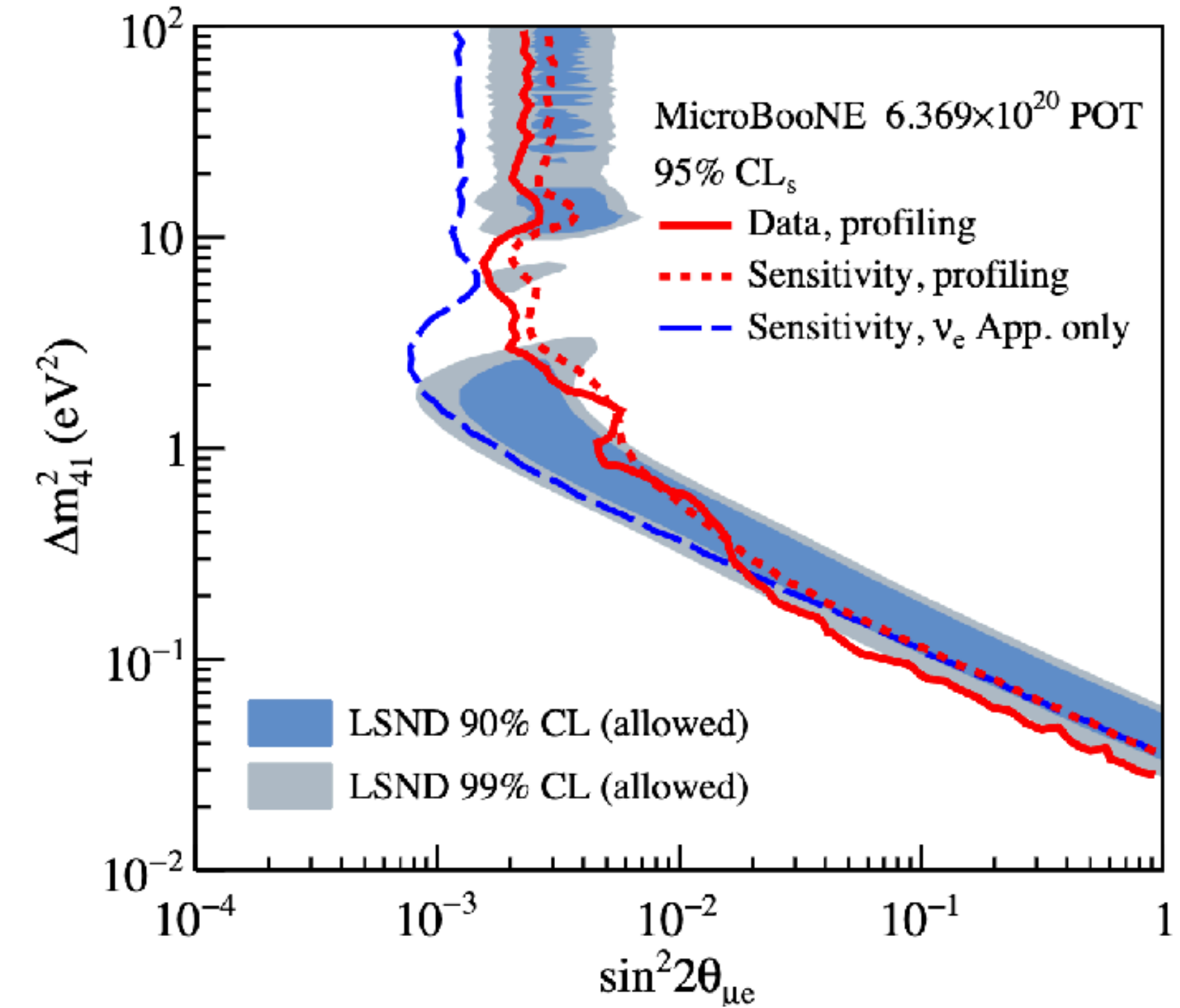


# 3+1 sterile neutrino search with BNB



$\nu_e ? \longrightarrow \nu_s ?$

Reinterpret LEE  $\nu_e$  analysis under 3+1 sterile neutrino oscillation framework



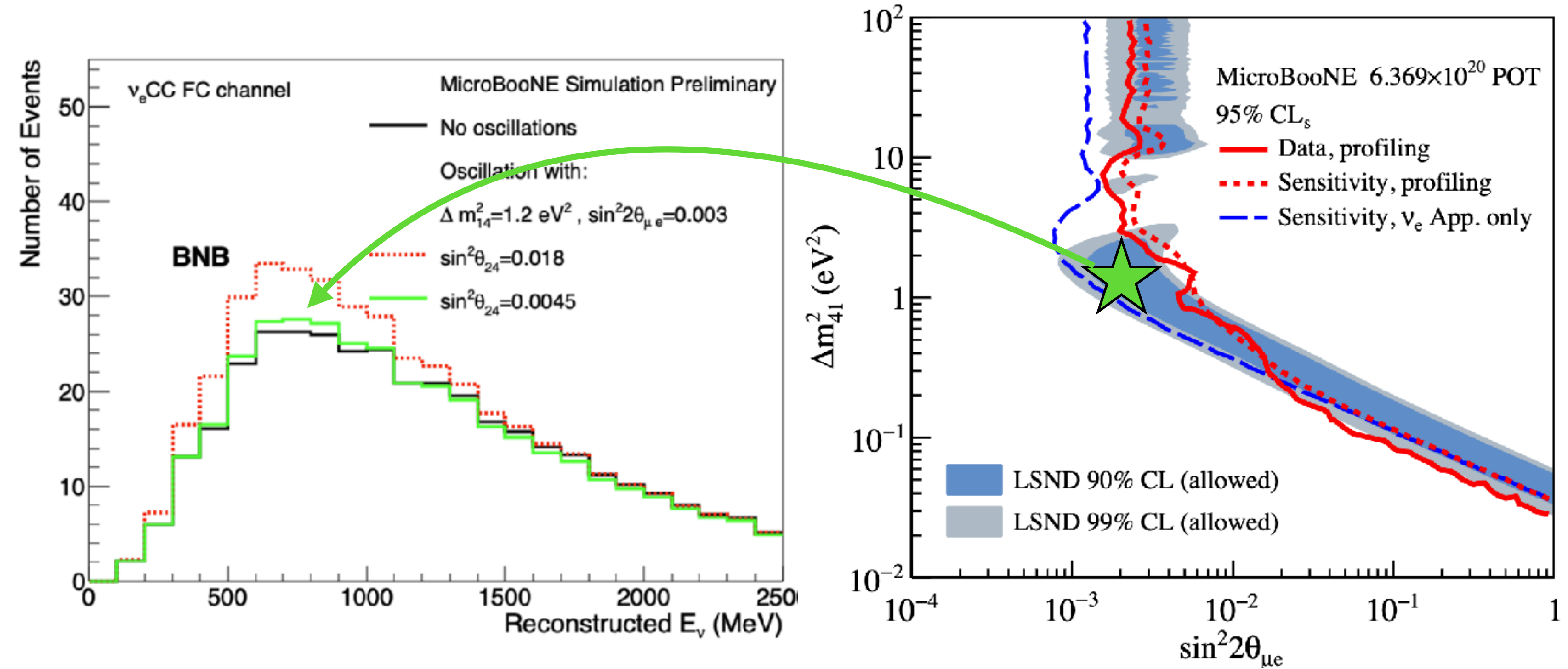
MicroBooNE's first 3+1 sterile neutrino search ('22)

PRL 130 (2023) 1, 01180

inclusive  $\nu_e$  analysis. performed with BNB data.

Sensitivity *not* statistics limited!

# 3+1 sterile neutrino search: degeneracy

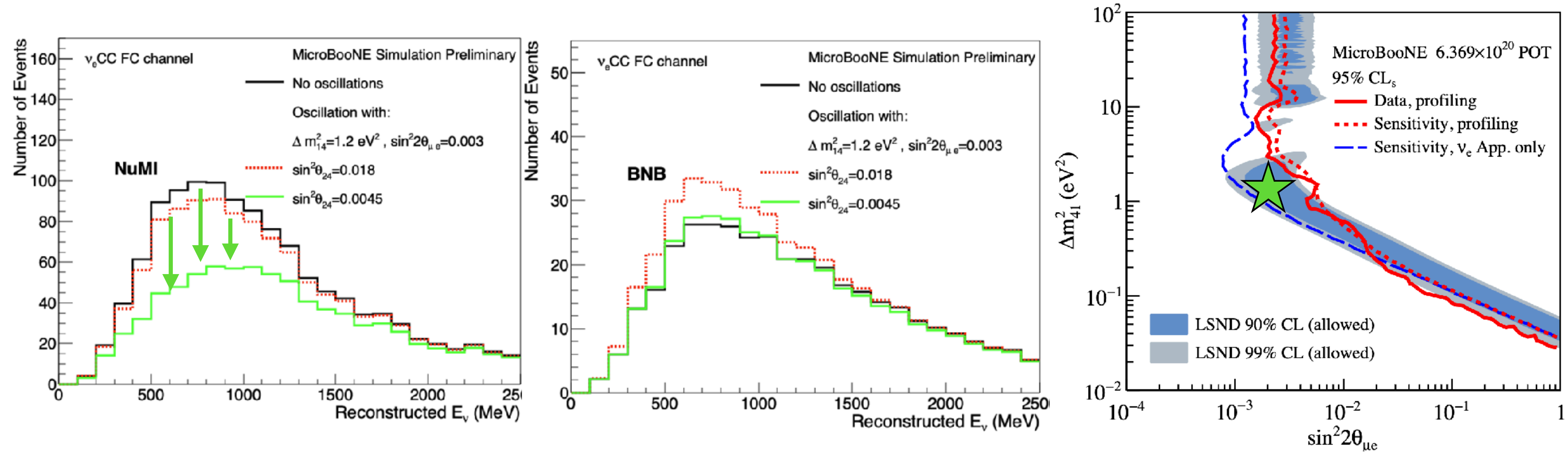


3+1 degeneracy:  $\nu_e$  appearance cancels out  $\nu_e$  disappearance

Degeneracy depends on intrinsic rate of  $\nu_e$  vs.  $\nu_\mu$  in the beam.

$$\text{For BNB } \frac{N_{\nu_\mu}}{N_{\nu_e}} \sim 200.$$

# 3+1 sterile neutrino search: NuMI



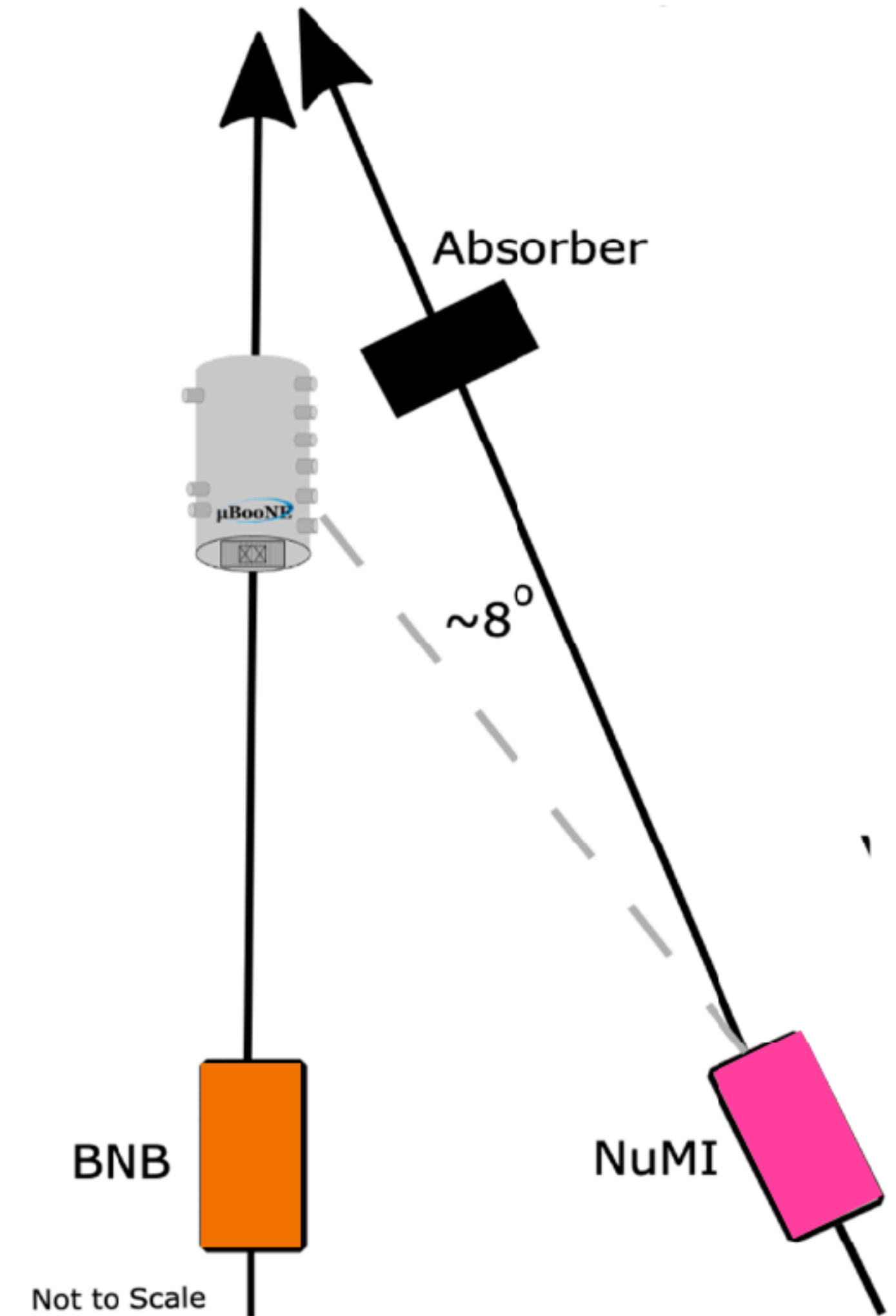
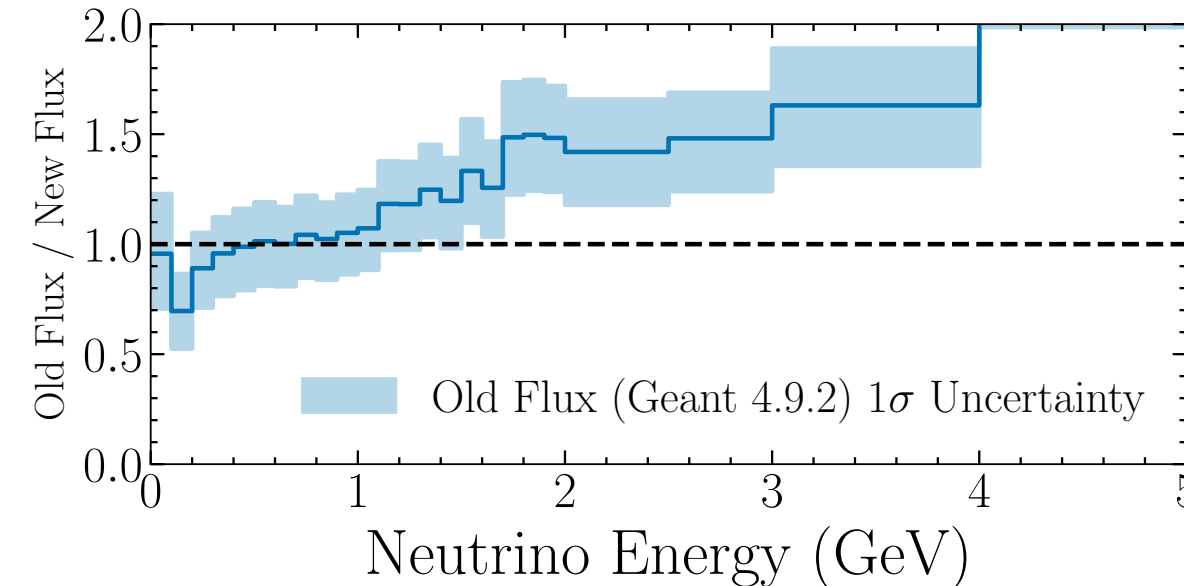
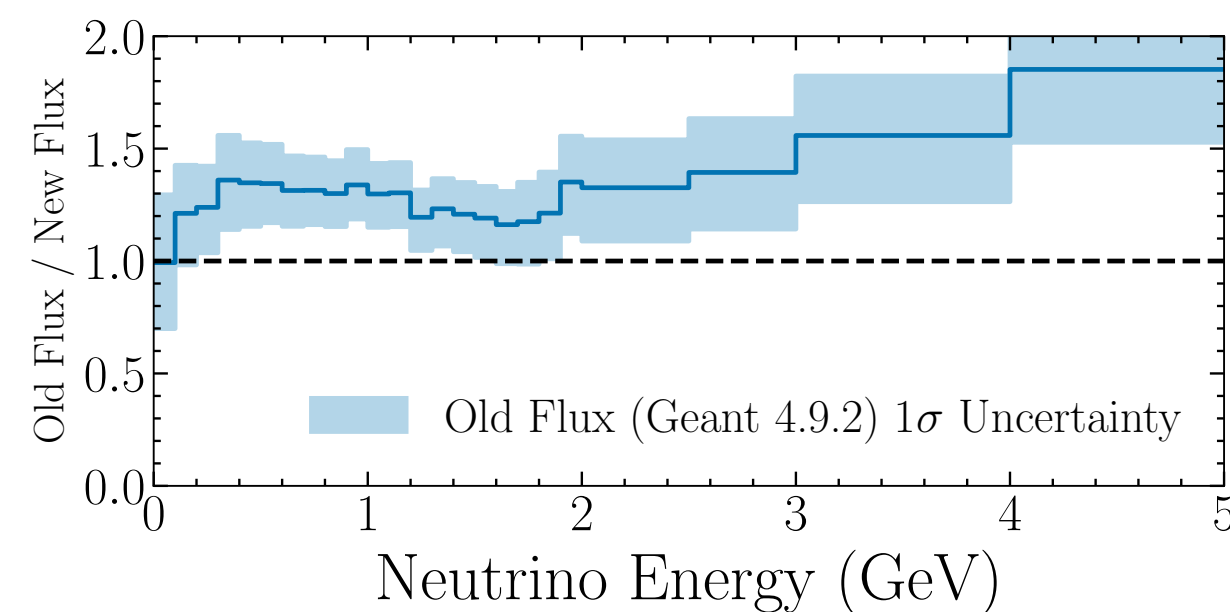
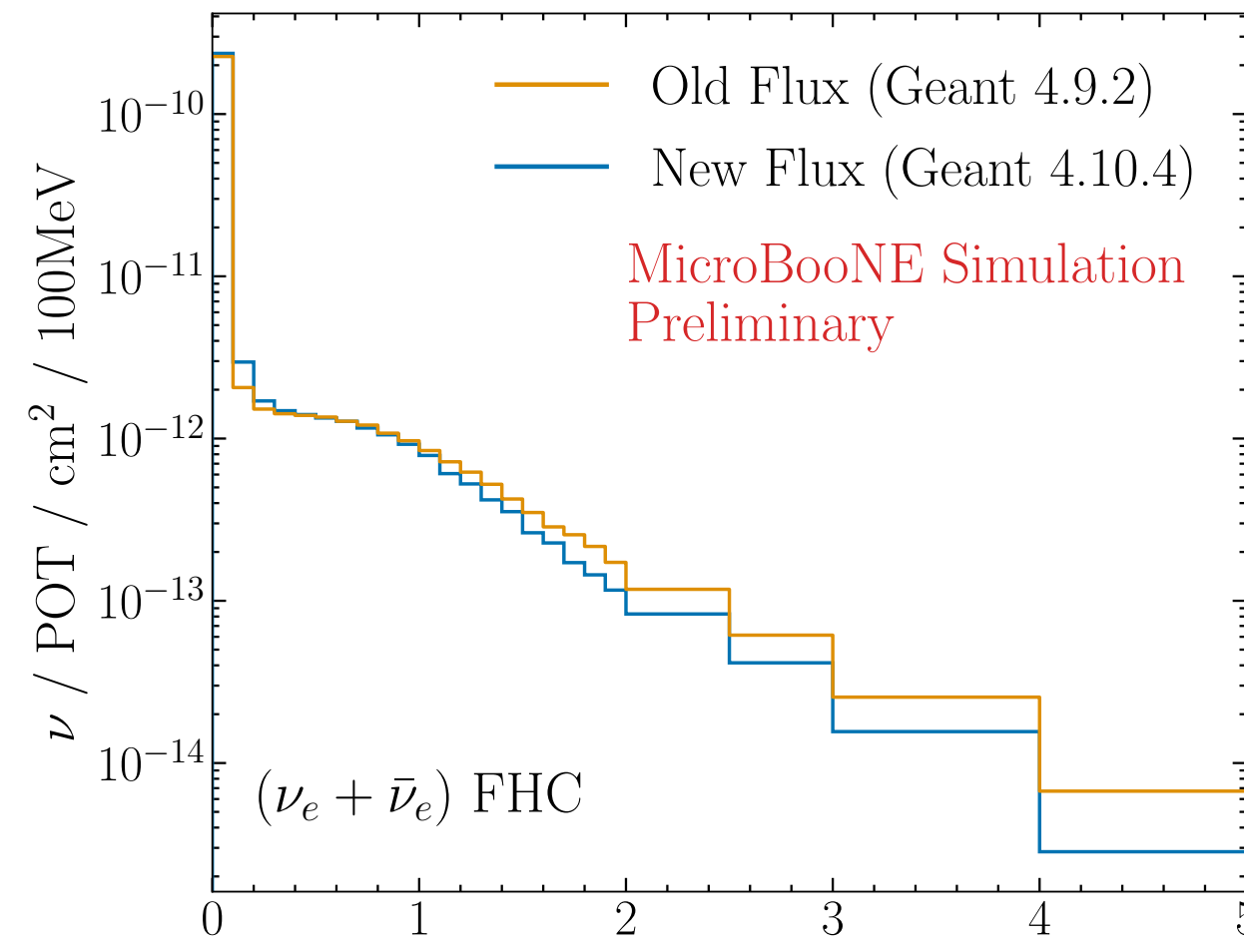
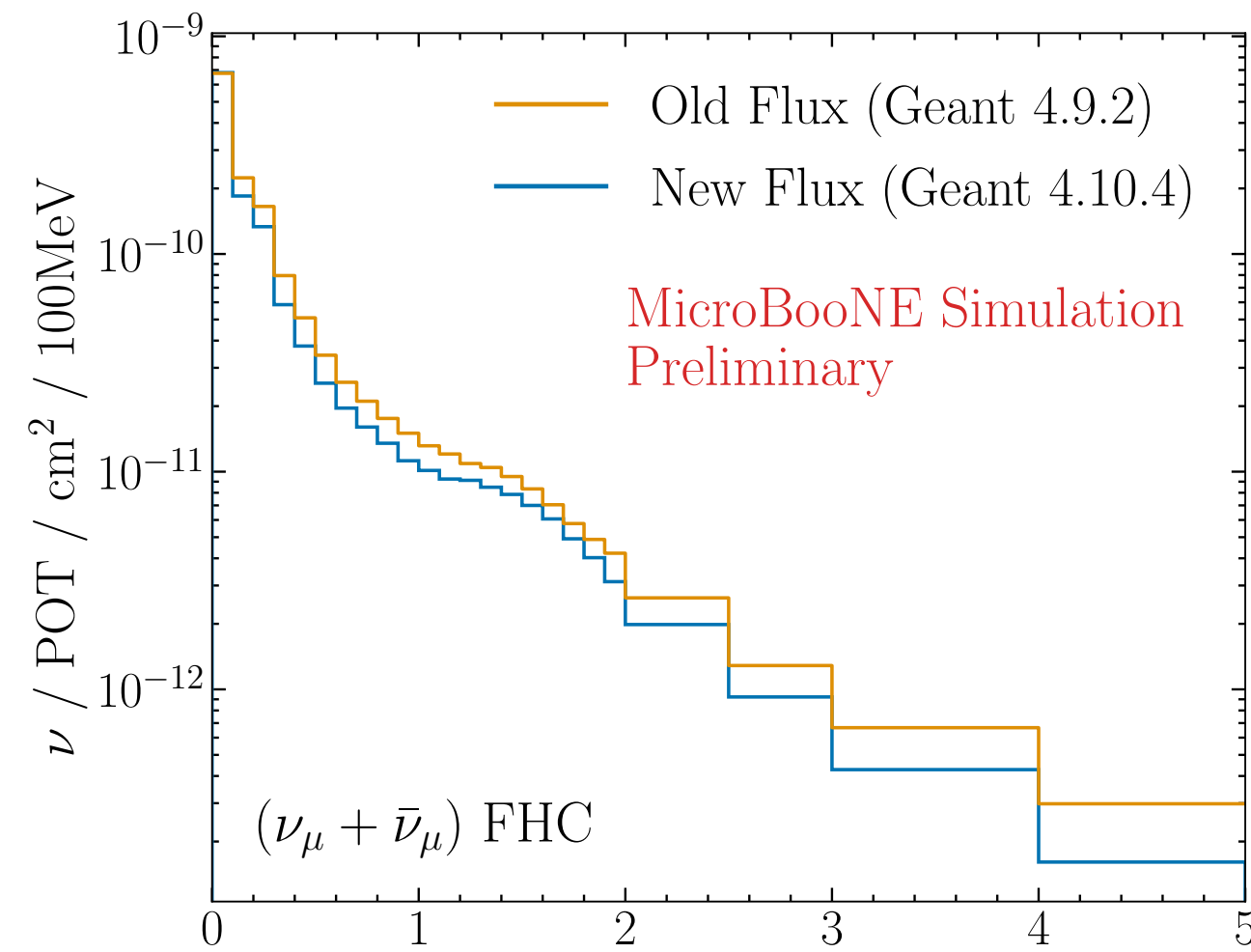
For the same mixing angles, impact on NuMI  $\nu_e$  spectrum is large due to the different  $\frac{N_{\nu\mu}}{N_{\nu e}} \sim 25$

NuMI beam allows us to break the degeneracy

# Updated NuMI flux @ MicroBooNE

MicroBooNE sits highly off-axis ( $\sim 8$  degrees) to the NuMI beam:

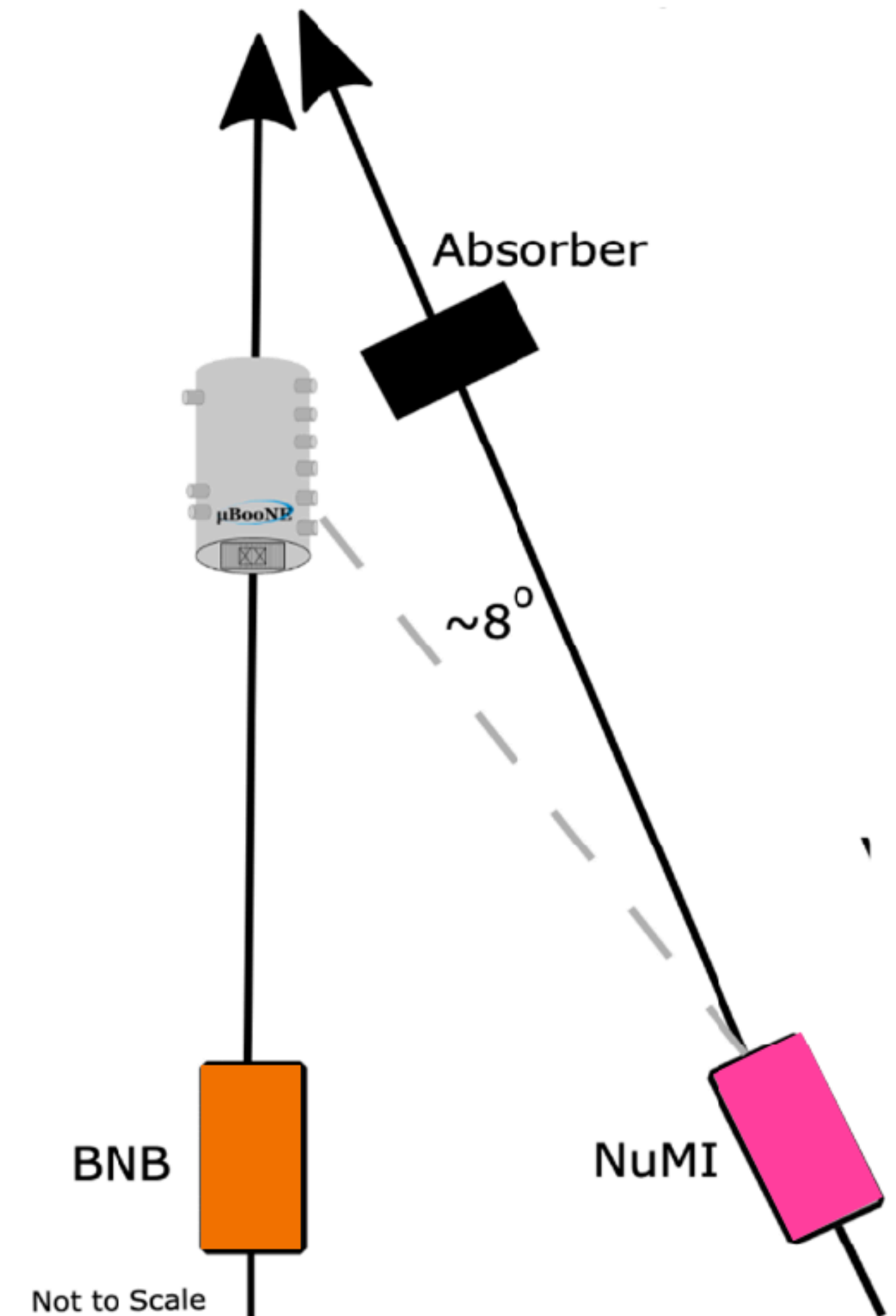
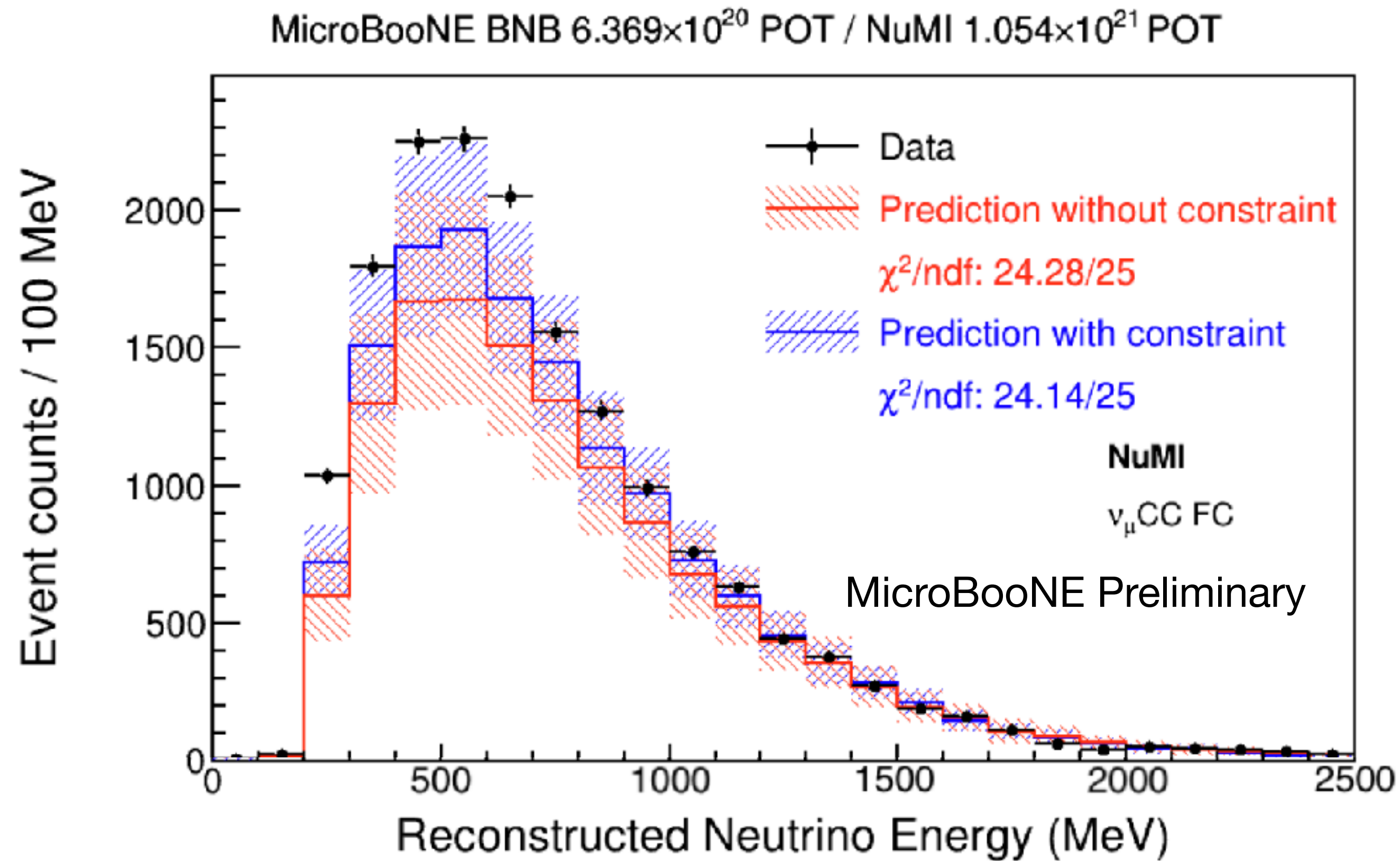
- flux dominated by hadron re-interactions with detector hall material
- phase space for hadron production not fully covered by world data
- flux simulation upgrade: beam line geometry, Geant4 version, systematics.



Updated NuMI flux at MicroBooNE  
More details in [MICROBOONE-NOTE-1129-PUB](#)

# Updated NuMI flux @ MicroBooNE

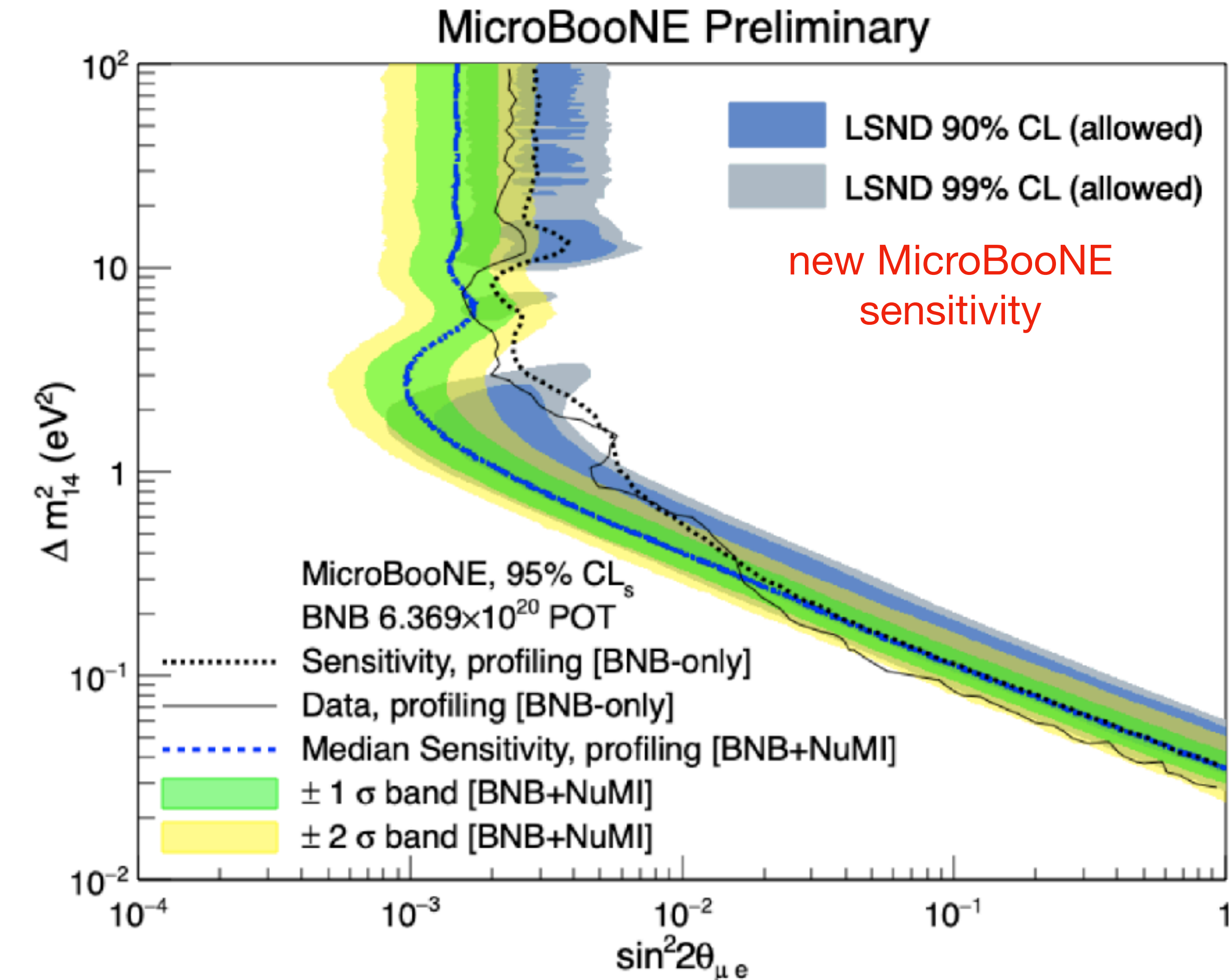
MicroBooNE's updated NuMI flux prediction vs.  $\nu_\mu$  data:



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



# 3+1 sterile neutrino search: new sensitivities



“one detector, two beams”

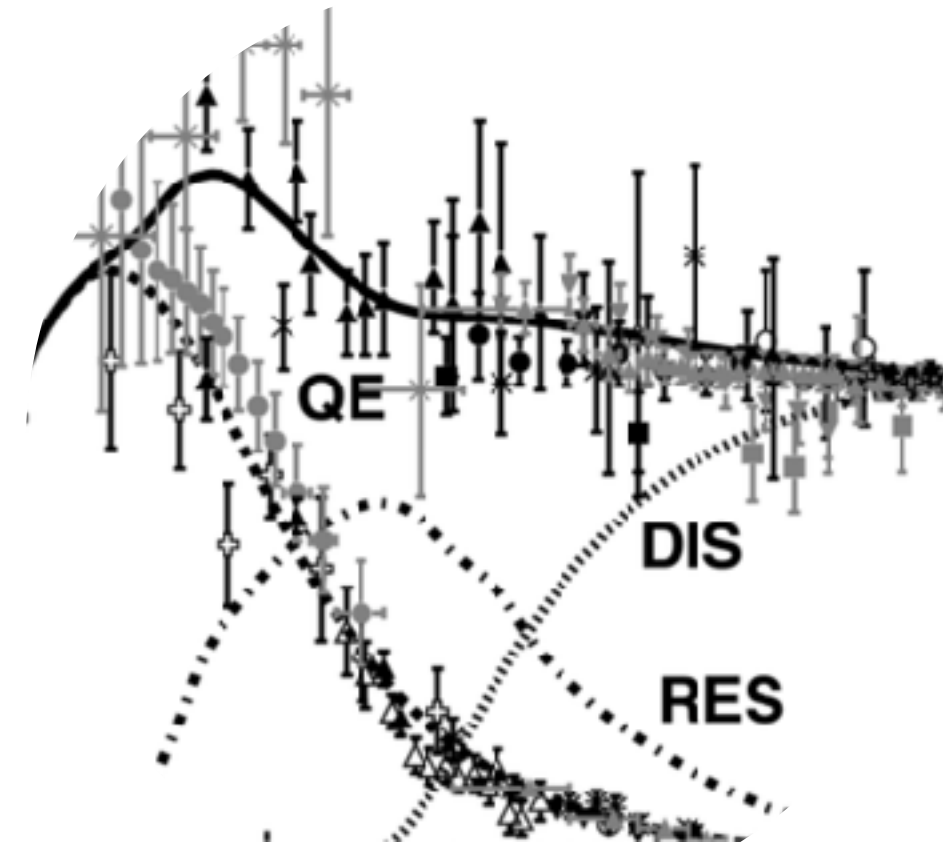
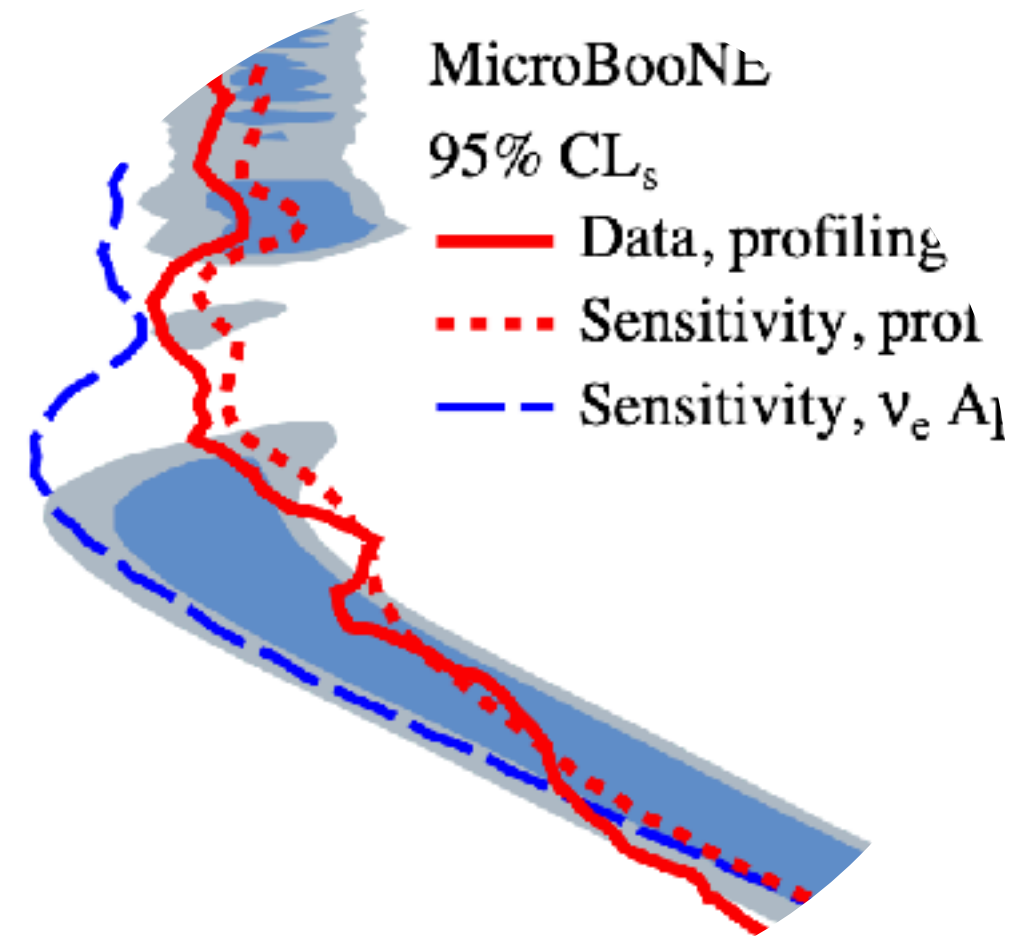
Joint 3+1 analyst with BNB + NuMI allows significant enhancement to sensitivity!

Stay tuned for upcoming results from MicroBooNE!

more details in [MICROBOONE-NOTE-1132-PUB](#)

# MicroBooNE's Physics Program

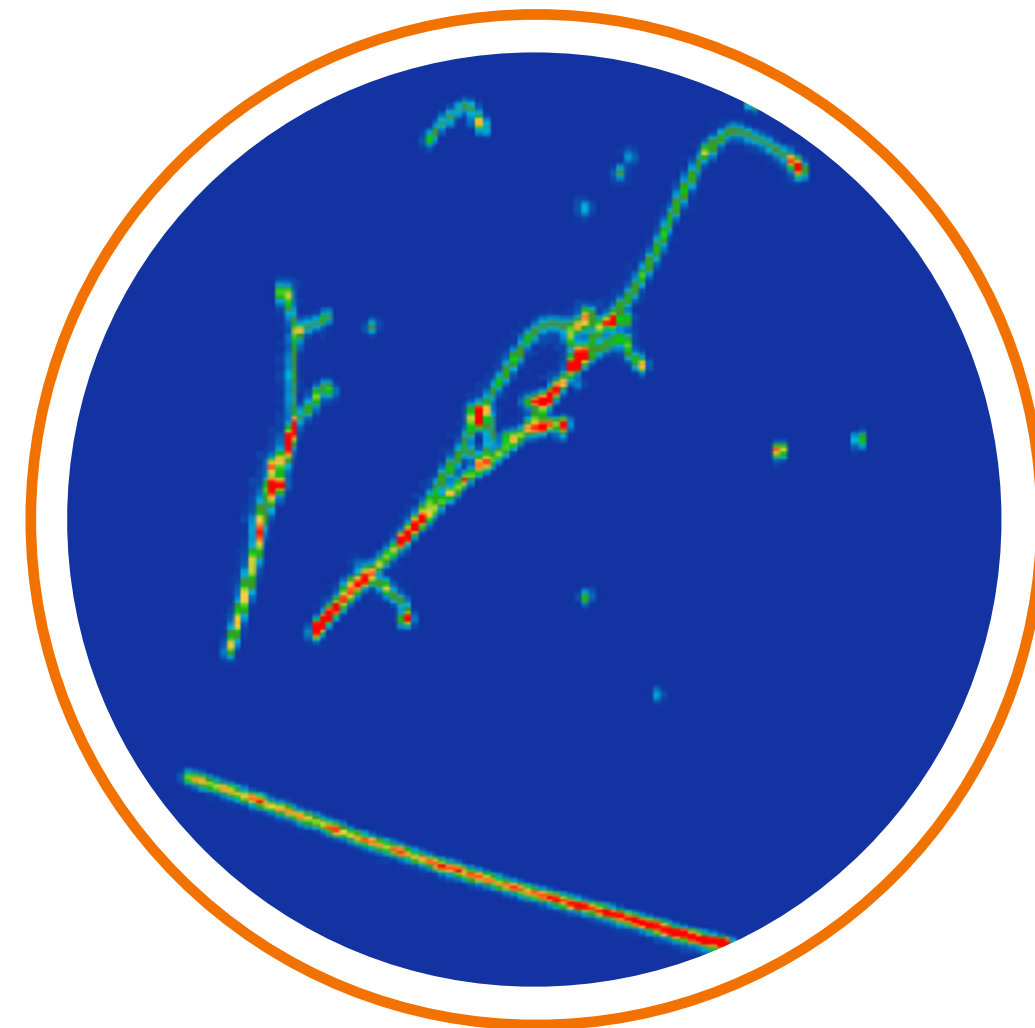
Beyond the Standard  
Model physics searches



$\nu$  - Ar scattering



advancing LArTPC  
technology capabilities



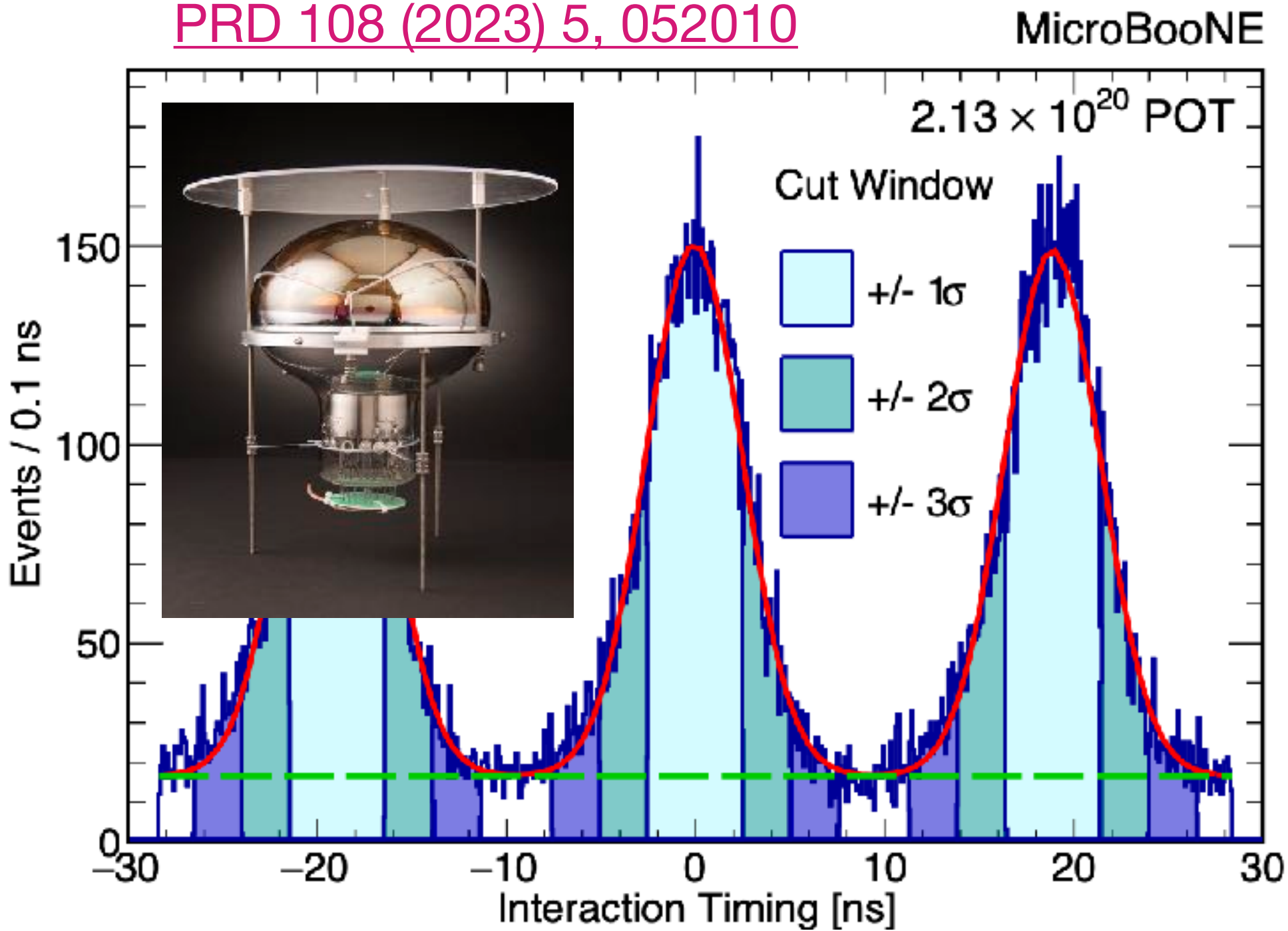
# Novel Tools & Techniques for LArTPC detectors

nanosecond timing in LArTPCs

Enhance BSM long-lived particle searches

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

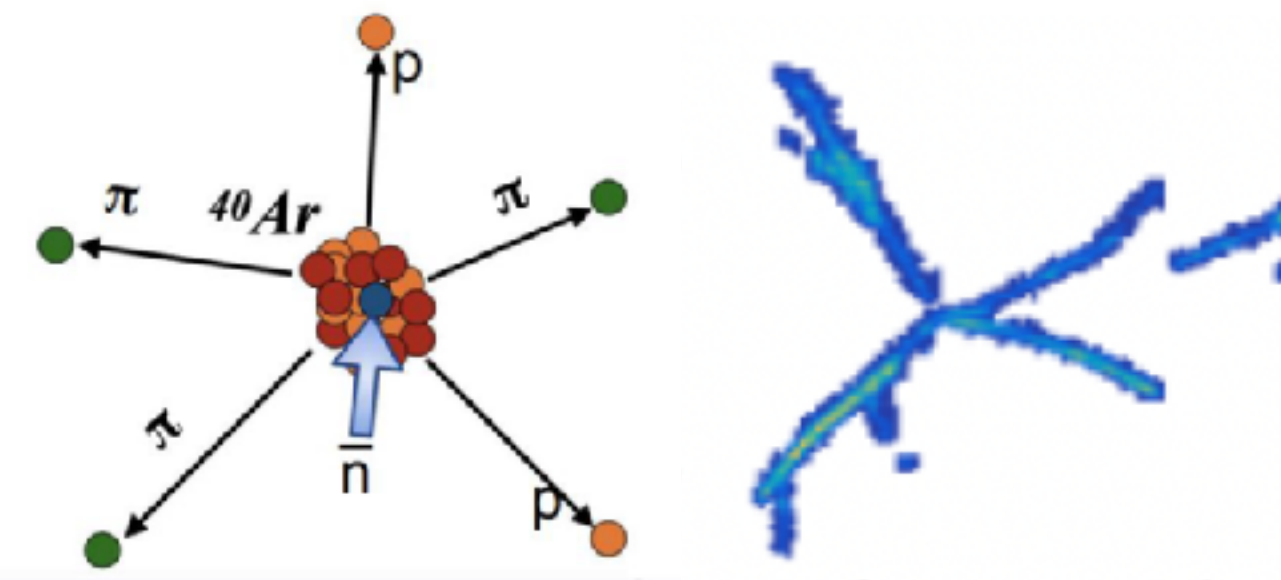
[PRD 108 \(2023\) 5, 052010](#)



New capabilities for LArTPC detectors!

n-nbar LArTPC demonstration

[\[POSTER #189, Friday\]](#)

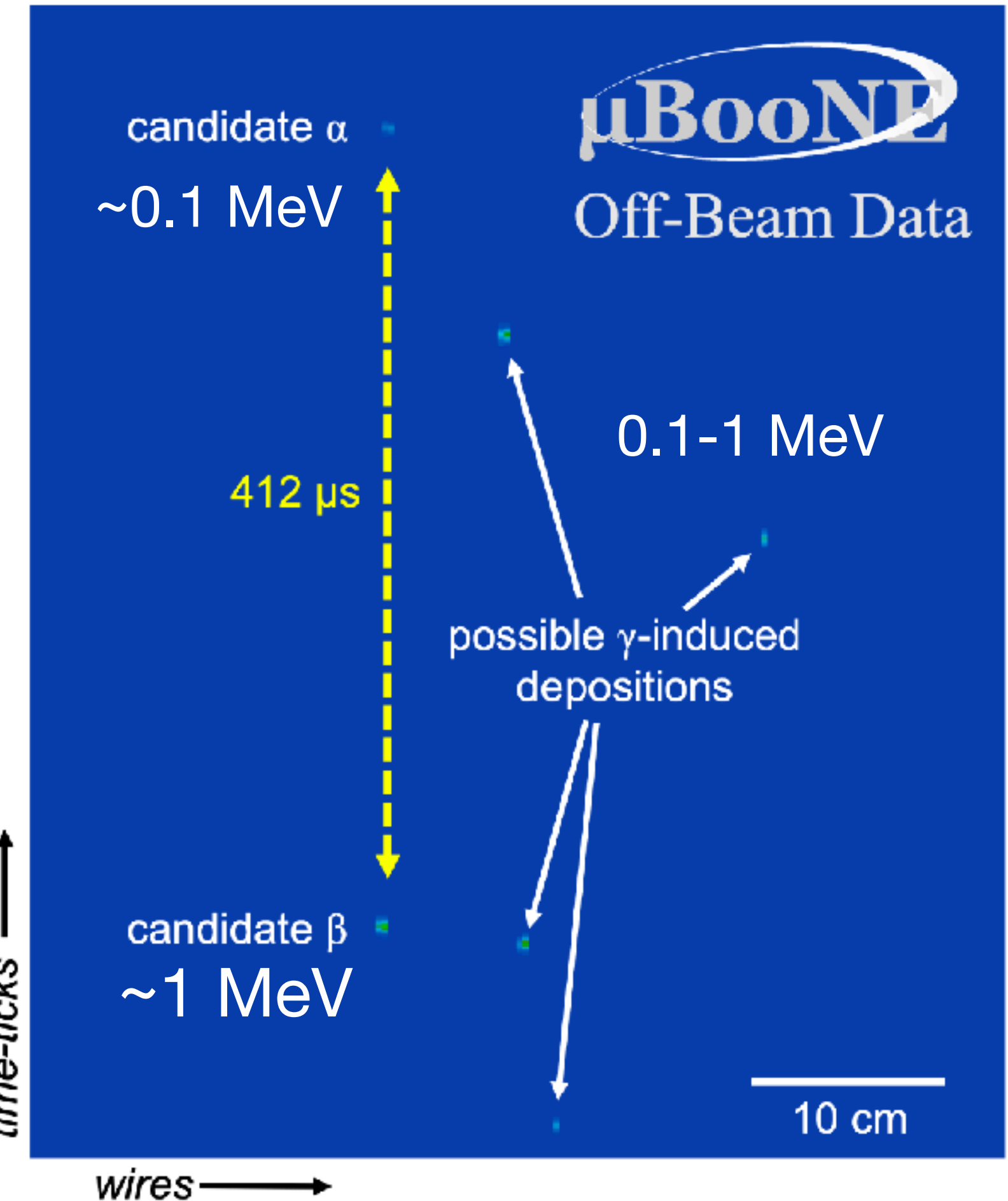
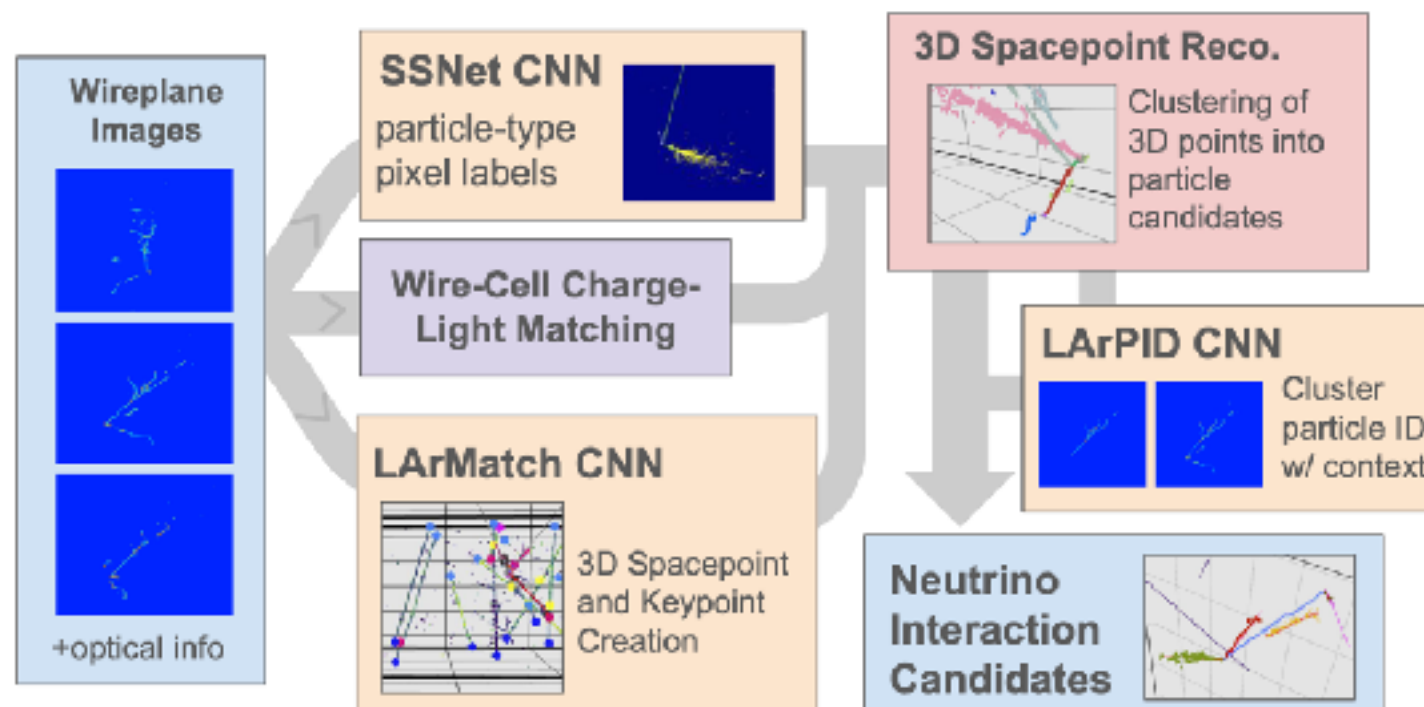


ML & Deep Learning Reconstruction

[\[POSTER #398, Tuesday\]](#)

MICROBOONE-NOTE-23-PUB

[arXiv:2406.10123](#)



MeV scale physics capabilities

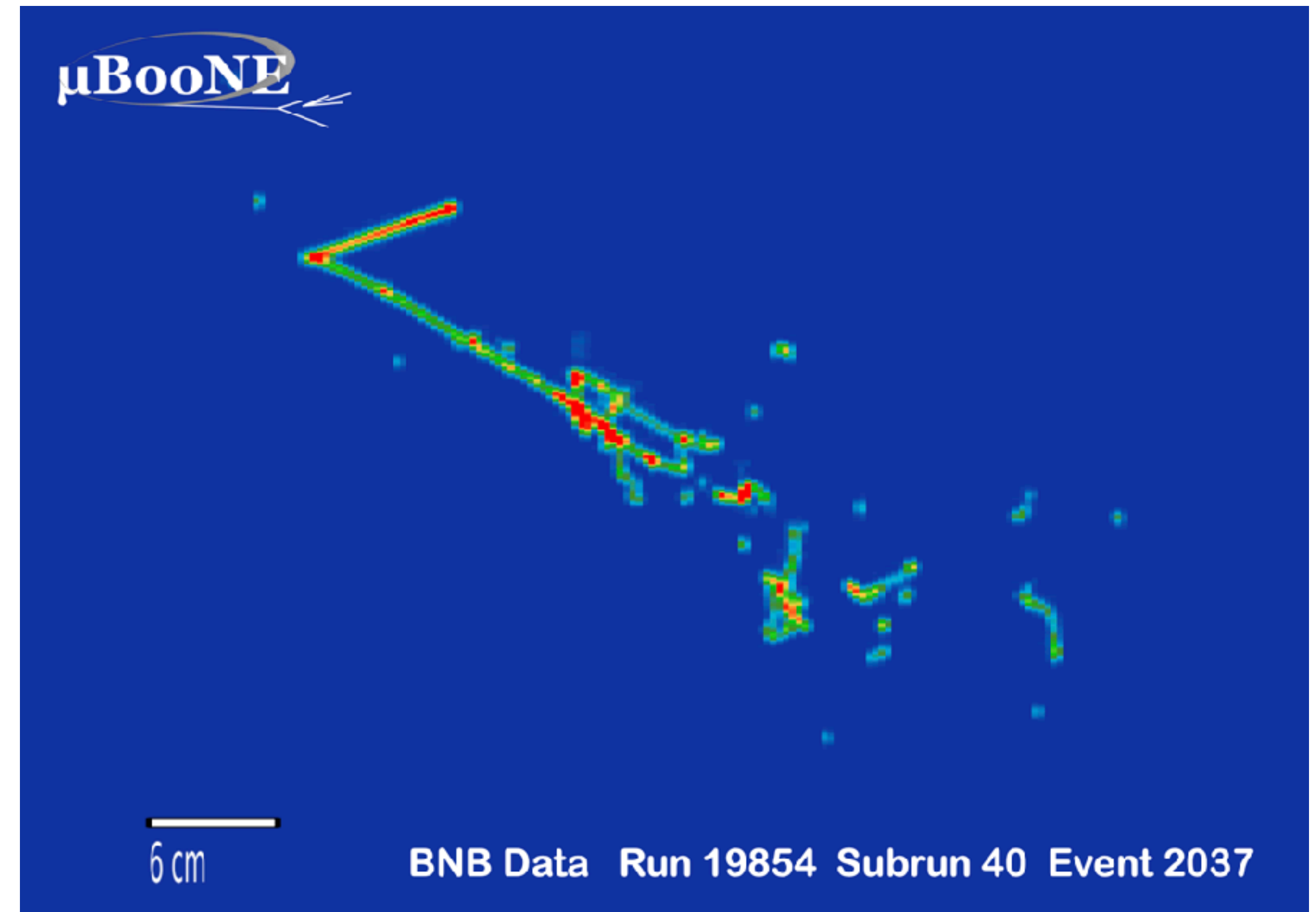
LArTPC astrophysics & more!

[\[POSTER #186, Tuesday\]](#)

# Conclusions

MicroBooNE has an active physics program:

- World-leading limits on low-mass BSM particles
- New  $\nu_e$  Low Energy Excess and upcoming results in **single- $\gamma$**  and  $e^+e^-$  channels.
- Novel “one detector - two beams” 3+1 sterile search
  - Leverage BNB + NuMI beams
- Many new LArTPCs developments and more to come with full 5-year dataset!




# More from MicroBooNE @ Neutrino '24

**MeV-Scale Blip Reconstruction and Measurements of Radon Progeny in the MicroBooNE Liquid Argon TPC**

Bryce Littlejohn, Will Foreman (Illinois Institute of Technology) representing the MicroBooNE Collaboration

**Poster #186 Tuesday**




**Low Energy Excess and New Physics Searches with MicroBooNE**

Fan Gao, Lee Hagaman, Alexandra Trettin, Mark Ross-Lonergan, Erin Yandel

**Poster #628 Tuesday**

**New Results!**





**New search for a sterile neutrino at MicroBooNE with BNB and NuMI beams**

Sergey Martynenko, Brookhaven National Laboratory, [smartyn@bnl.gov](mailto:smartyn@bnl.gov)

Xiangpan Ji, Nankai University, [jixp@mail.nk.uj.edu.cn](mailto:jixp@mail.nk.uj.edu.cn)

On behalf of the MicroBooNE Collaboration



**Poster #144 Tuesday**

**First demonstration for a LArTPC-based search for intranuclear neutron transitions and annihilation in  $^{40}\text{Ar}$  using the MicroBooNE**

Daisy Kalra, on behalf of the MicroBooNE Collaboration

**Poster #189 Friday**

**Inclusive and Exclusive Pionless Cross Section Measurements with MicroBooNE**

Lee Hagaman on behalf of the MicroBooNE Collaboration

[lhagaman@uchicago.edu](mailto:lhagaman@uchicago.edu)

**Poster #626 Tuesday**




**Detecting Neutrons in MicroBooNE**

Andy Furmanski, Burke Irwin, on behalf of the MicroBooNE Collaboration



**Poster #636 Tuesday**



**Data-Driven Light Model for the MicroBooNE Experiment**

Polina Abratenko on behalf of the MicroBooNE Collaboration



**Poster #185 Tuesday**

**Identifying Neutrino Final States and Energies in MicroBooNE: New Deep-Learning Based LArTPC Reconstruction Framework**

Matthew Rosenberg on behalf of the MicroBooNE Collaboration

**Poster #398 Tuesday**

**Rare Neutrino Interaction and  $n^0$  Production Cross Sections with MicroBooNE**

Christopher Thorpe on Behalf of the MicroBooNE Collaboration

[christopher.thorpe-3@manchester.ac.uk](mailto:christopher.thorpe-3@manchester.ac.uk)

**Poster #627 Tuesday**



**MicroBooNE cross section talk:**

*“High-precision neutrino interaction measurements with MicroBooNE”*

A. Papadopoulou, Friday @ 11 AM

**Dark sector searches with the MicroBooNE Detector**

Stefan Söldner-Rembold on behalf of the MicroBooNE Collaboration

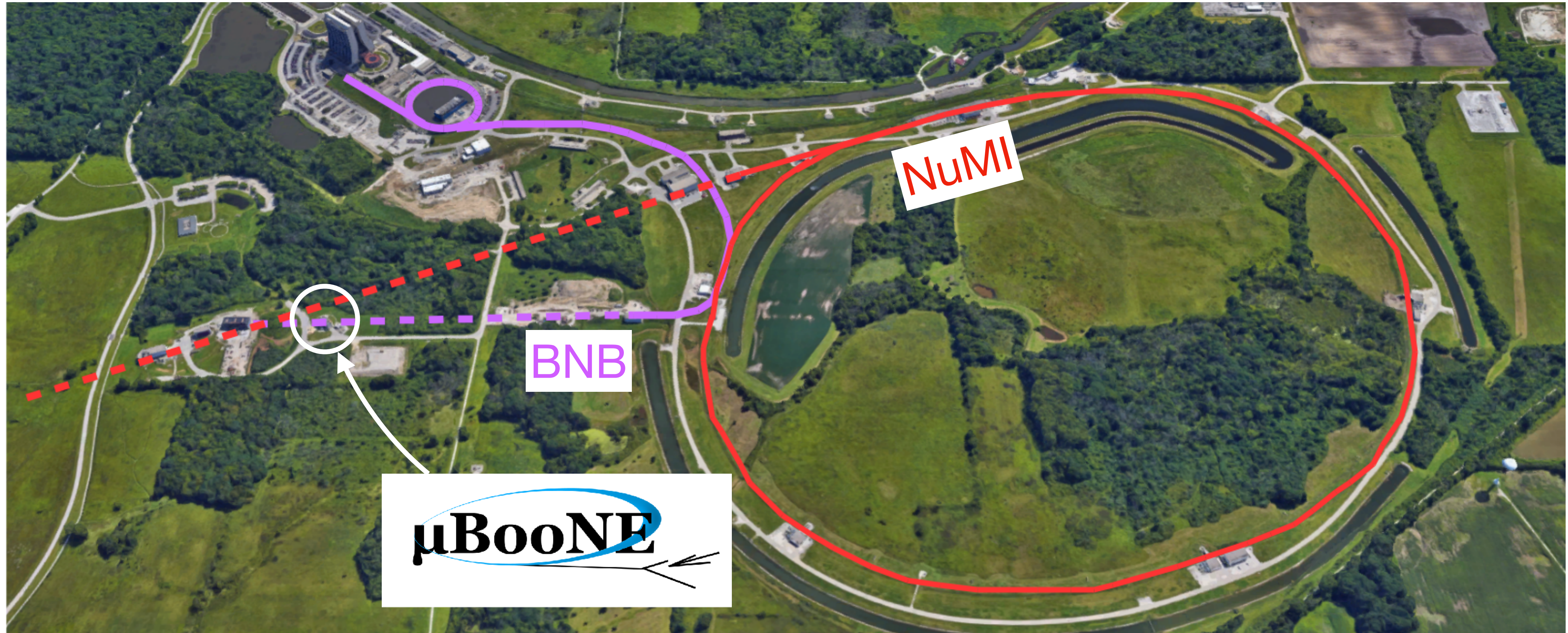
[s.soldner-rembold@imperial.ac.uk](mailto:s.soldner-rembold@imperial.ac.uk)

**Poster #634 Friday**




# Backup

# BNB & NuMI At MicroBooNE



# Liquid Argon Time Projection Chamber

MicroBooNE detector paper: [JINST 12 \(2017\) 02, P02017](#)

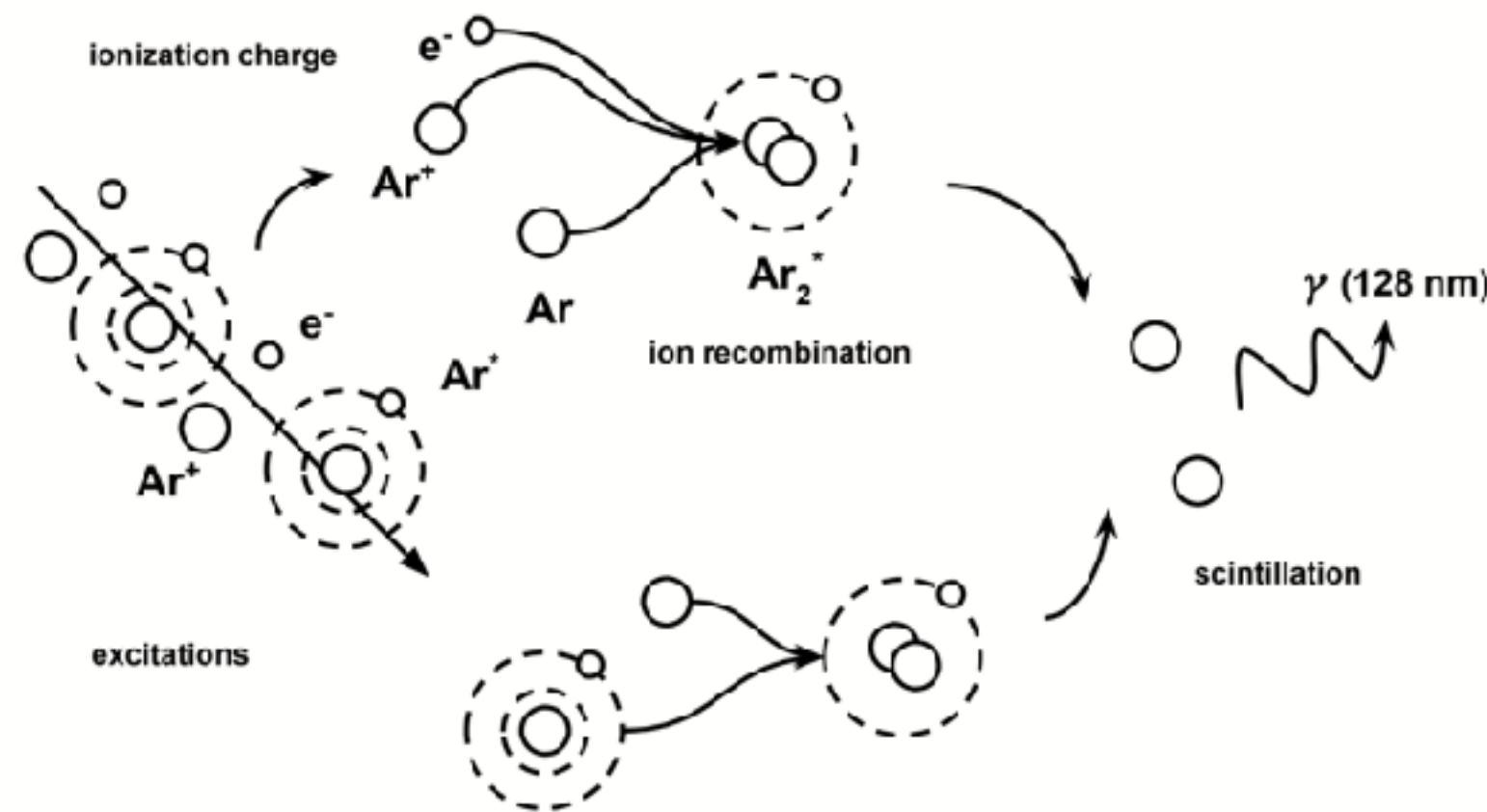
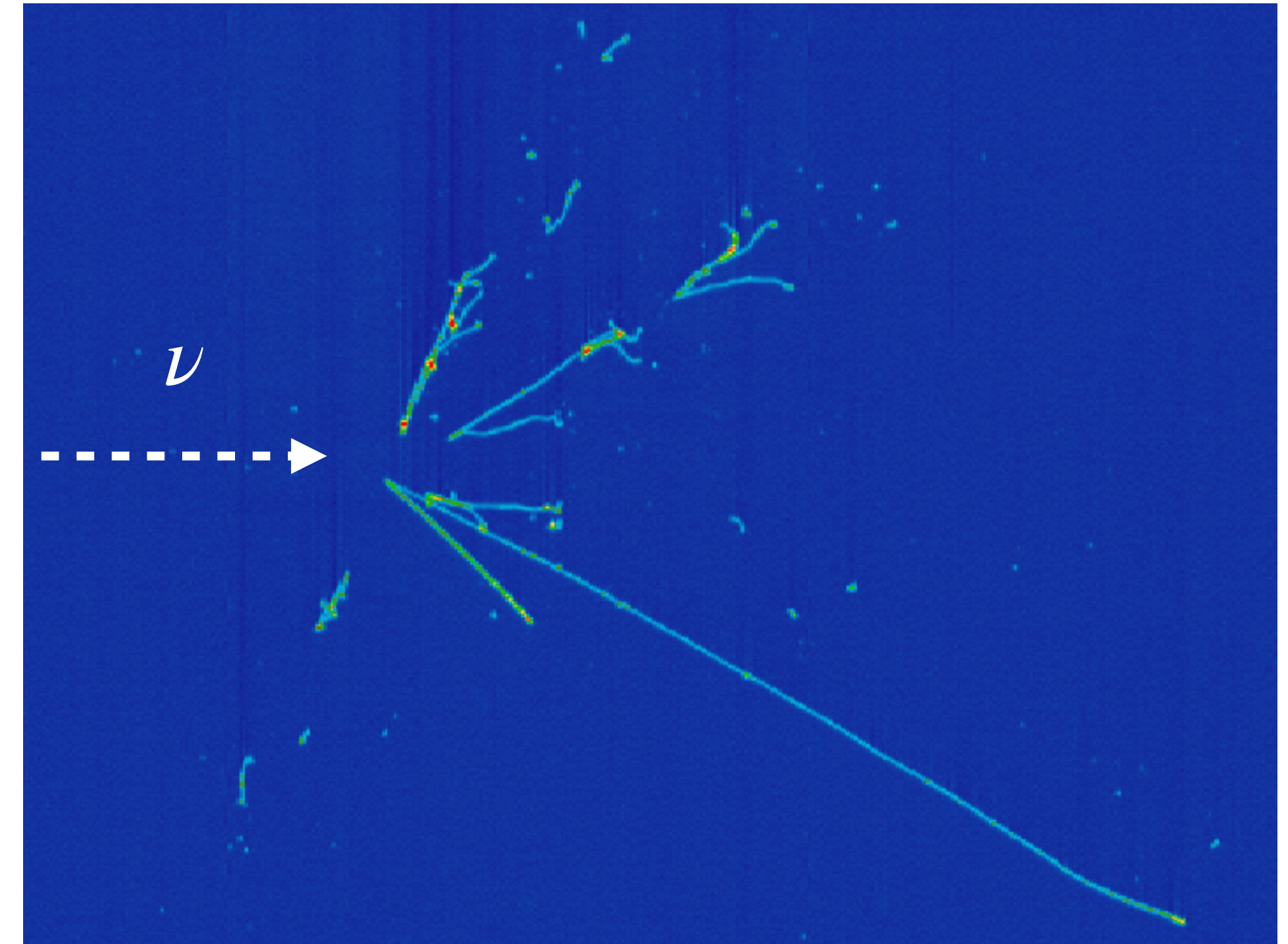
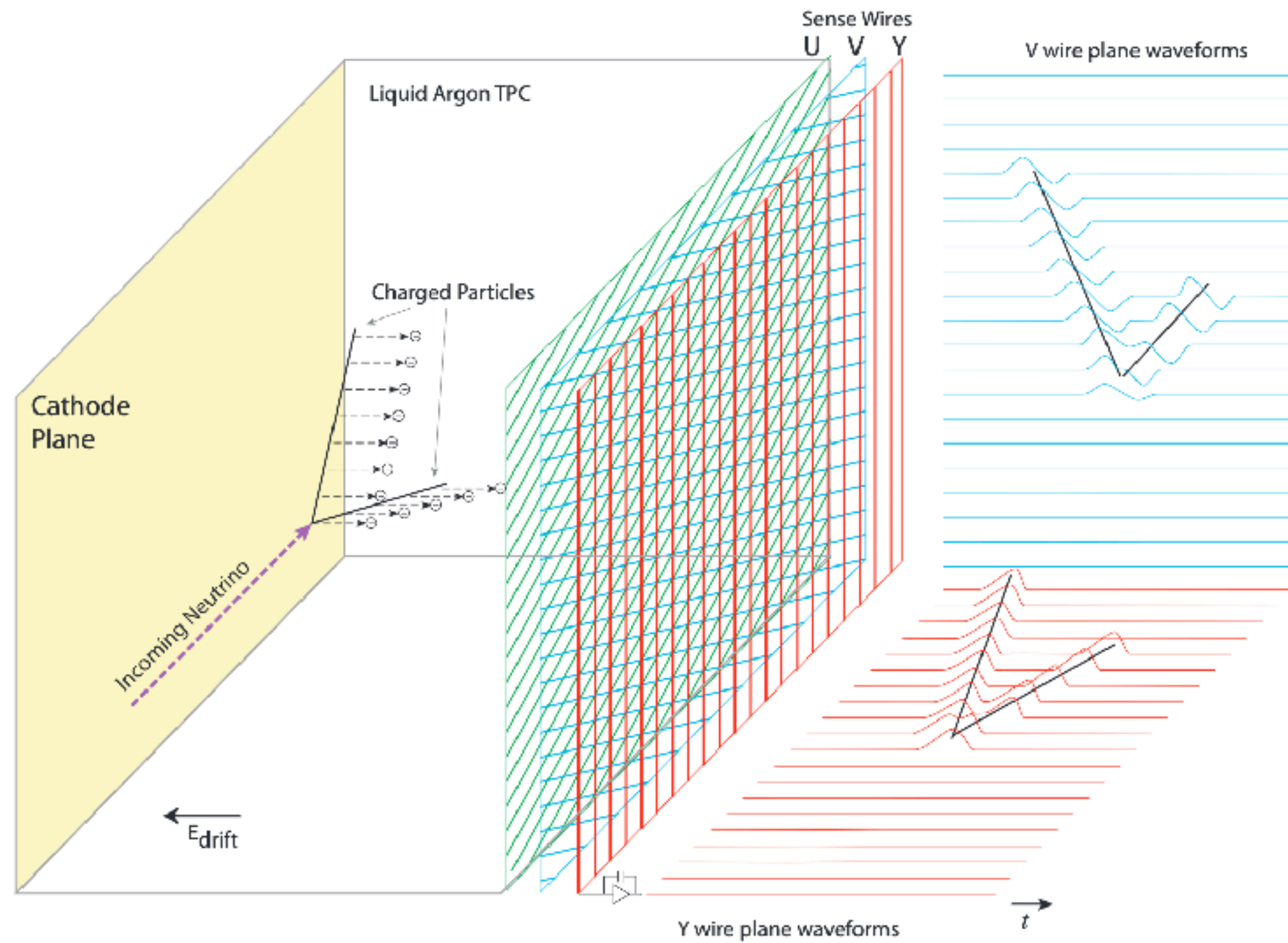


Image neutrino interactions leveraging:

Ionization electrons:

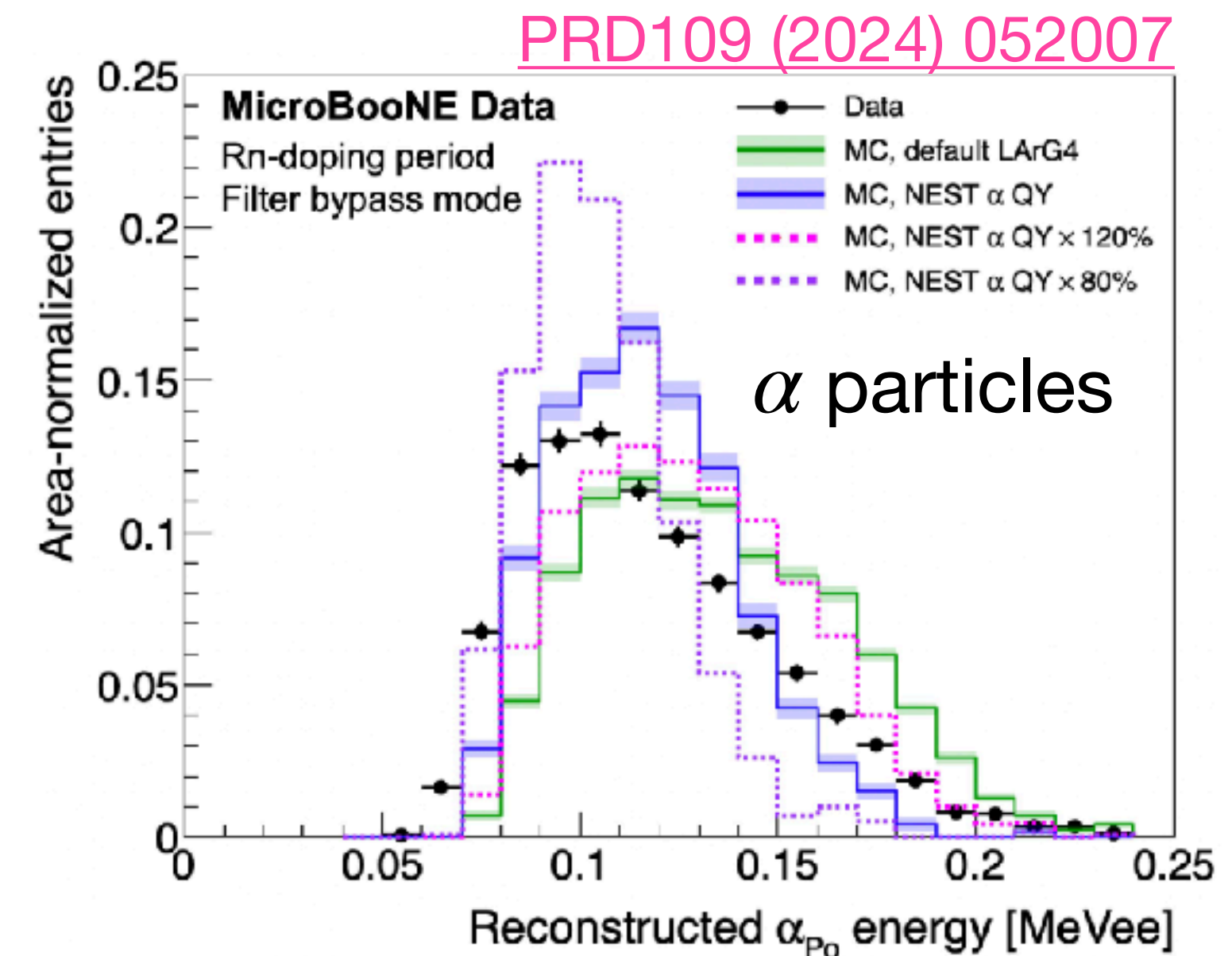
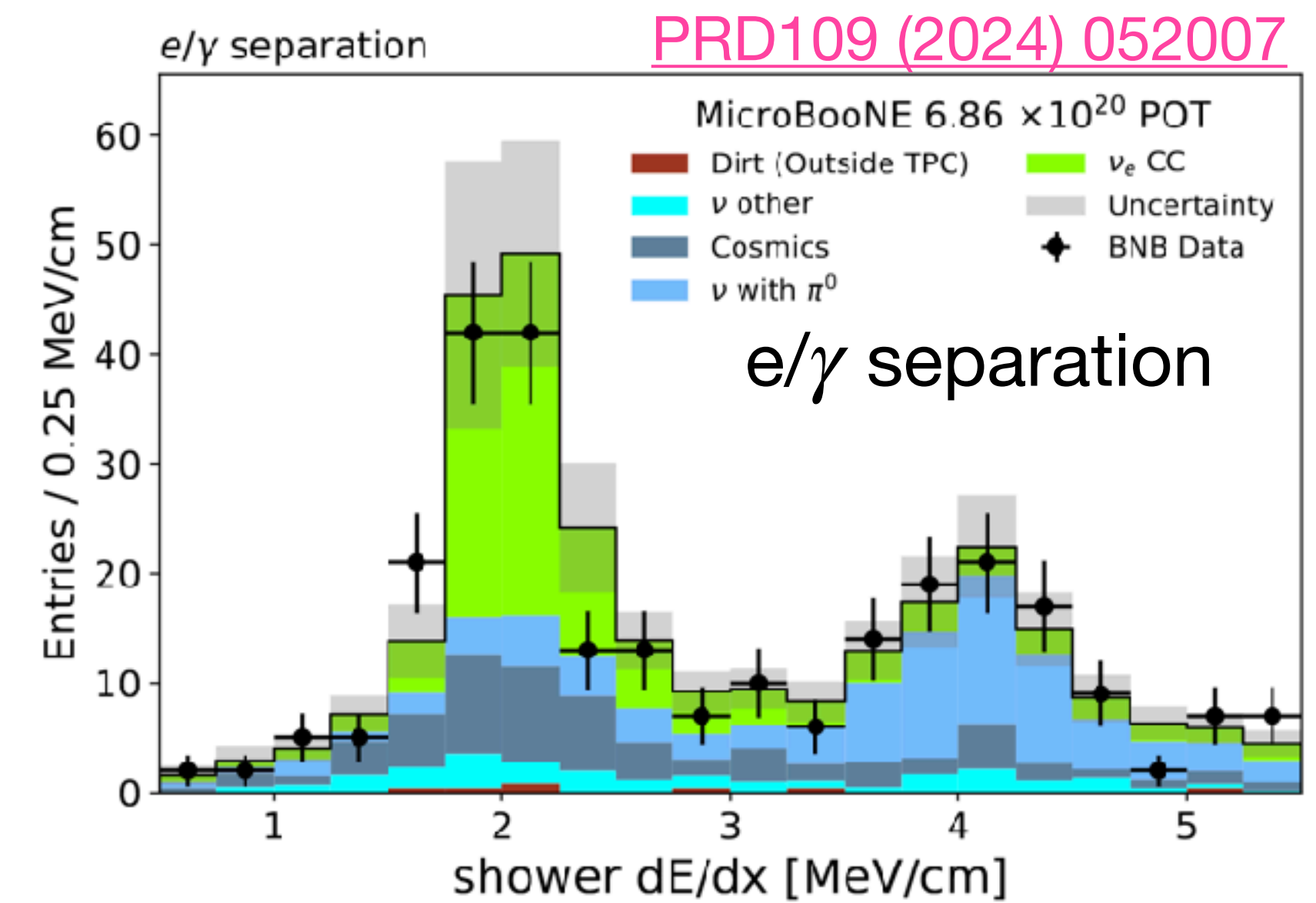
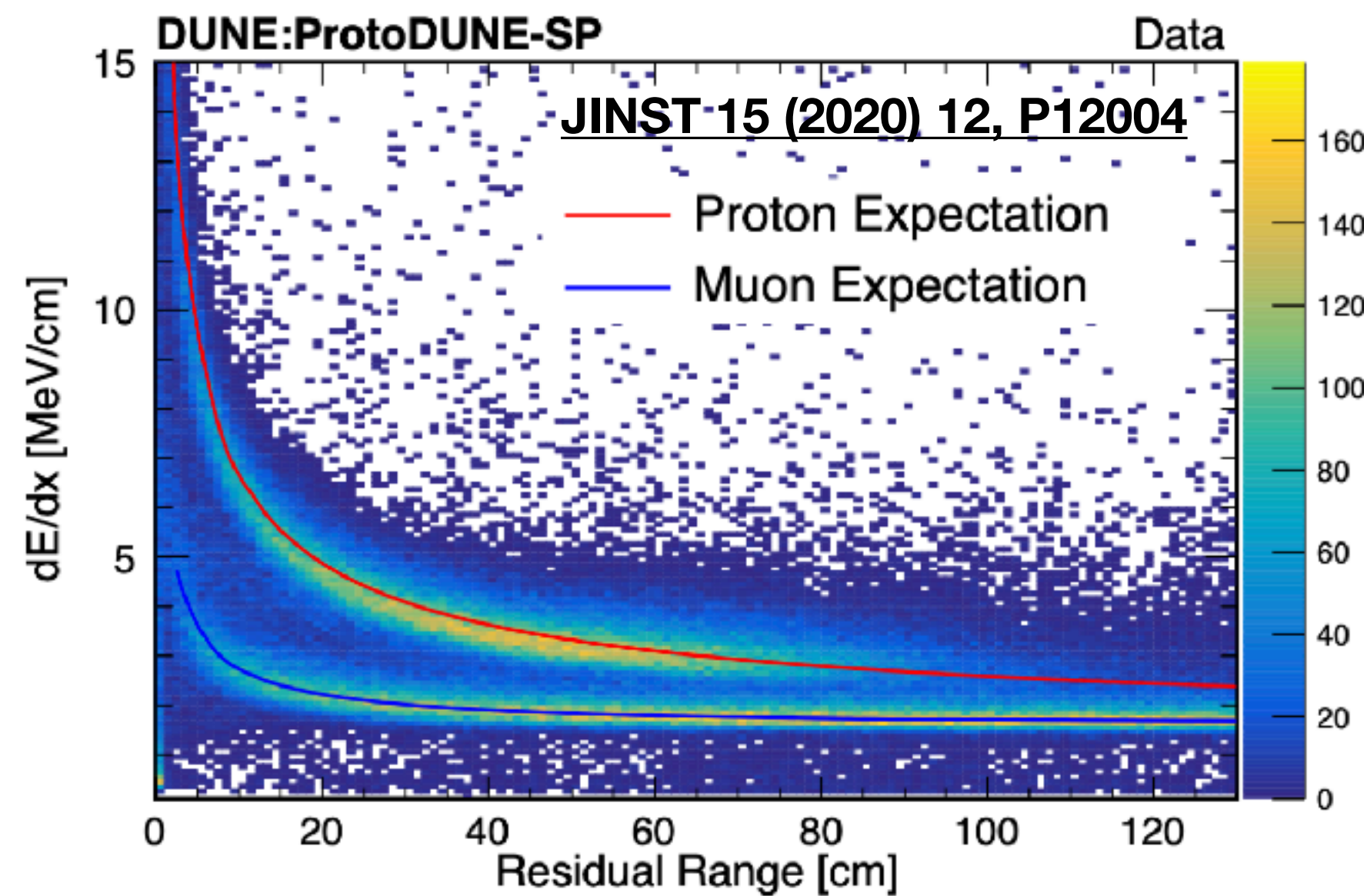
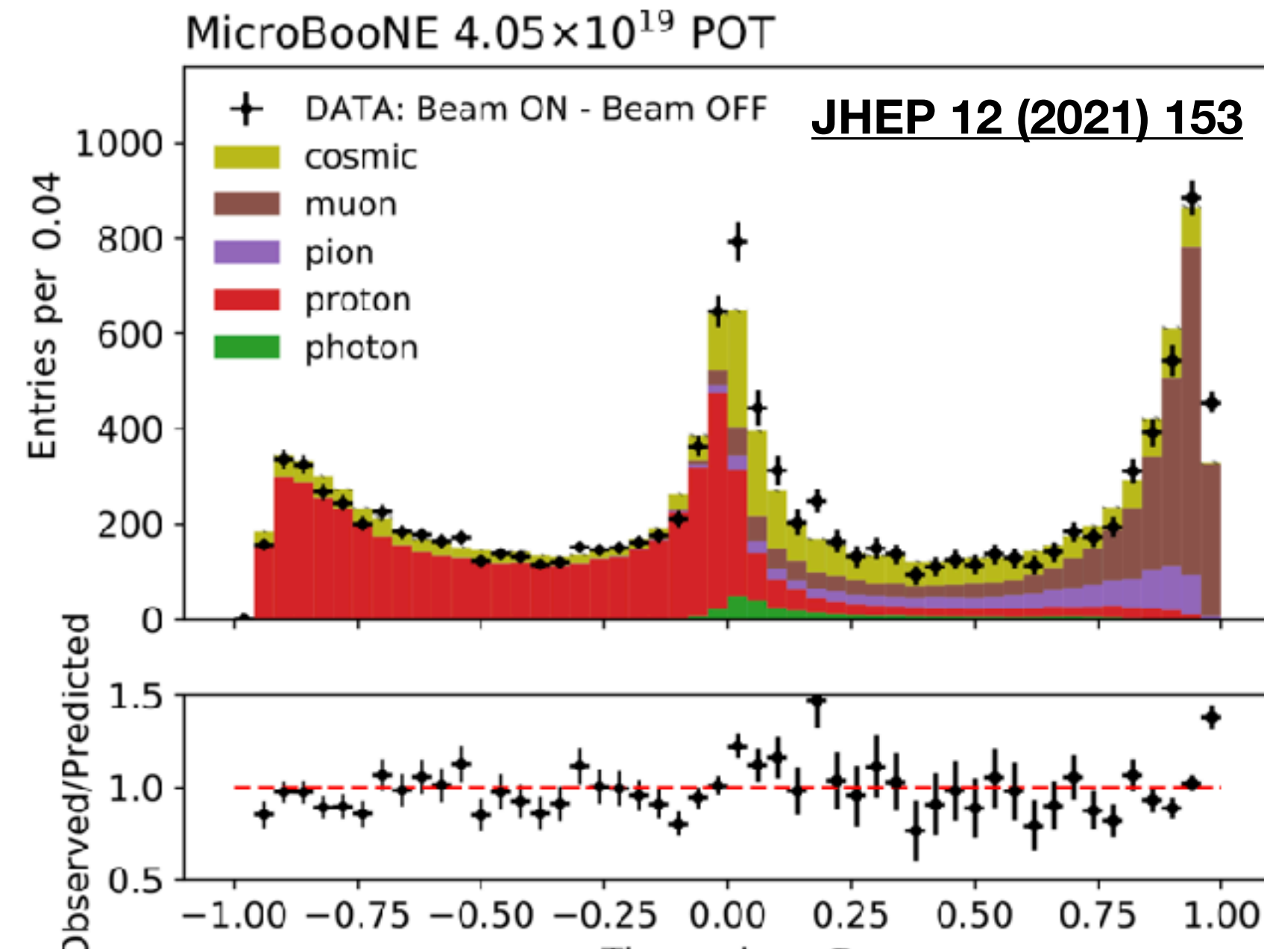
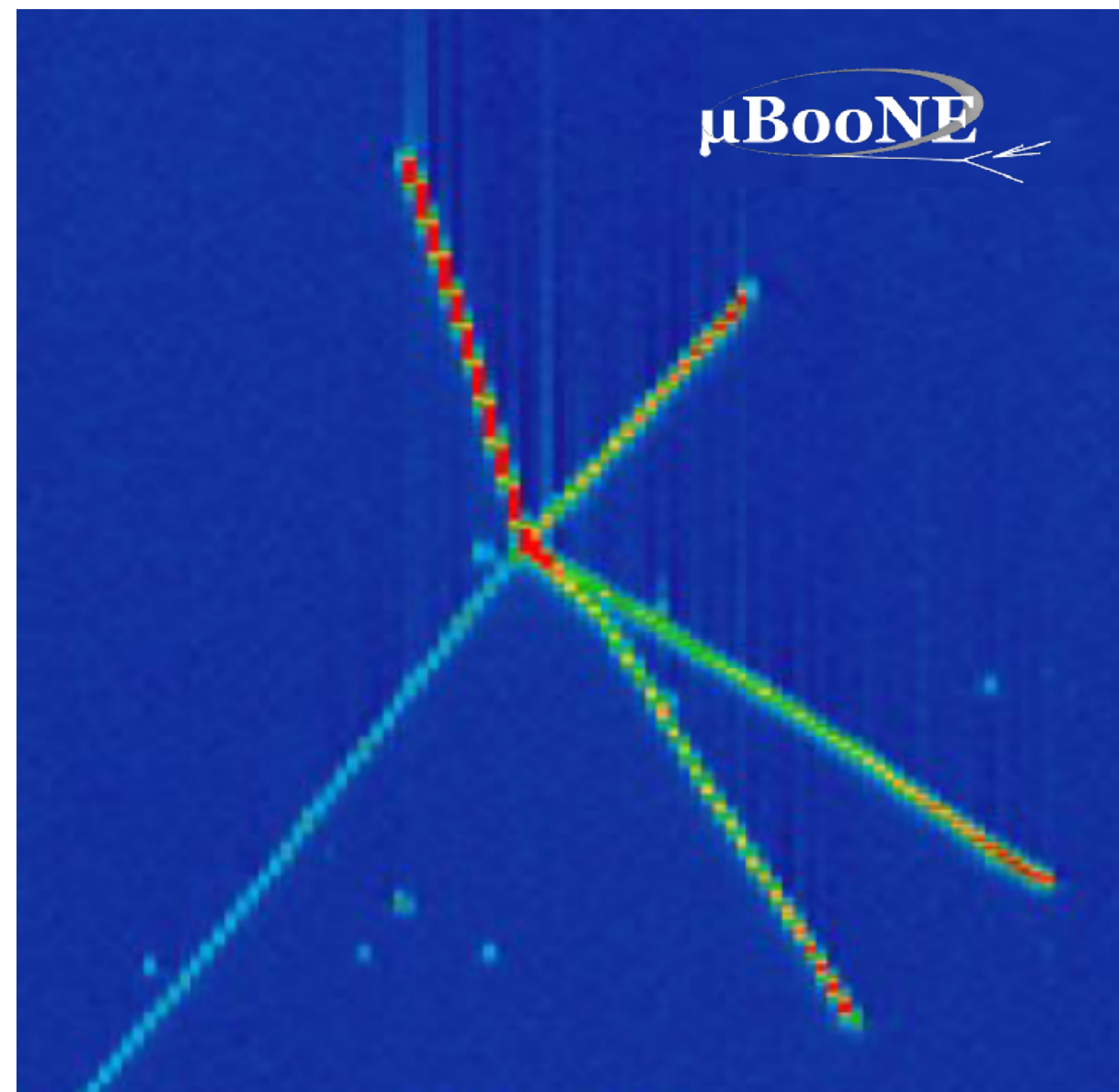
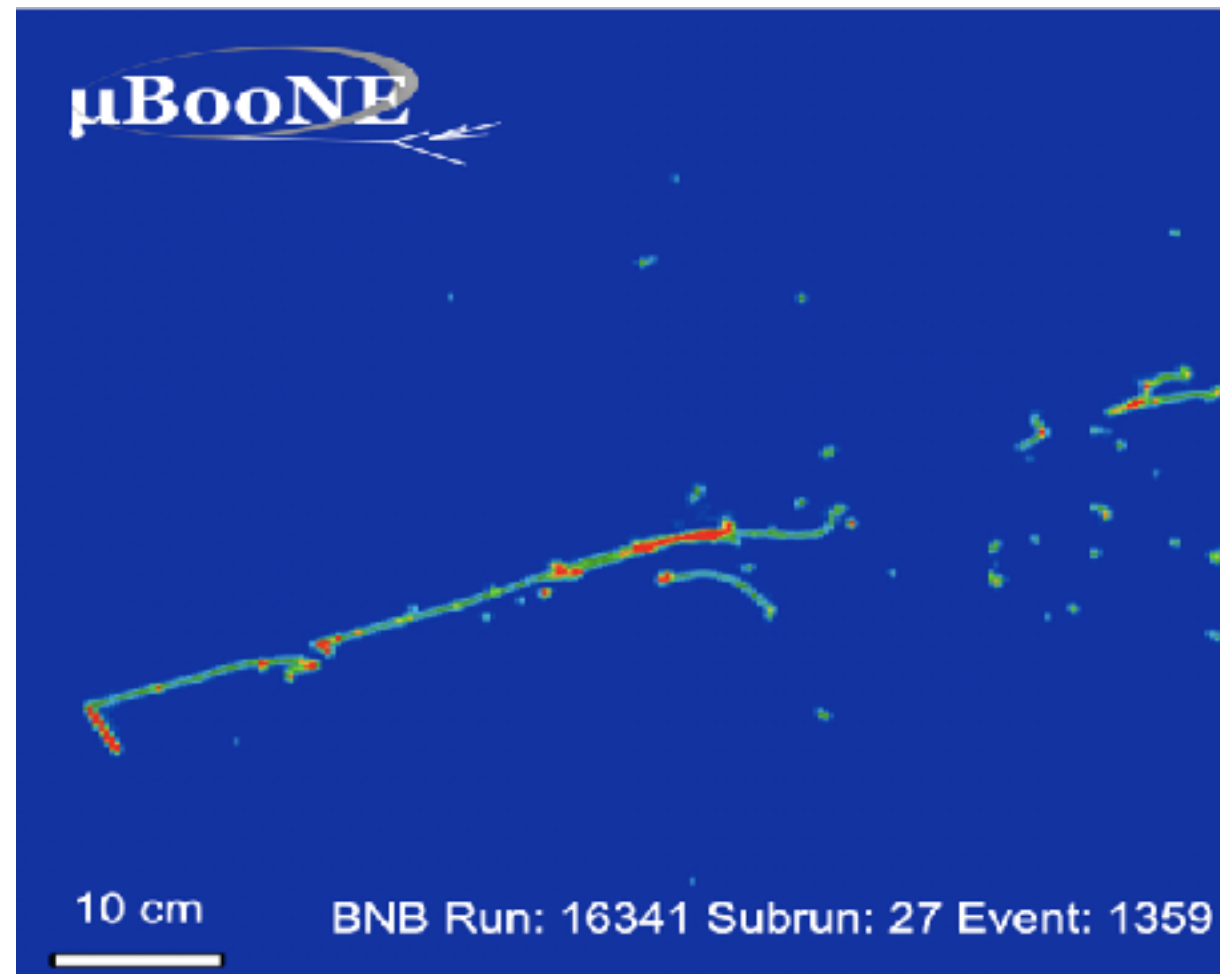
- 30:1-50:1 signal-to-noise
- millimeter spatial resolution
- %-level calorimetry

Scintillation photons:

- nanosecond timing resolution



# Particle Identification in MicroBooNE



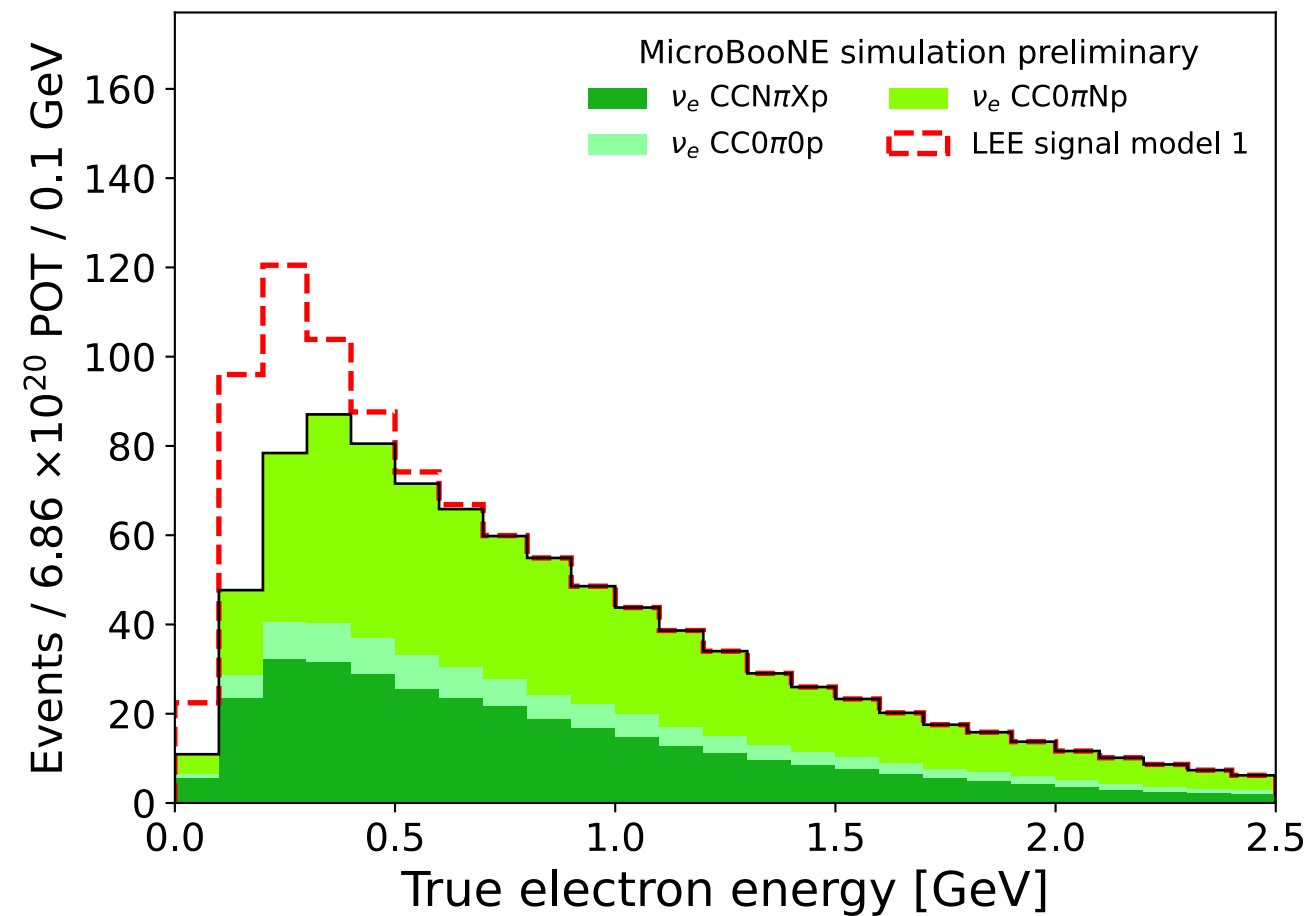
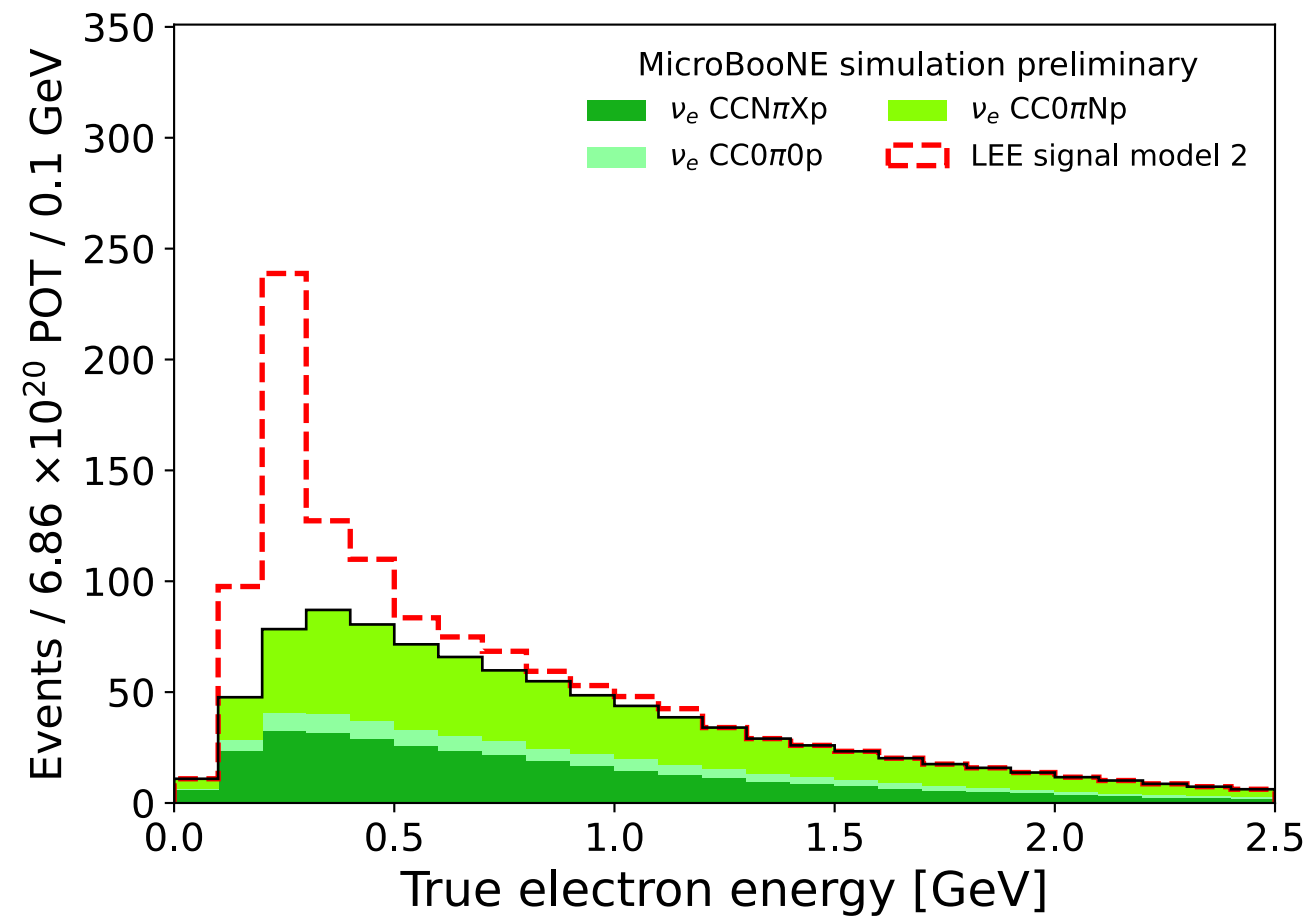
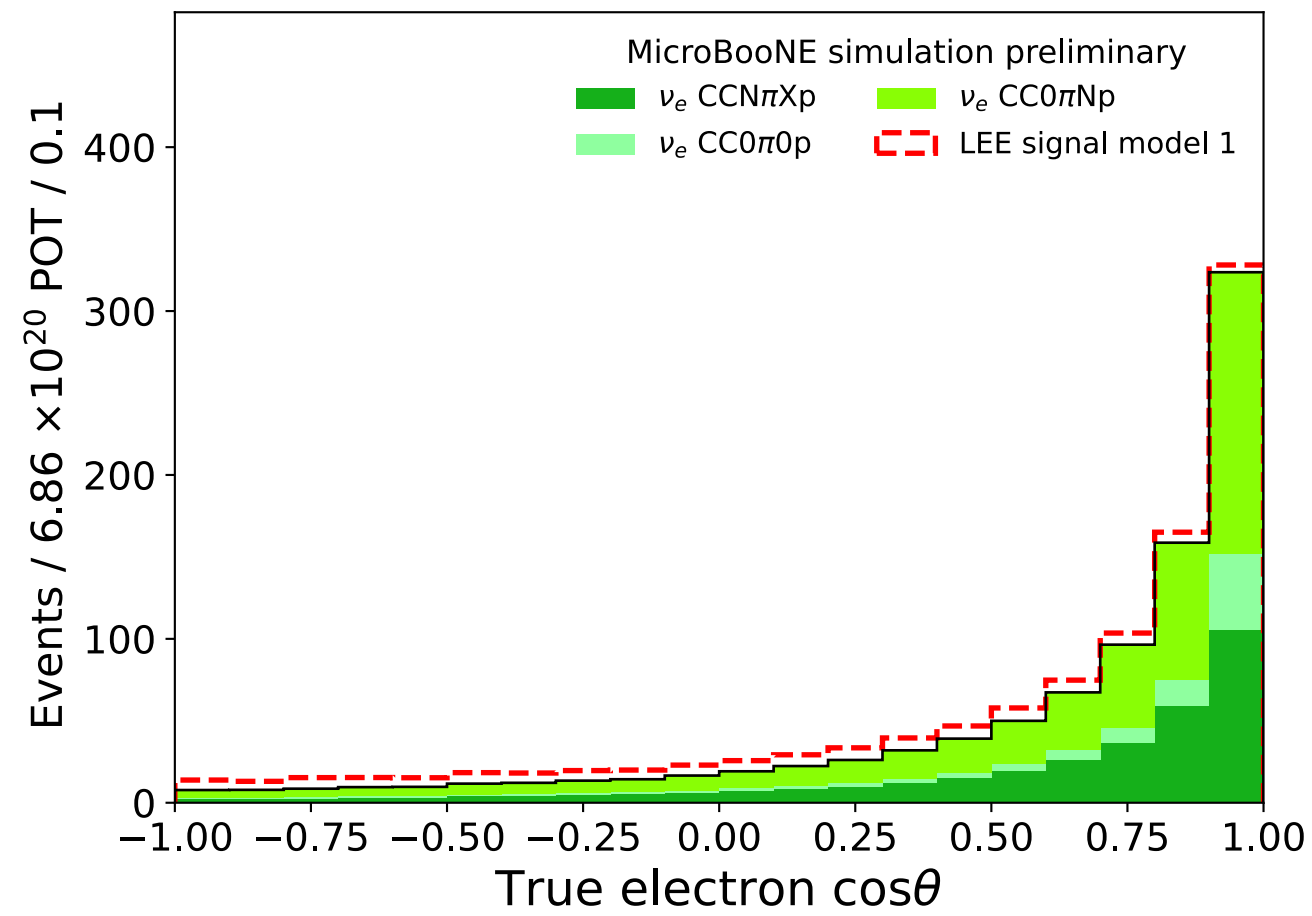
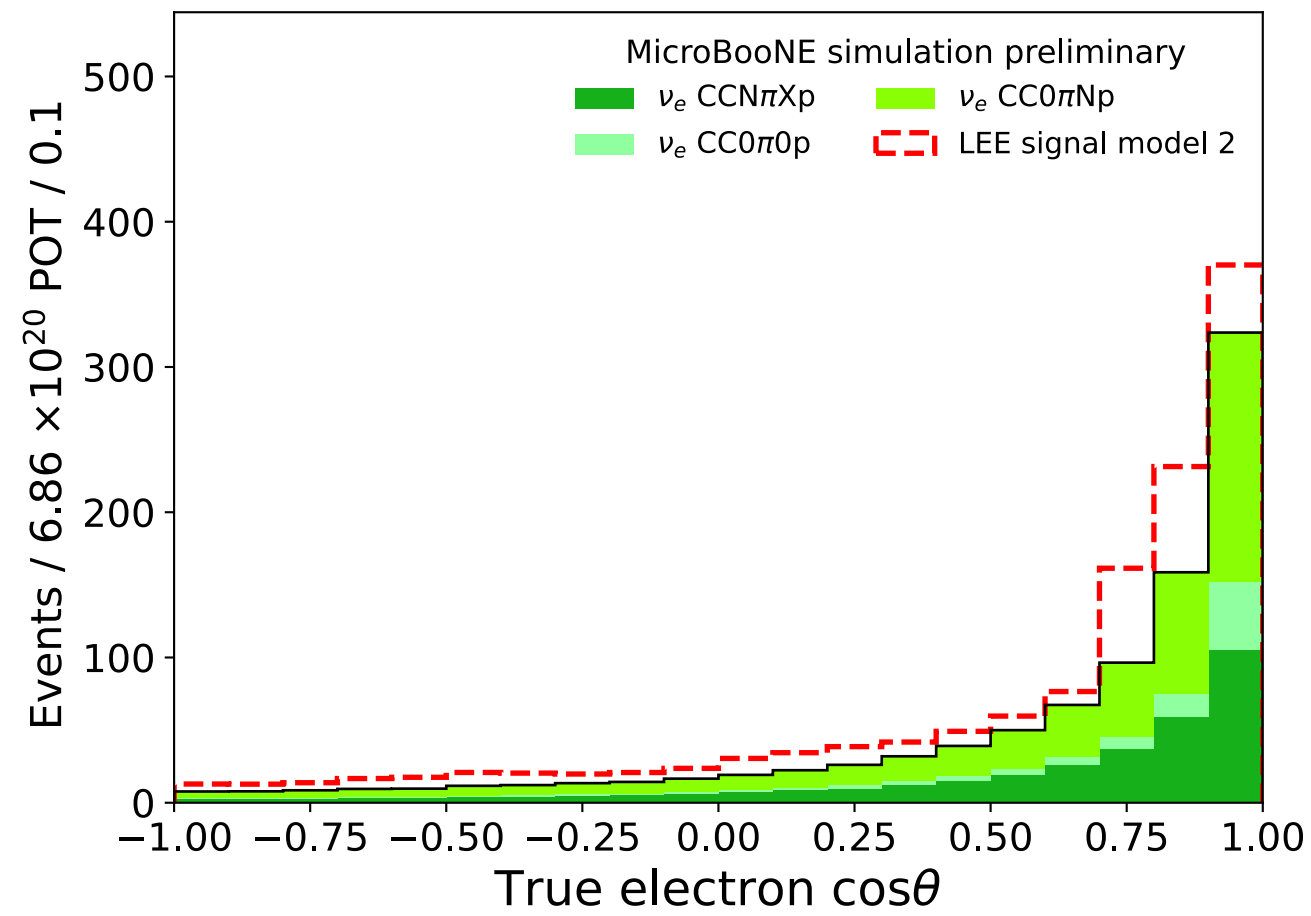
# MicroBooNE papers

2017 2018 2019 2020 2021 2022 2023 2024

- Published and submitted articles on [INSPIRE](#)
- MicroBooNE website (<https://microboone.fnal.gov>)
  - Public Notes [webpage](#).
  - MicroBooNE public datasets [webpage](#).
- MicroBooNE on social media: [twitter](#) & [Facebook](#)

First double-differential cross section measurement of neutral-current  $\pi^0$  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-trident 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 LArTPC-based search for intranuclear neutron-antineutron transitions and annihilation in  $^{40}\text{Ar}$  using the MicroBooNE detector  
Measurement of triple-differential inclusive muon-neutrino charged-current cross section on argon with the MicroBooNE detector  
Measurement of ambient radon daughter decay rates and energy spectra in liquid argon using the MicroBooNE detector  
First measurement of  $\eta$  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 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 antineutrino 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<sub>nu</sub> ~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

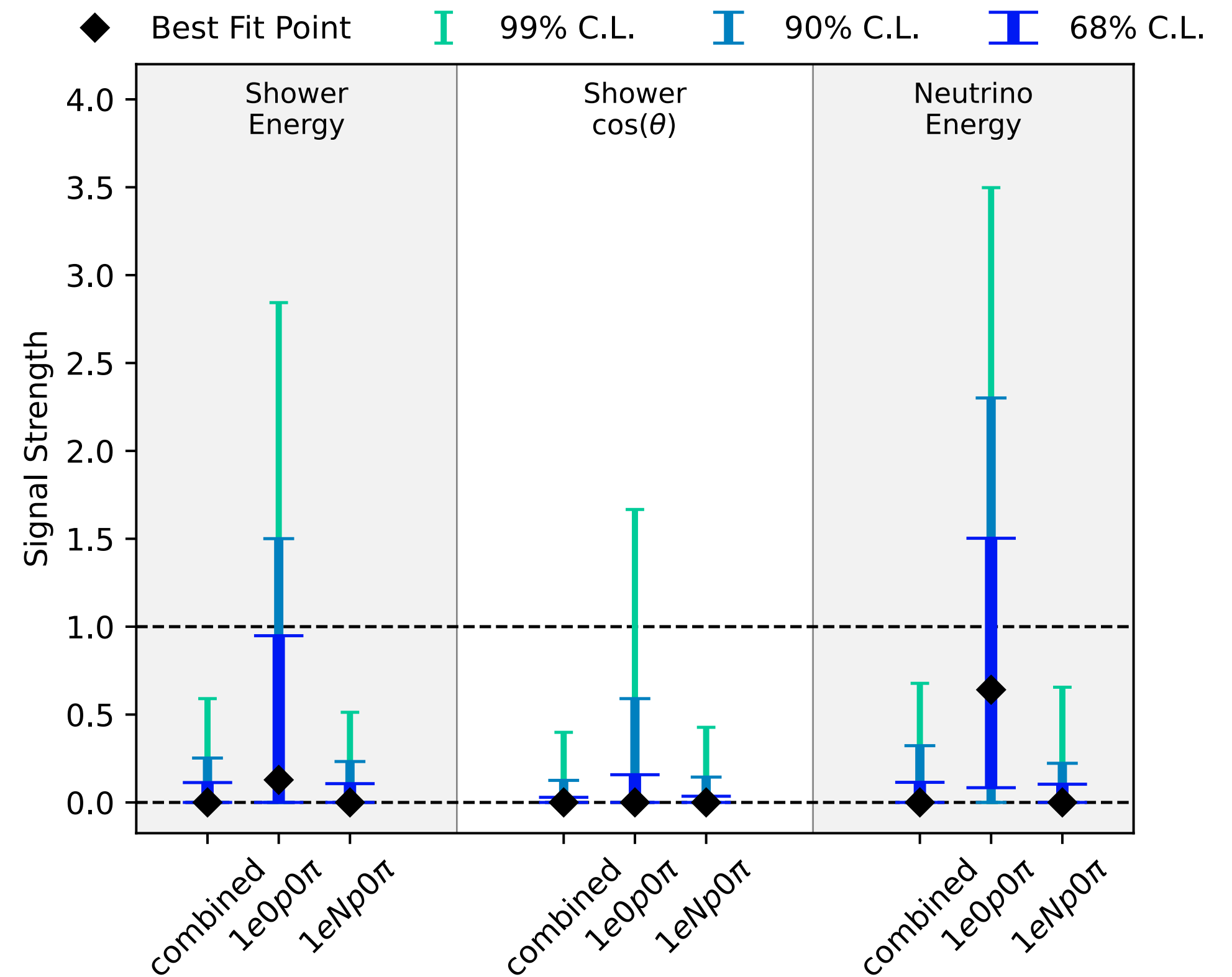
# $\nu_e$ LEE models and results



shower kinematics signal model  
[model #2]

Neutrino energy signal model  
[model #1]

## $\nu_e$ LEE analysis



Results in Np / 0p channels separately and combined

# 3+1 parametrization

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Full 3+1 search  $\longrightarrow$

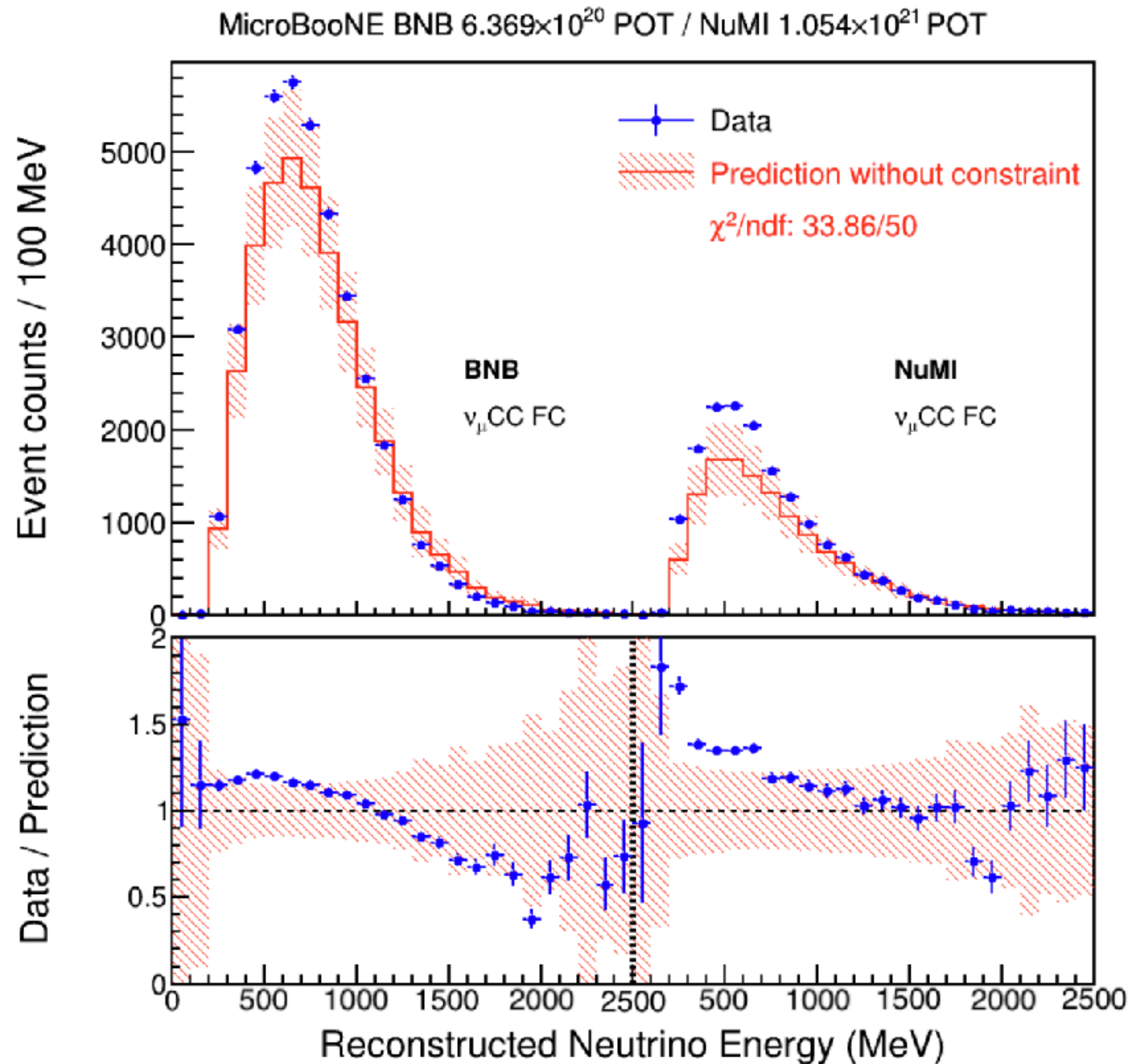
$$P_{\nu_e \rightarrow \nu_e} = 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2 \Delta_{41},$$
$$P_{\nu_\mu \rightarrow \nu_\mu} = 1 - 4(1 - |U_{\mu4}|^2)|U_{\mu4}|^2 \sin^2 \Delta_{41},$$
$$P_{\nu_\mu \rightarrow \nu_e} = 4|U_{\mu4}|^2|U_{e4}|^2 \sin^2 \Delta_{41}.$$

---

$\sin^2 2\theta_{ee}$	$= \sin^2 2\theta_{14}$	$= 4(1 -  U_{e4} ^2) U_{e4} ^2$
$\sin^2 2\theta_{\mu\mu}$	$= 4 \cos^2 \theta_{14} \sin^2 \theta_{24} (1 - \cos^2 \theta_{14} \sin^2 \theta_{24})$	$= 4(1 -  U_{\mu4} ^2) U_{\mu4} ^2$
$\sin^2 2\theta_{\mu e}$	$= \sin^2 2\theta_{14} \sin^2 \theta_{24}$	$= 4 U_{\mu4} ^2 U_{e4} ^2$
$\sin^2 2\theta_{es}$	$= \sin^2 2\theta_{14} \cos^2 \theta_{24} \cos^2 \theta_{34}$	$= 4 U_{e4} ^2 U_{s4} ^2$
$\sin^2 2\theta_{\mu s}$	$= \cos^4 \theta_{14} \sin^2 2\theta_{24} \cos^2 \theta_{34}$	$= 4 U_{\mu4} ^2 U_{s4} ^2$

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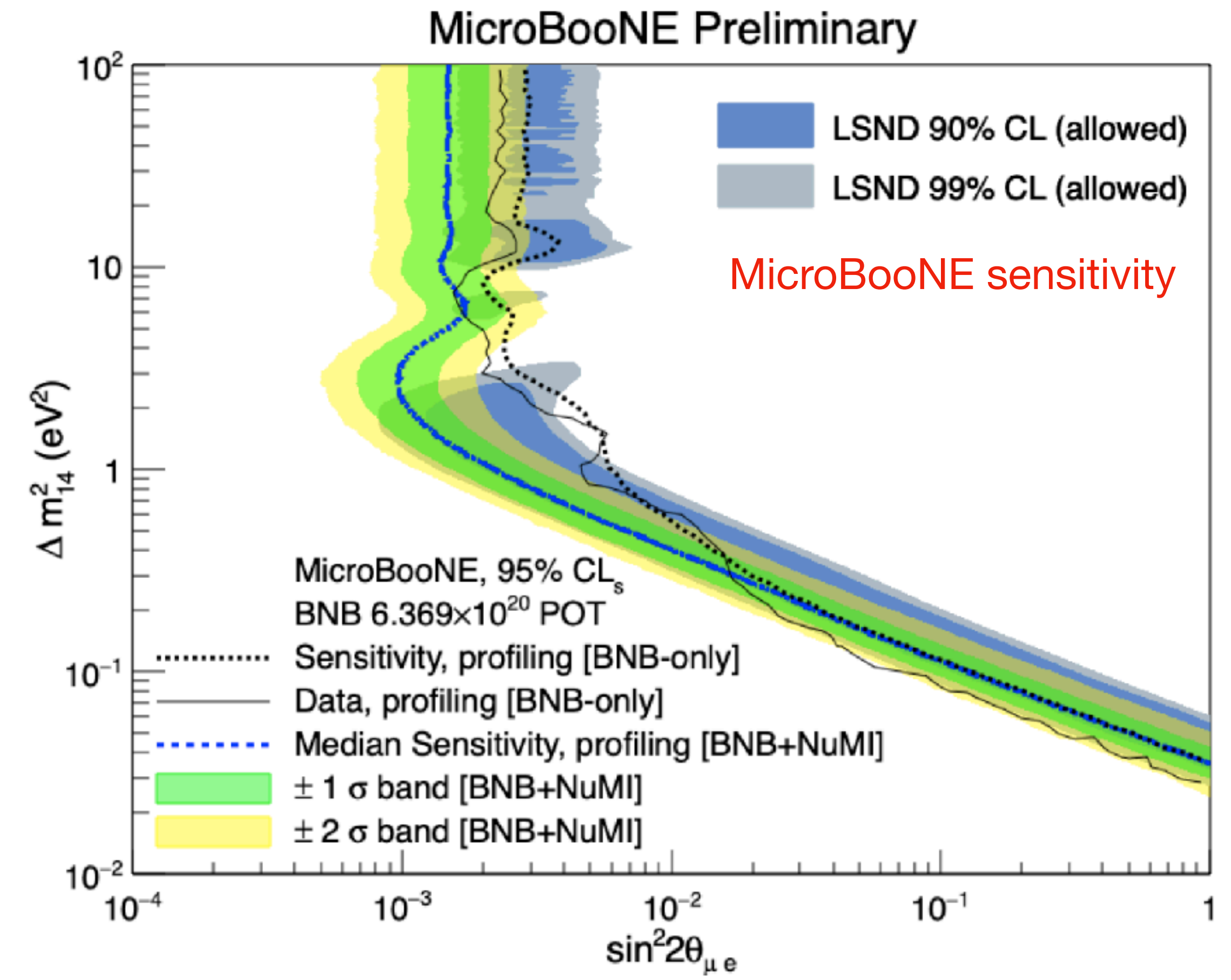
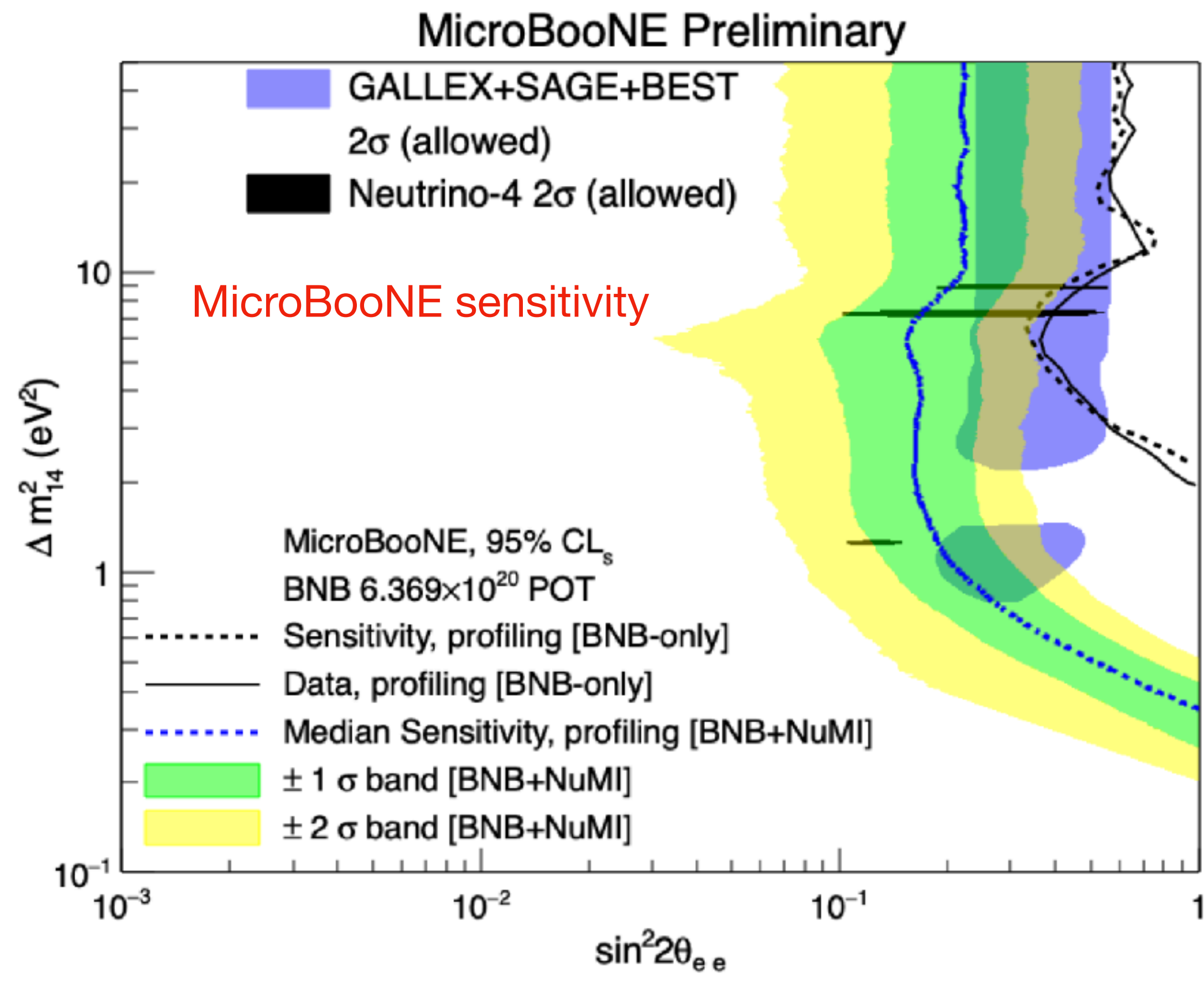
# NuMI $\nu_\mu$ data-simulation comparison



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

# 3+1 sensitivities



BNB + NuMI 3+1 MicroBooNE sensitivities