Latest Results from the MicroBooNE Experiment

Wanwei Wu

University of Pittsburgh
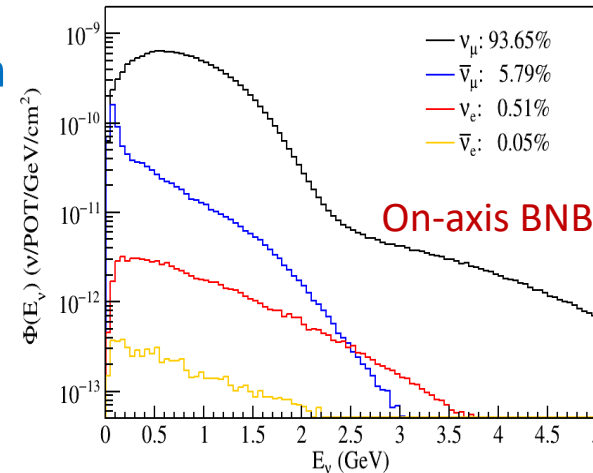On behalf of the MicroBooNE Collaboration

Lake Louise Winter Institute
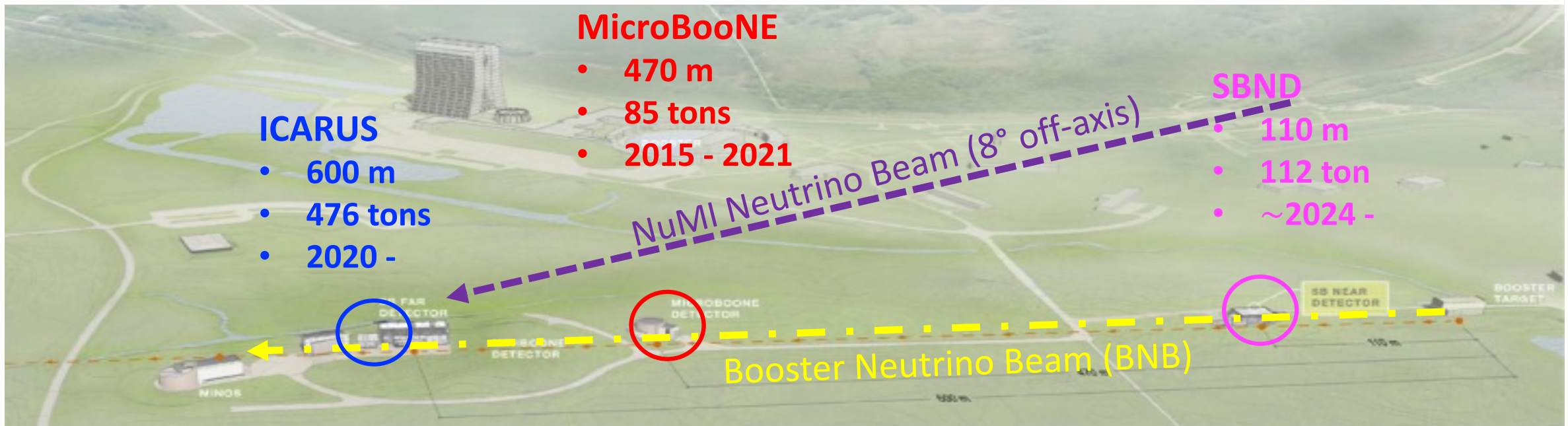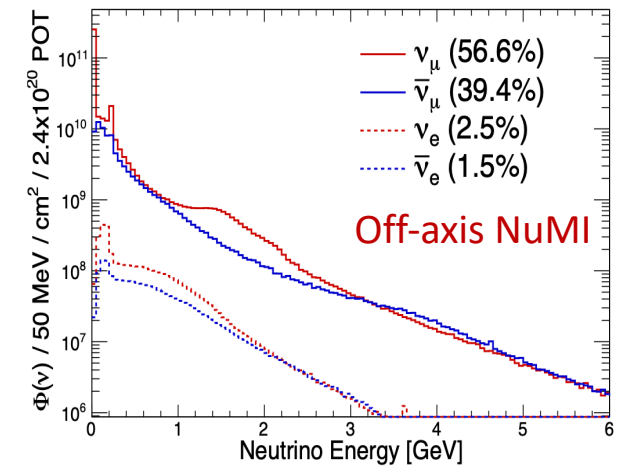
February 22, 2024

MicroBooNE Experiment

- Part of the Fermilab Short-Baseline Neutrino (**SBN**: SBND, MicroBooNE, and ICARUS) Program

- Liquid Argon Time Projection Chamber (**LArTPC**) detector

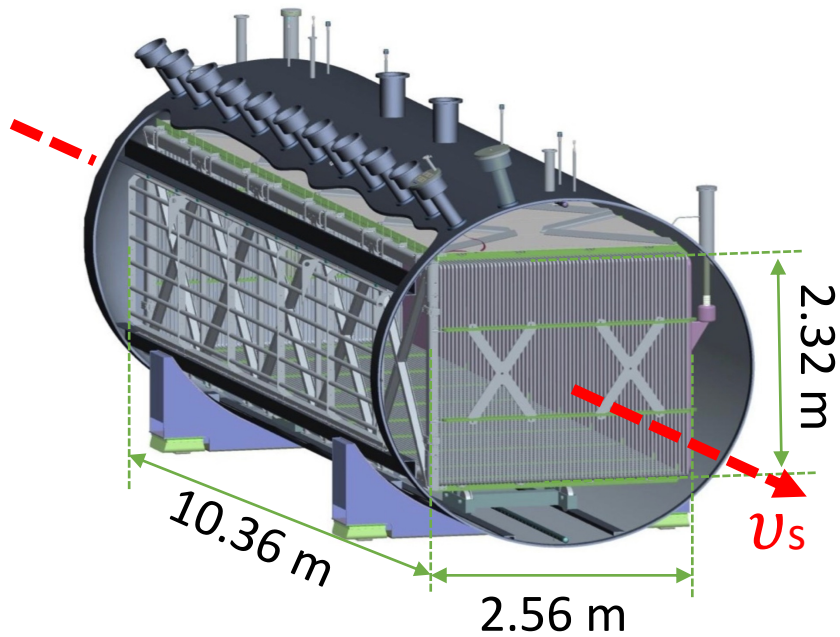- MicroBooNE Collaboration: ~190 collaborators (~ 50% students and postdocs)
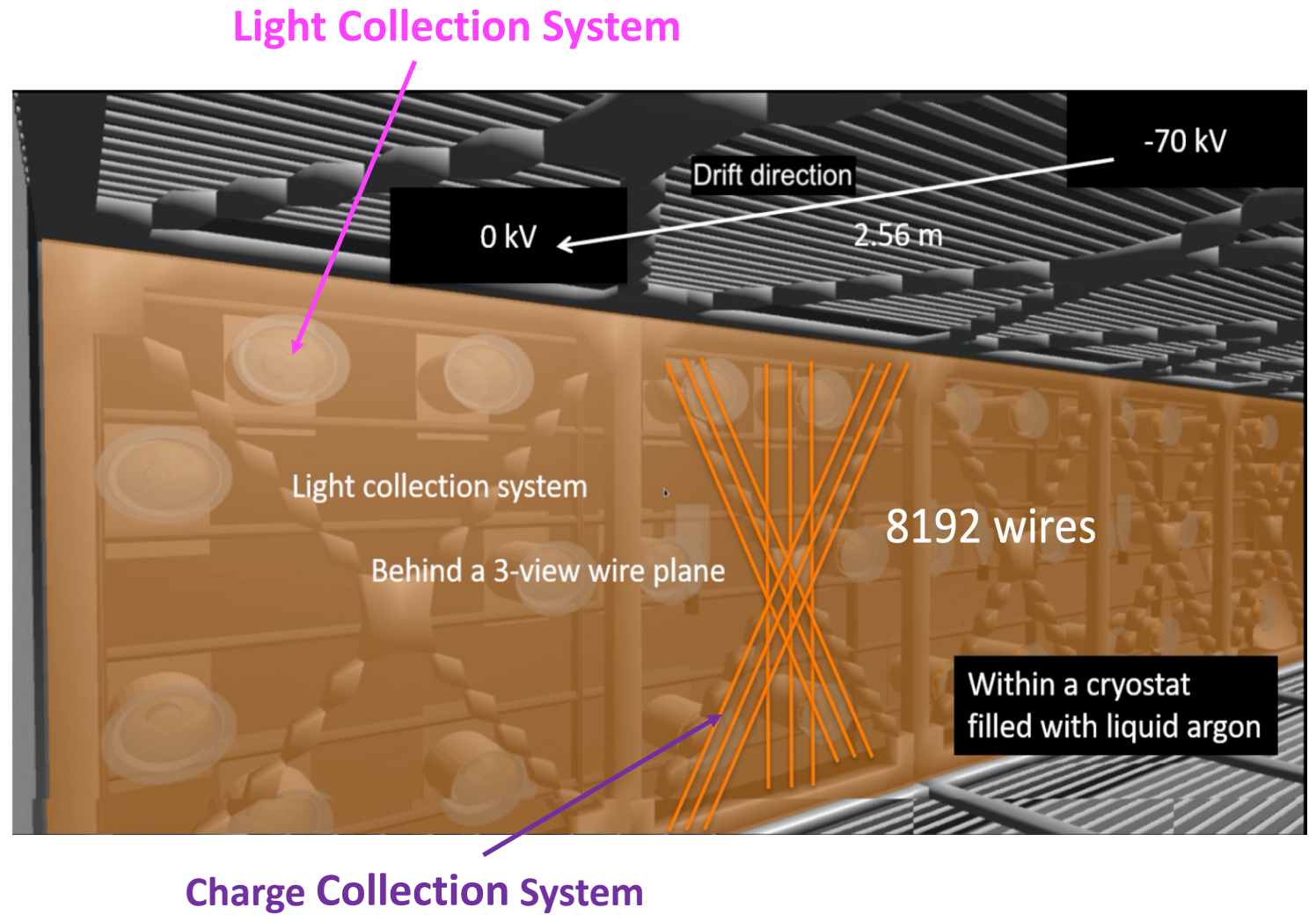
PRD 105, 112005 (2022)

PRD 104, 052002 (2021)

On-axis BNB — ν_μ: 93.65%, $\bar{\nu}_\mu$: 5.79%, ν_e: 0.51%, $\bar{\nu}_e$: 0.05%

Off-axis NuMI — ν_μ (56.6%), $\bar{\nu}_\mu$ (39.4%), ν_e (2.5%), $\bar{\nu}_e$ (1.5%)

MicroBooNE
- **470 m**
- **85 tons**
- **2015 - 2021**

ICARUS
- **600 m**
- **476 tons**
- **2020 -**

SBND
- **110 m**
- **112 ton**
- **~2024 -**

NuMI Neutrino Beam (8° off-axis)

Booster Neutrino Beam (BNB)

MicroBooNE Detector

JINST 12 P02017 (2017)

10.36 m

2.56 m

2.32 m

v_s

Light Collection System

Drift direction

-70 kV

0 kV

2.56 m

Light collection system

Behind a 3-view wire plane

8192 wires

Within a cryostat filled with liquid argon

Charge Collection System

MicroBooNE LArTPC

Liquid Argon TPC

Sense Wires
U V Y

V wire plane waveforms

Cathode Plane

Charged Particles

Incoming Neutrino

E = 273 V/cm

Y wire plane waveforms

t

A candidate of neutral-current interaction

Vertex of neutrino interaction

Delta-ray candidate

μBooNE

Proton candidates

Pion candidates

photon candidates from π^0 decay

13 cm

BNB DATA : RUN 5370 EVENT 7227. MARCH 10, 2016.

Detailed images of events:

- ~mm spatial resolution.
- Sub-MeV energy threshold
- ~ns timing resolution

JINST 15, P03022 (2020)

arXiv:2307.03102

PRD 108, 052010 (2023)

MicroBooNE Science Program

Investigate MiniBooNE Low Energy Excess (LEE) & search for BSM
- same neutrino beamline & roughly same location as MiniBooNE

Study neutrino-argon interactions
- Largest ν-Ar data collected to date (~500k neutrino interactions)

Develop LArTPC techniques (hardware and software R&D)
- First large-scale LArTPC constructed in U.S. and longest-running LArTPC in the world
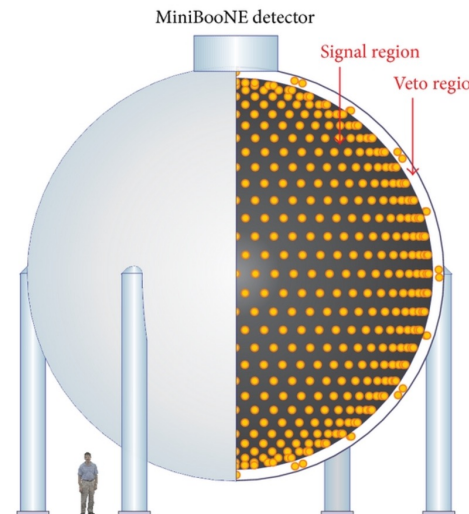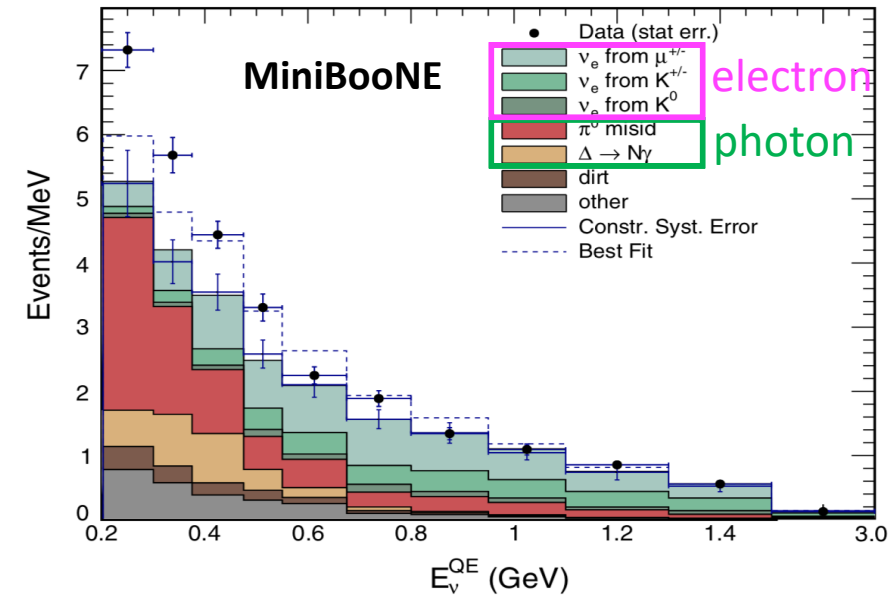
Short-baseline Neutrino Anomalies

- Series of anomalous results seen at short-baselines using a variety of neutrino sources (LSND, MiniBooNE, BGALLEX/SAGE, etc.)
  - if caused by oscillations, are not consistent with a 3-ν picture
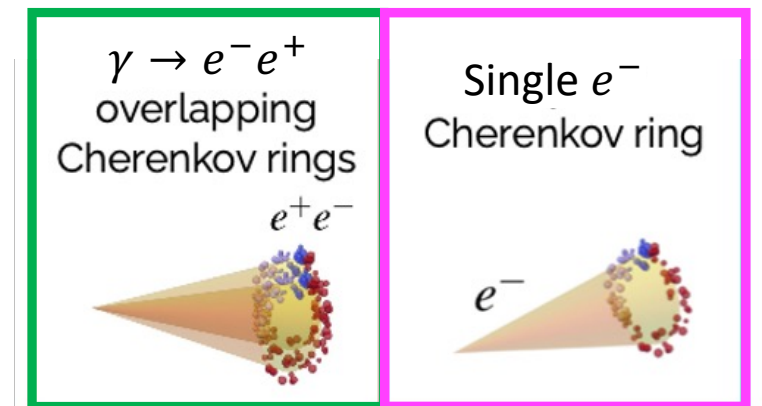
MiniBooNE:

- Mineral oil Cherenkov detector
- Measured $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance
- Observed low energy excess (LEE): 4.8σ
- Largest background from photons (π^0 or $\Delta \to N\gamma$)
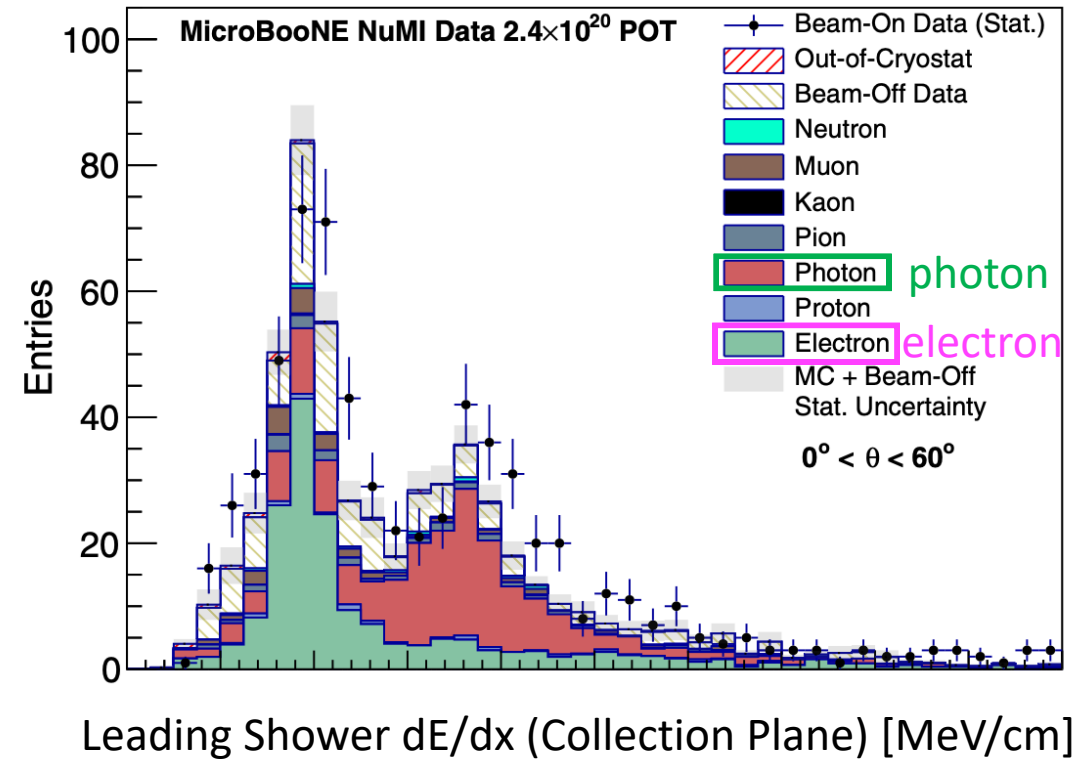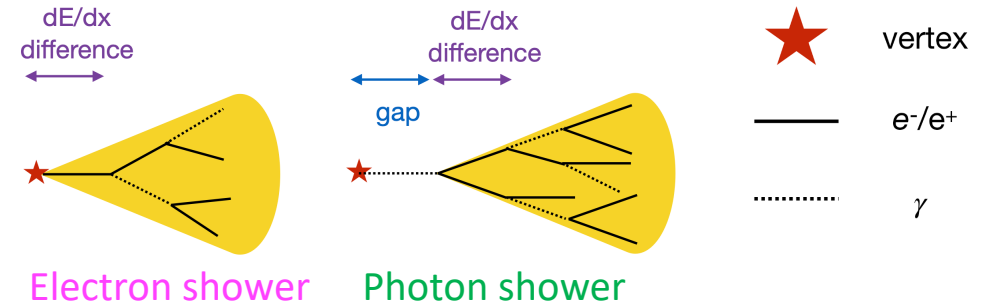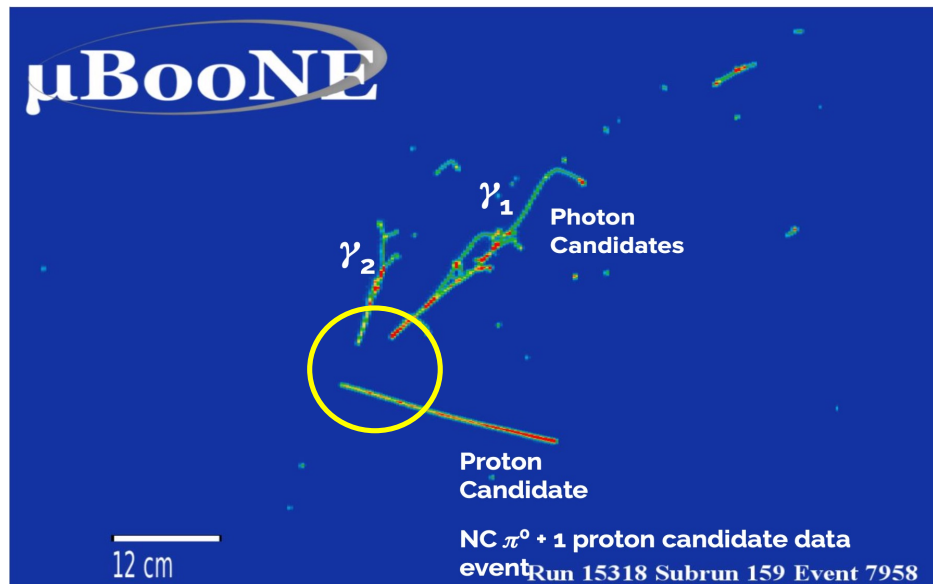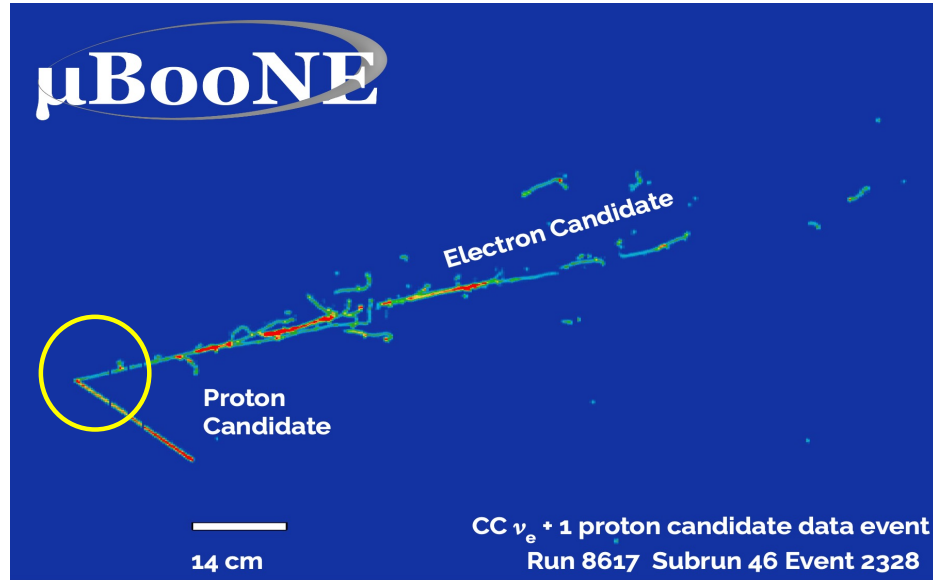- Could not distinguish between $e^\pm$ and γ

PRD 103, 052002 (2021)

Hard to distinguish

$\gamma \to e^- e^+$ overlapping Cherenkov rings $e^+ e^-$

Single e^- Cherenkov ring e^-

e/γ Separation in MicroBooNE

μBooNE

Electron Candidate

Proton Candidate

14 cm

CC ν_e + 1 proton candidate data event
Run 8617 Subrun 46 Event 2328

μBooNE

γ_1

Photon Candidates

γ_2

Proton Candidate

12 cm

NC π^0 + 1 proton candidate data event
Run 15318 Subrun 159 Event 7958

dE/dx difference

dE/dx difference

gap

★ vertex

—— e^-/e^+

······· γ

Electron shower   Photon shower

MicroBooNE NuMI Data 2.4×10^{20} POT

- Beam-On Data (Stat.)
- Out-of-Cryostat
- Beam-Off Data
- Neutron
- Muon
- Kaon
- Pion
- Photon — photon
- Proton
- Electron — electron
- MC + Beam-Off Stat. Uncertainty

$0° < \theta < 60°$
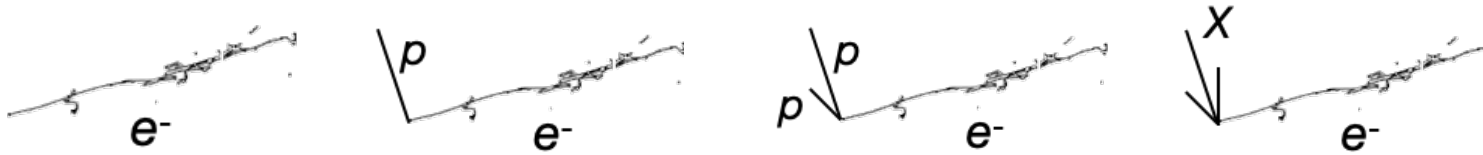
Entries

Leading Shower dE/dx (Collection Plane) [MeV/cm]

PRD 104, 052002 (2021)

MicroBooNE – Low Energy Excess Searches

Possible MiniBooNE LEE final state topologies mainly include

- **Electron**

- **Photon**

- e^+e^- **pair**

Overlapping e^+e^- Overlapping e^+e^- Highly asymmetric e^+e^- Highly asymmetric e^+e^-
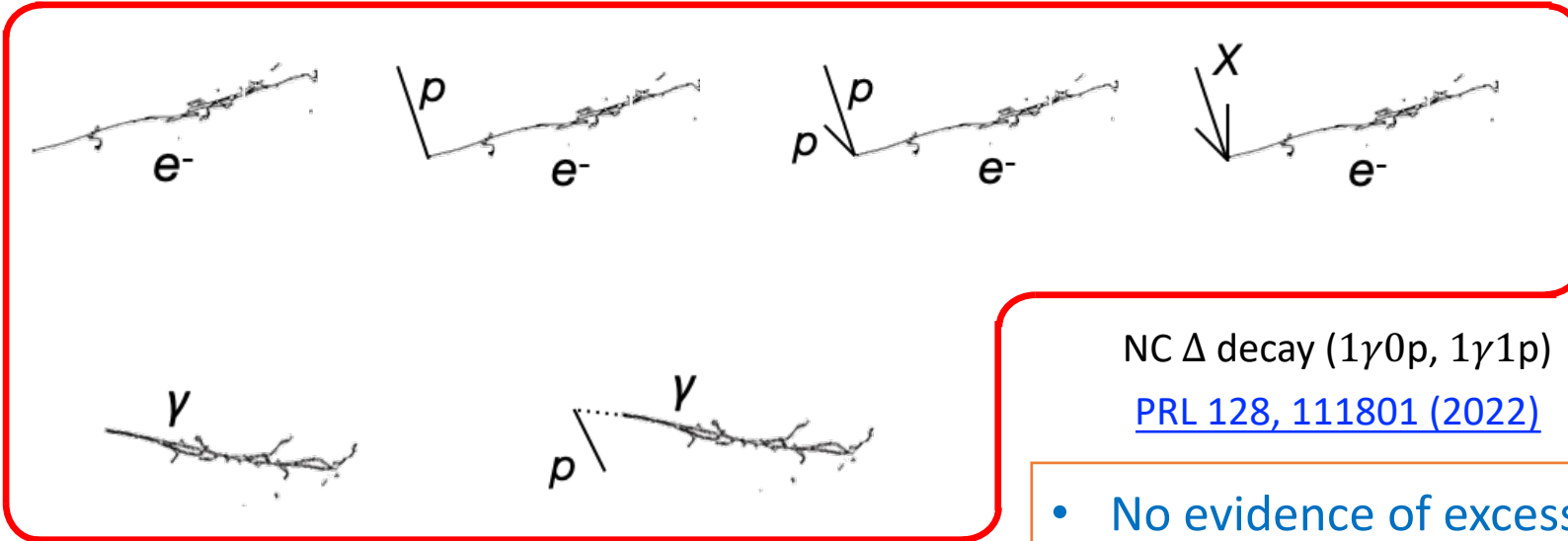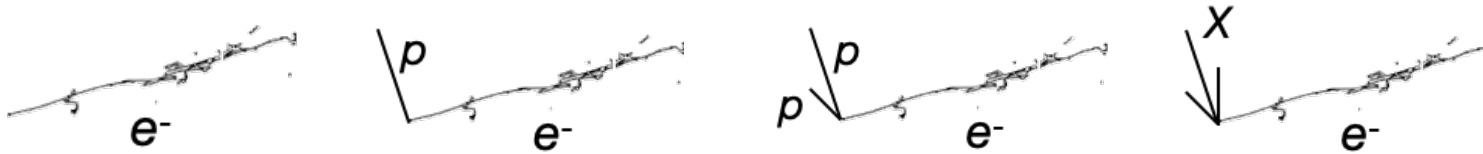
MicroBooNE – Low Energy Excess Searches

Possible MiniBooNE LEE final state topologies mainly include

- **Electron**

MicroBooNE's first series of LEE search results (~50% BNB data)

CC ν_e multiple final states

[PRL 128, 241801 (2022)](#)

[PRD 105, 112004 (2022)](#)

[PRD 105, 112003 (2022)](#)

[PRD 105, 112005 (2022)](#)

- **Photon**

NC Δ decay ($1\gamma 0p$, $1\gamma 1p$)

[PRL 128, 111801 (2022)](#)

Light sterile ν oscillation

[PRL 130, 011801 (2023)](#)

- No evidence of excessive ν_e and NC Δ decay as a sole source of MiniBooNE LEE anomaly
- No evidence of sterile neutrino oscillations

- e^+e^- **pair**

Overlapping e^+e^- Overlapping e^+e^- Highly asymmetric e^+e^- Highly asymmetric e^+e^-

Possible MiniBooNE LEE final state topologies mainly include

- **Electron**

- **Photon**

- $e^+ e^-$ **pair**

Additional analyses under development

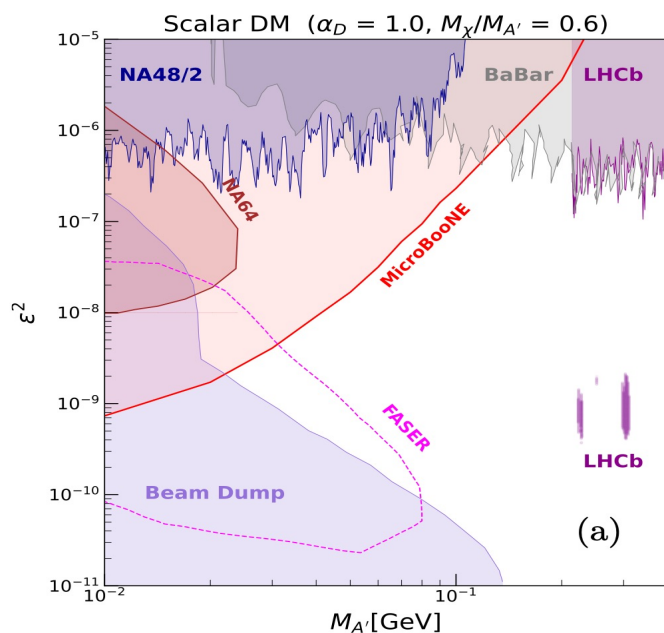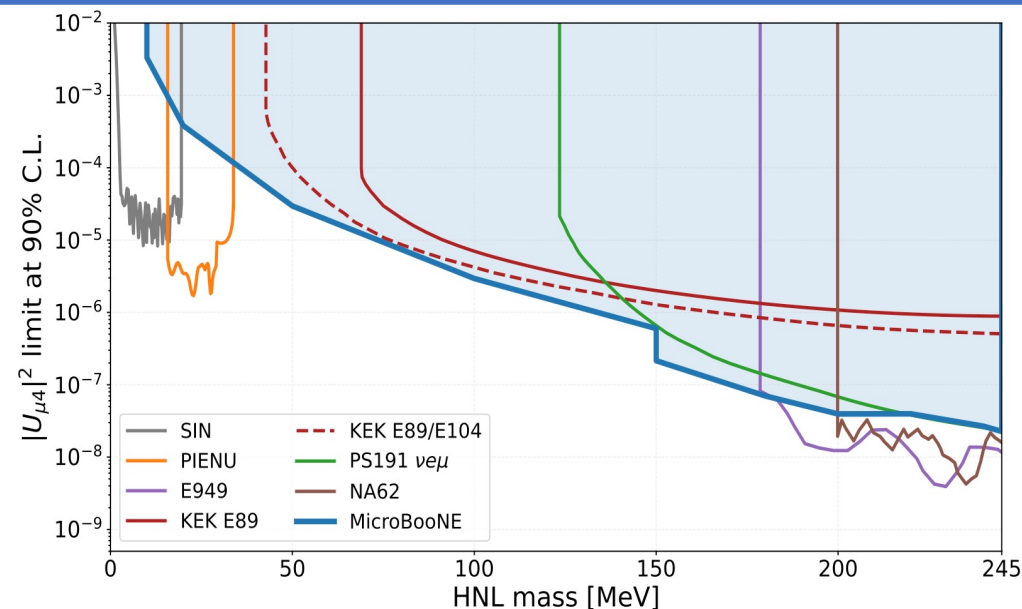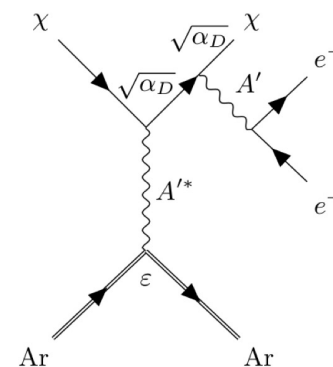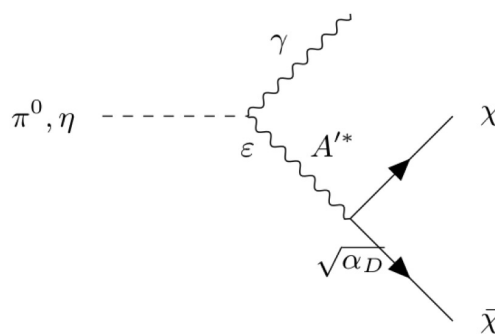Overlapping $e^+ e^-$ Overlapping $e^+ e^-$ Highly asymmetric $e^+ e^-$ Highly asymmetric $e^+ e^-$

MicroBooNE – BSM Searches

- **Heavy Neutral Lepton (HNL)**

  - HNL$\rightarrow \mu^{\pm}\pi^{\mp}$ (BNB)

    PRD 101, 052001 (2020)

  - HNL$\rightarrow \mu^{\pm}\pi^{\mp}$ (NuMI)

    PRD 106, 092006 (2022)

  - HNL$\rightarrow \nu e^{+}e^{-}$ or HNL $\rightarrow \nu\pi^{0}$ (NuMI)

    PRL 132, 041801 (2024)

- **Dark-trident process**

Scalar DM ($\alpha_D = 1.0$, $M_\chi/M_{A'} = 0.6$)

Additional BSM searches, including Higgs portal scaler, neutron-antineutron oscillation, millicharged particles, and heavy QCD axions, are not covered here.

- First search (NuMI). arXiv:2312.13945

MicroBooNE – Neutrino-Argon Interactions

Extensive cross section program

- Largest neutrino-argon interaction data to date
- High resolutions for exploring multiple final state topologies
- 15 publications, plus $\sim$30 active analyses ν-Ar cross section using BNB and NuMI data

One of the largest uncertainties in neutrino oscillation experiments

CC Inclusive

- **1D & 2D ν_μ (BNB)**
  PRL 123, 131801 (2019)
- 1D $\nu_e + \overline{\nu}_e$ (NuMI)
  PRD 104, 052002 (2021)
  PRD 105, L051102 (2022)
- 1D ν_μ E_ν-dependent (BNB)
  PRL 128, 151801 (2022)
- 3D ν_μ (BNB)
  arXiv:2307.06413

Pion production

- ν_μ NC π^0 (BNB)
  PRD 107, 012004 (2023)

Rare channels

- Λ production (NuMI)
  PRL 130, 231802 (2023)
- η production (BNB)
  arXiv:2305.16249

Today's Topics

CC 0π

- 1D ν_μ QE 1p0π (BNB)
  PRL 125, 201803 (2020)
- 1D ν_μ Np0π (BNB)
  PRD 102, 112013 (2020)
- 1D ν_e Np0π (BNB)
  PRD 106, L051102 (2022)
- 1D ν_μ 2p0π (BNB)
  arXiv:2211.03734
- ν_μ 1p0π 1D & 2D TKI/GKI (BNB)
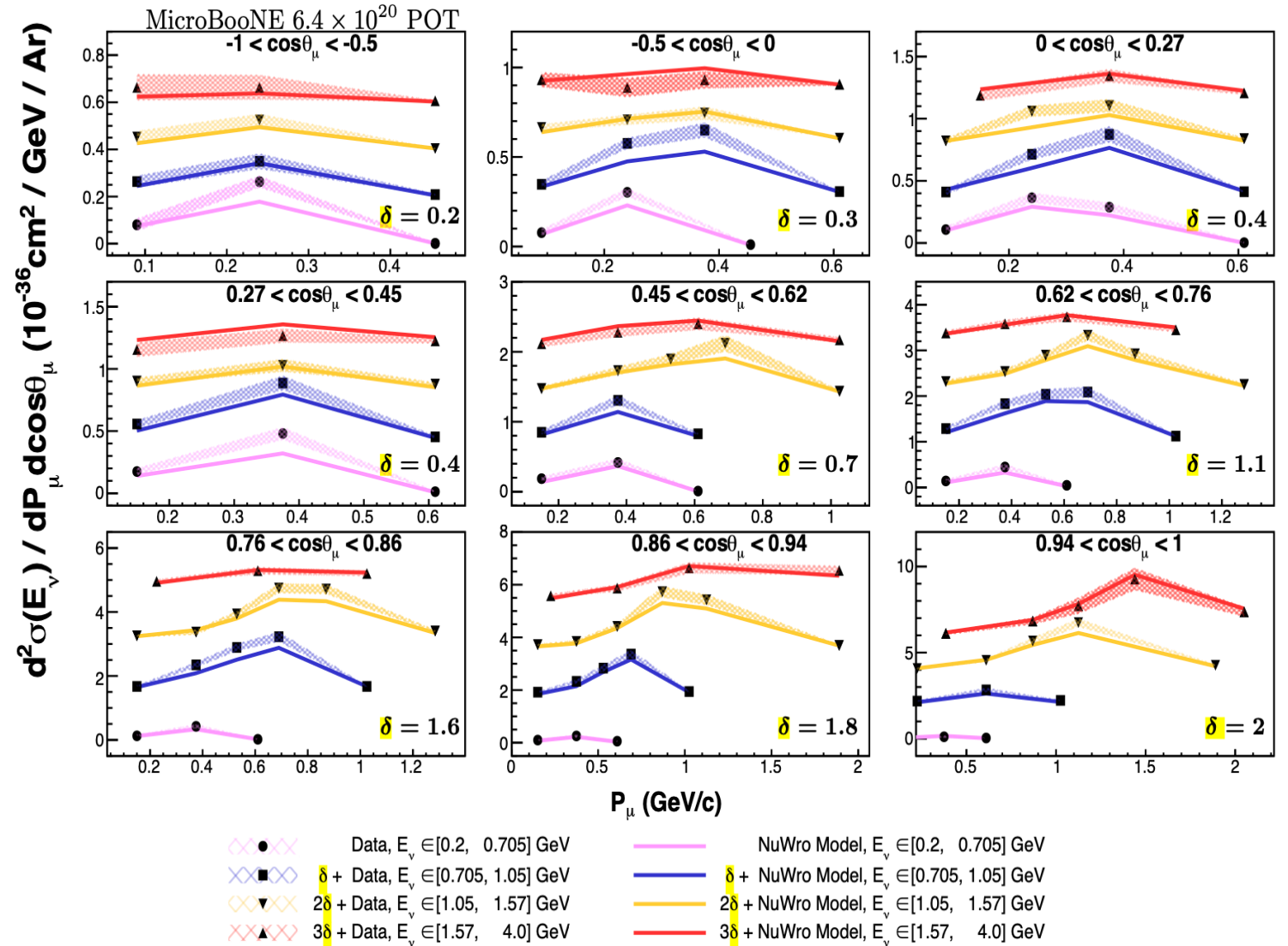 PRL 131, 101802 (2023)
  PRD 108, 053002 (2023)
  arxiv:2310.06082

First triple-differential inclusive ν_μ CC cross section measurement

- 3D kinematic phase space
- Extensive validation of missing energy model
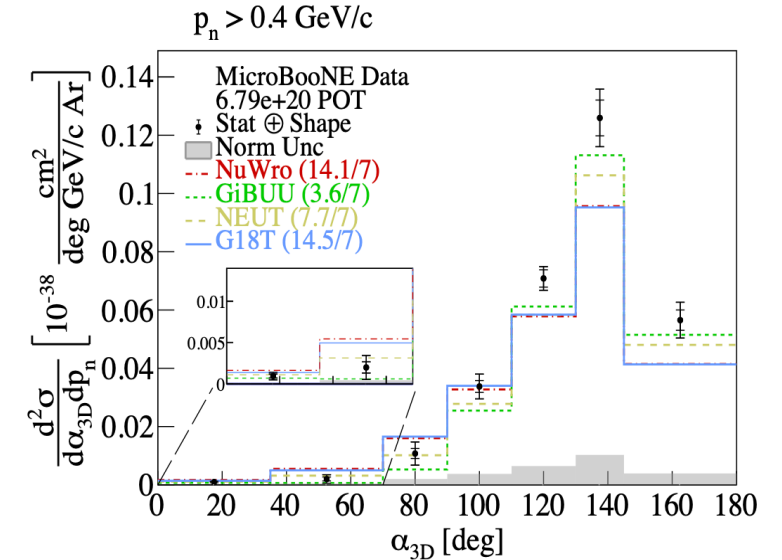- Better understanding of the performance of various neutrino event generators
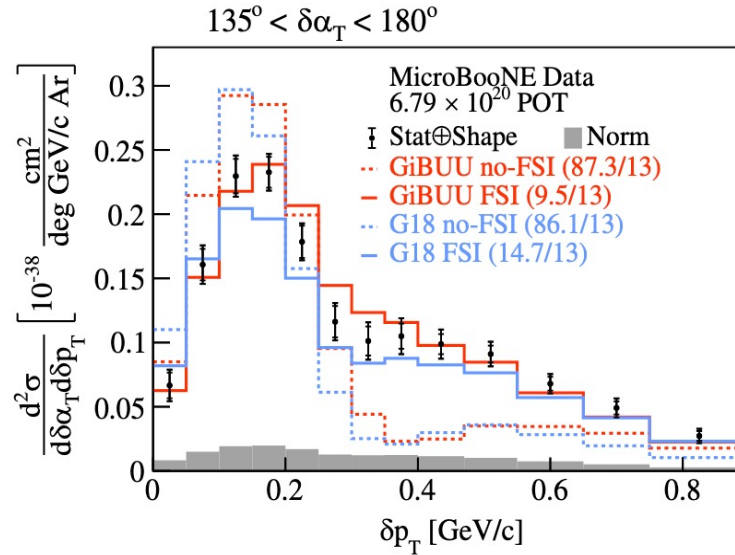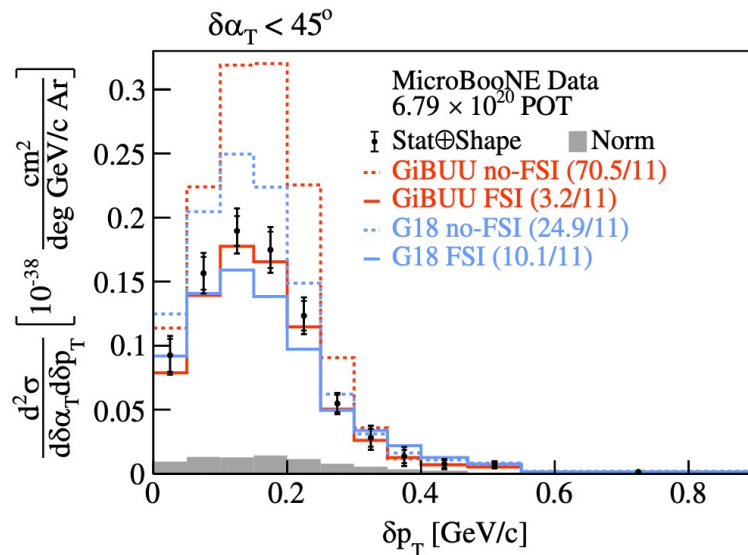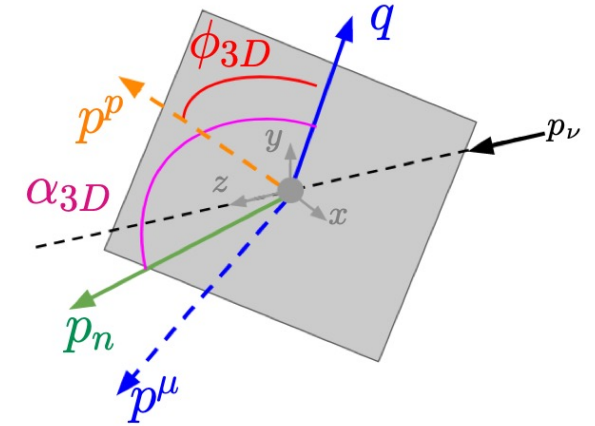

arXiv:2307.06413

MicroBooNE – Neutrino-Argon Interactions

CC QE-like Kinematic Imbalance

PRD 108, 053002 (2023), PRL 131, 101802 (2023), arxiv:2310.06082

- Assumptions about ν kinematics
  - Missing momentum & visible energy
  - Indicators for FSI / nuclear effects
- First 1D & 2D analysis for Ar using Transverse Kinematic Imbalance (**TKI**)
- New Generalized Kinematic Imbalance (**GKI**)
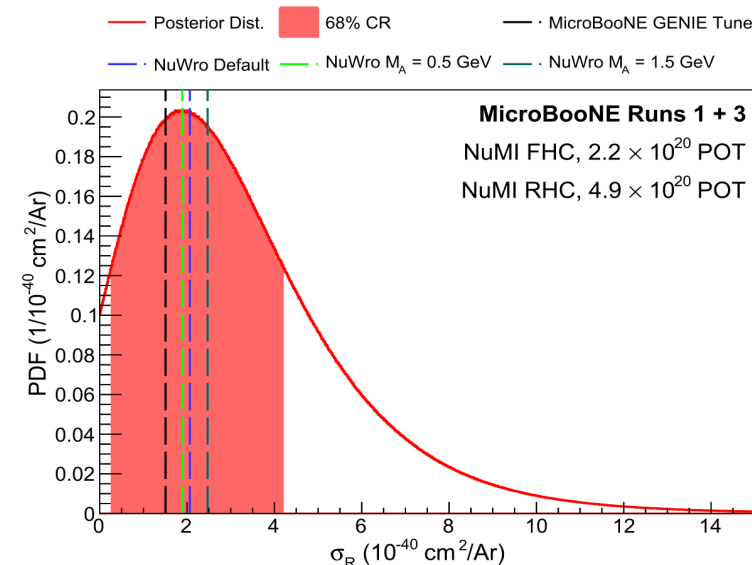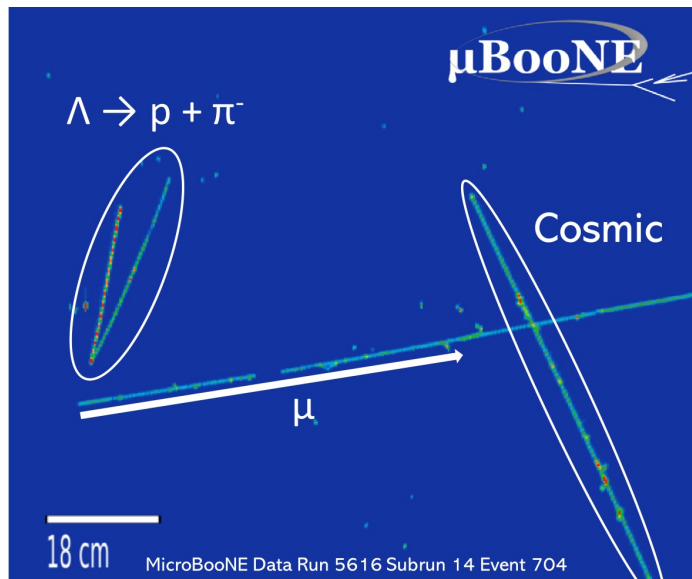 - Also consider longitudinal component

MicroBooNE – Neutrino-Argon Interactions

Λ Baryon Production

- First measurement of quasielasticlike Λ baryon production in a LArTPC
- Λ baryons through invariant mass and separated vertex
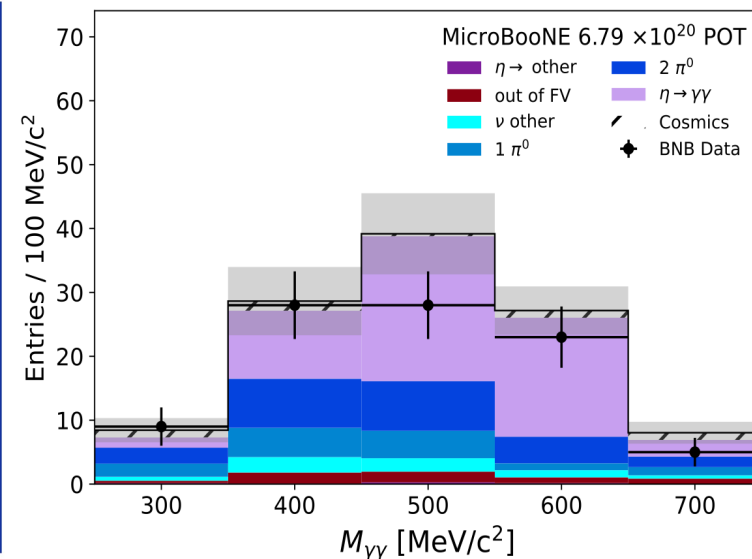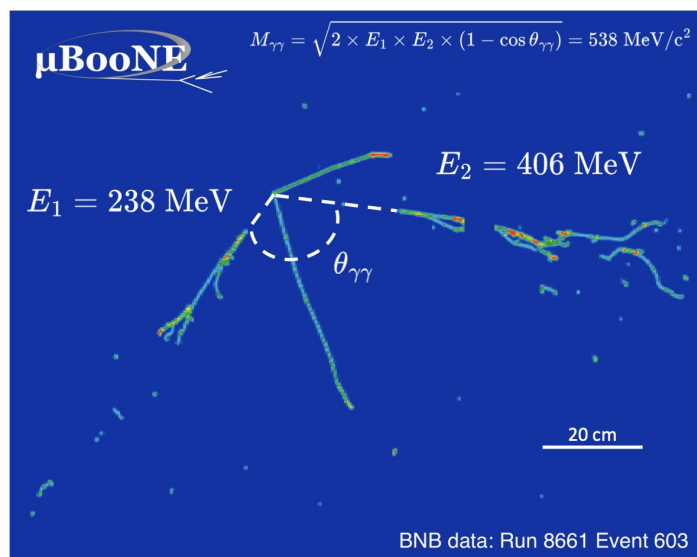- Rare channel — Identify 5 candidates

PRL 130, 231802 (2023)

η Production

- First measurement of η production from neutrino interactions on argon
- Rare process – no selection cuts on the presence of an outgoing lepton

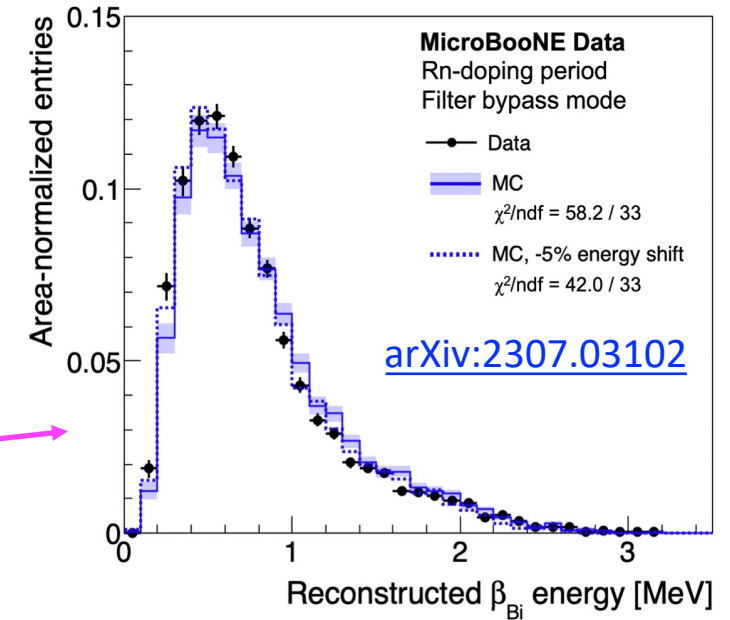$$\nu_{\mathrm{CC+NC}} \to \eta + X \to 2\gamma + 0\pi^0 + X$$

arXiv:2305.16249

MicroBooNE – LArTPC Techniques

- MicroBooNE continues to achieve interesting results at the MeV-scale using R&D running data
  - Measured the ambient radon daughter decay rates and energy spectra
  - Obtained the first ever reported radon radiopurity limit of < 0.38 mBq/kg (well below DUNE requirement of < 1 mBq/kg)

arXiv:2307.03102

- MicroBooNE detector entered its decommissioning phase in early 2023
  - Unique opportunity to characterize the detector after ~7 years of operation
  - Potential to understand some of unresolved mysteries
  - Probes some R&D efforts related to operations

Summary

- MicroBooNE completed its ~7 years data taking in 2021
  - Longest running LArTPC and largest ν-Ar data collected to date
  - Detector is currently in a decommissioning phase

- No evidence of excessive ν_e and NC Δ decay as a sole source of MiniBooNE LEE anomaly to date (BNB Run 1-3 data)
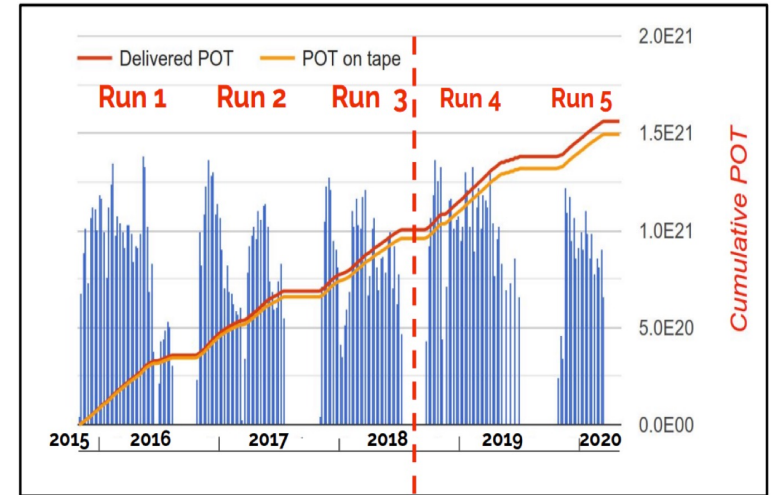

- No evidence of sterile neutrino oscillations in 3+1 model (BNB Run 1–3 data)
  - Results can be improved in upcoming search with combining BNB & NuMI data

- Various advanced searches for new physics with rich phenomenology are under development
  - More results on exotic searches, with e^+e^- focus are coming soon

- Wealth of neutrino-argon cross section measurements have been carried out
  - Important inputs for oscillation experiments

- Full dataset results are expected soon, which will approximately double the statistics

Thank You!

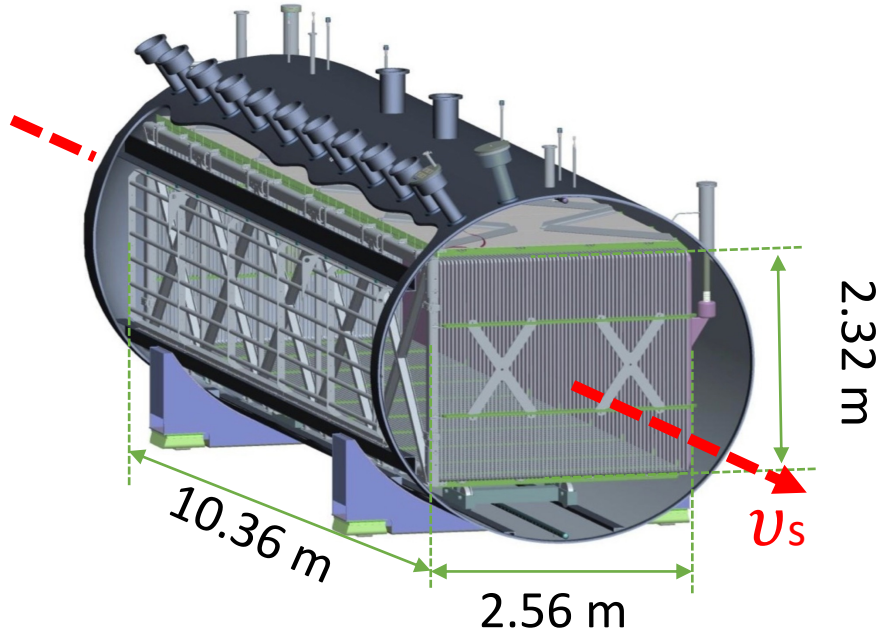# Backup

MicroBooNE Papers

63 papers

Among submitted/published papers:
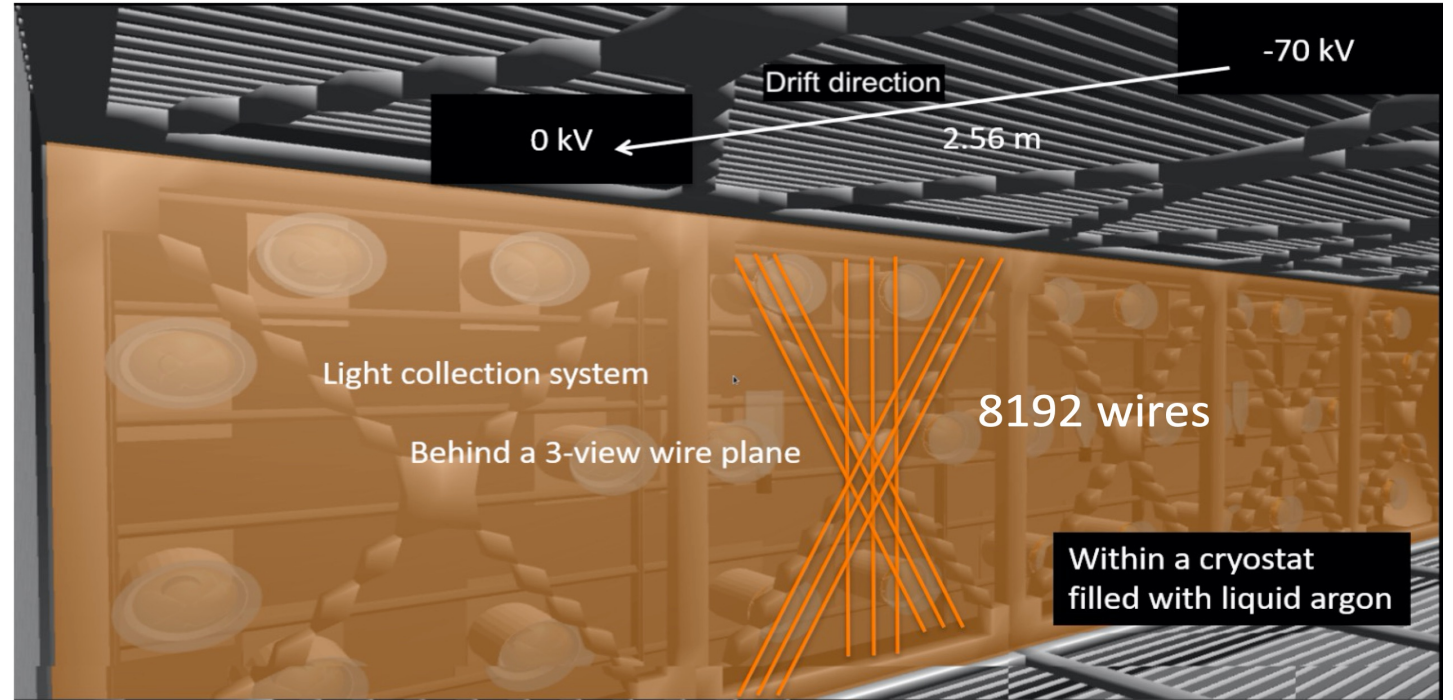
- 12 PRL
- 20 PRD
- 22 JINST

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}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 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 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 Λ 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 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 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 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 theory-driven GENIE tune 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
Wire-Cell 3D pattern recognition techniques for neutrino event reconstruction in large LArTPCs
Electromagnetic shower reconstruction and energy validation with Michel electrons and π^0 samples for the deep-learning-based analyses in MicroBooNE
Search for neutrino-induced NC Δ 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 Enu ~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

[MicroBooNE INSPIRE Page](#)

MicroBooNE Detector

2.32 m
10.36 m
2.56 m
v_s

JINST 12 P02017 (2017)

Drift direction
-70 kV
0 kV
2.56 m

Light collection system
Behind a 3-view wire plane

8192 wires

Within a cryostat filled with liquid argon
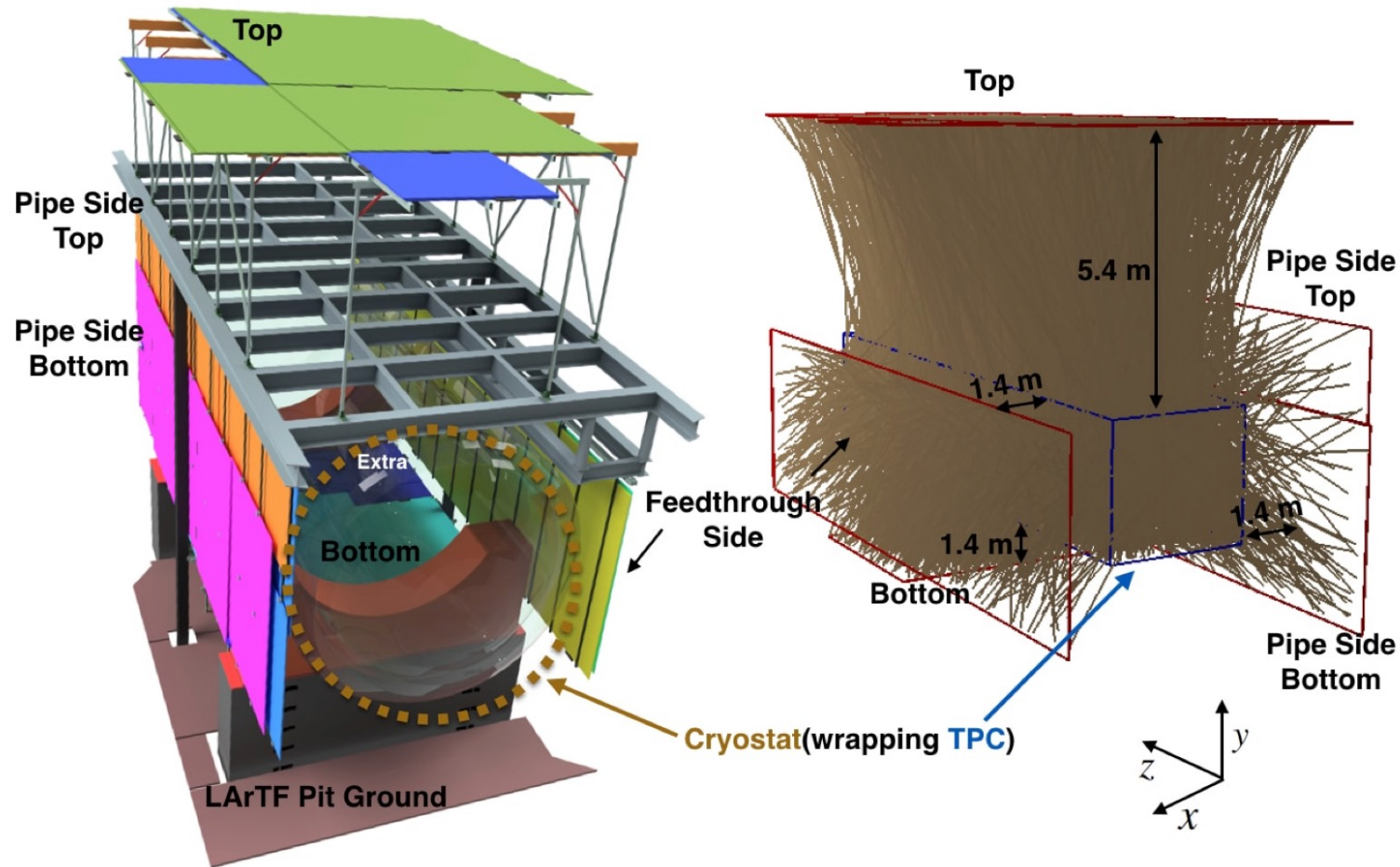
Charge Collection System

- 3 anode wire planes
- 3 mm plane-to-plane spacing with a 3 mm wire pitch
- Mainly for Reconstruction of event and calorimetry

Light Collection System

- 32 PMTs as primary subsystem
- 4 light guide paddles for R&D studies
- Mainly for trigger and event selection

Cosmic Ray Tagger System

- 73 plastic scintillation modules
- Situated on the top, bottom, and long sides
- Mainly for reducing cosmogenic backgrounds

MicroBooNE Detector – CRT

MicroBooNE CRT was installed at Fermilab in July-September 2016 (Phase I) and February 2017 (Phase II). It was incorporated into physics data taking in October 2016.
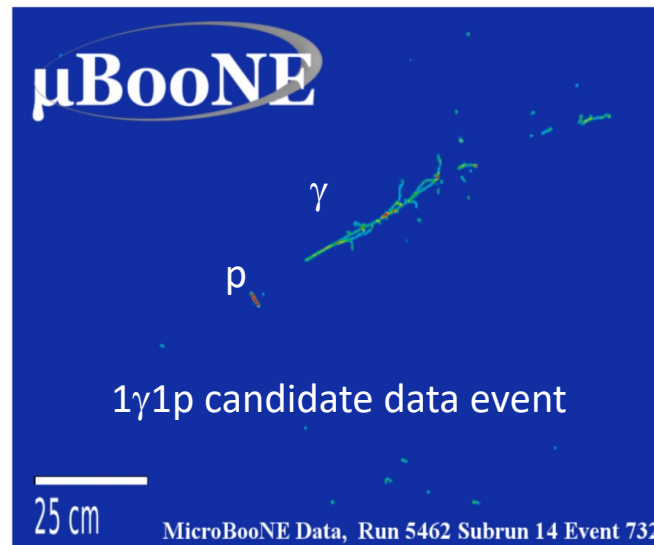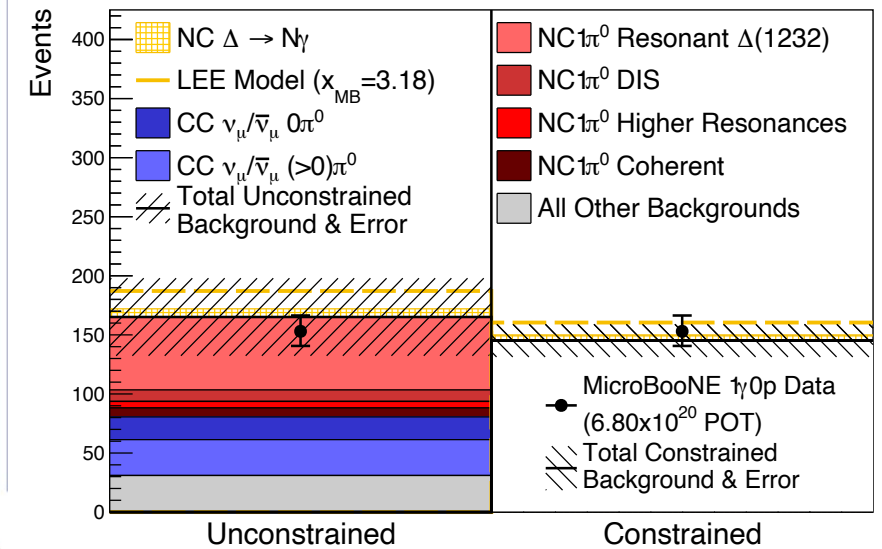
JINST 14 P04004 (2019)

MicroBooNE LEE Results – Photon Excess

Disfavor a candidate photon interpretation of MiniBooNE LEE as a x3.18 enhancement of nominal rate NC Δ radiative decay rate at the 94.8% CL.
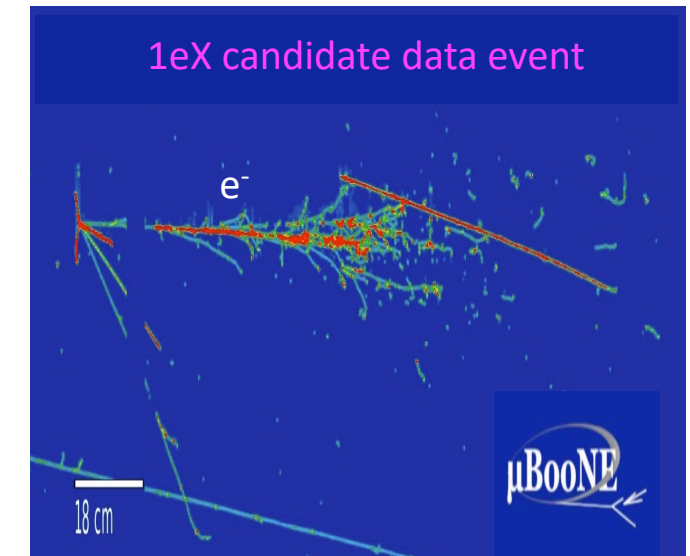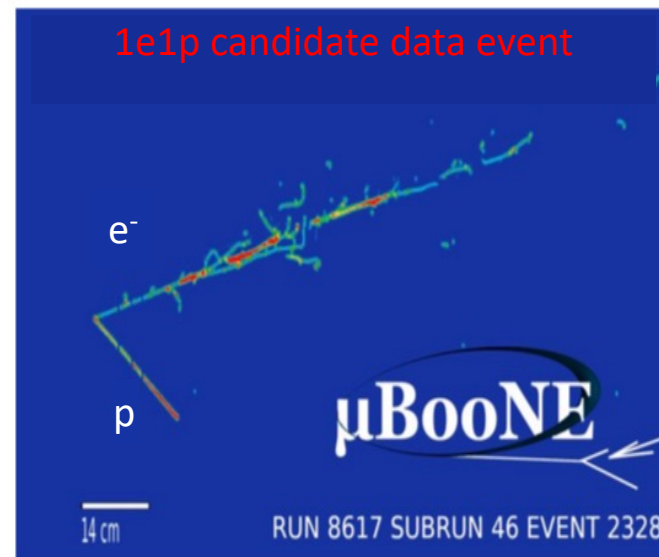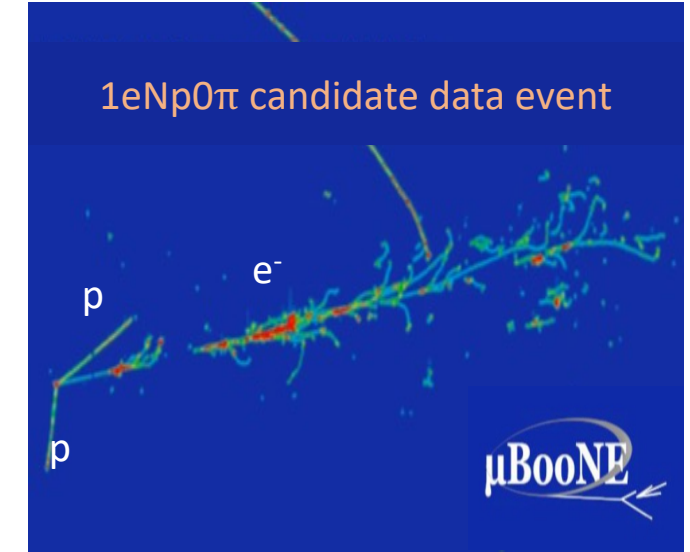

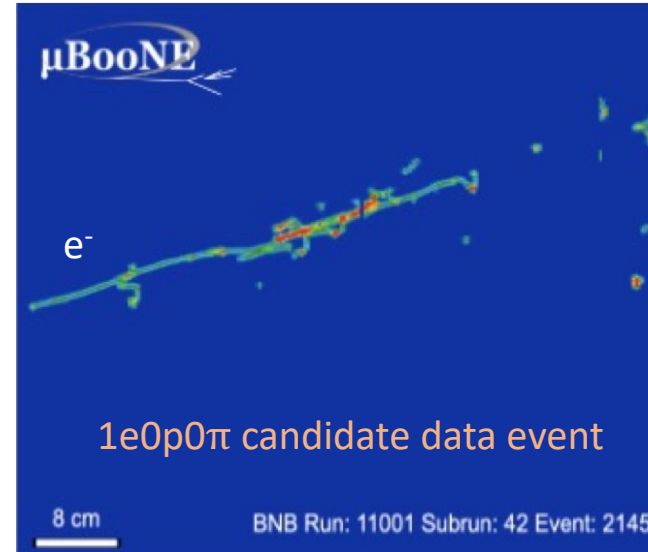1γ0p candidate data event

μBooNE

15 cm   MicroBooNE Data
Run 5187 Subrun 188 Event 9430

μBooNE

γ

p

1γ1p candidate data event

25 cm   MicroBooNE Data, Run 5462 Subrun 14 Event 732
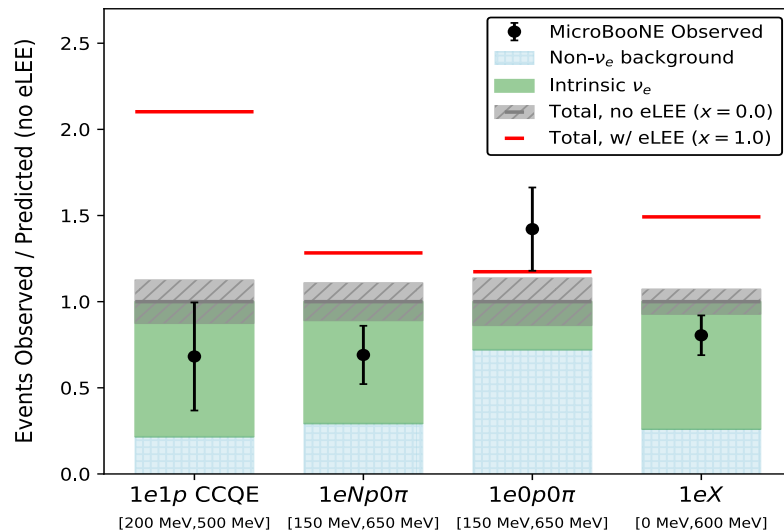
MicroBooNE LEE Results – Electron Excess

3 ν_e analyses using different reconstructions:

- "Pandora" based: MiniBooNE-like final states (1e0p0π, 1eNp0π)
  Phys. Rev. D 105, 112004 (2022)

- "Deep Learning" based: restricting to quasi-elastic kinematics (1e1p)
  Phys. Rev. D 105, 112003 (2022)

- "Wire-Cell" based:
  all CC ν_e final states (1eX)
  Phys. Rev. D 105, 112005 (2022)

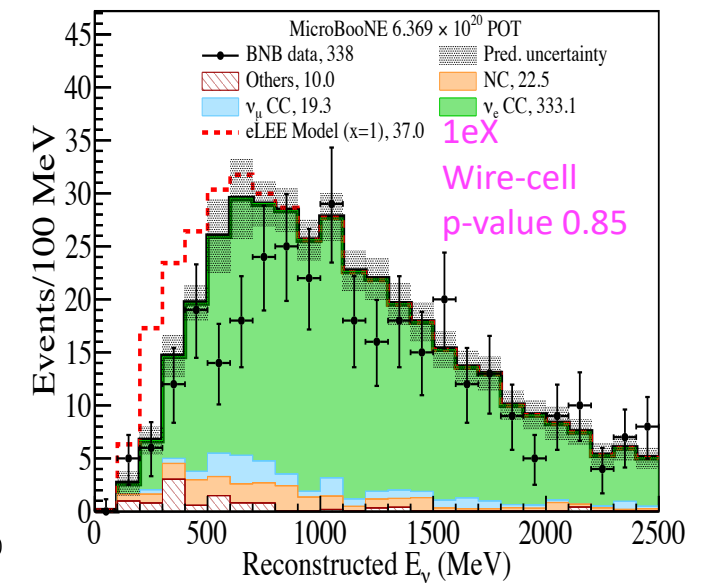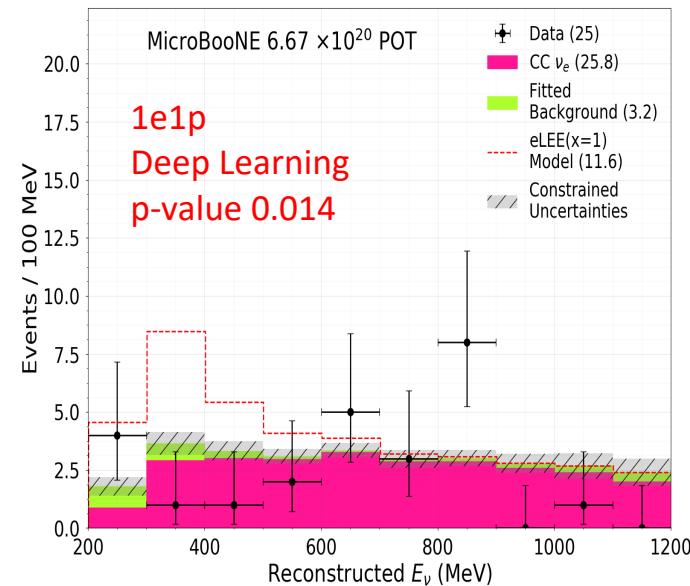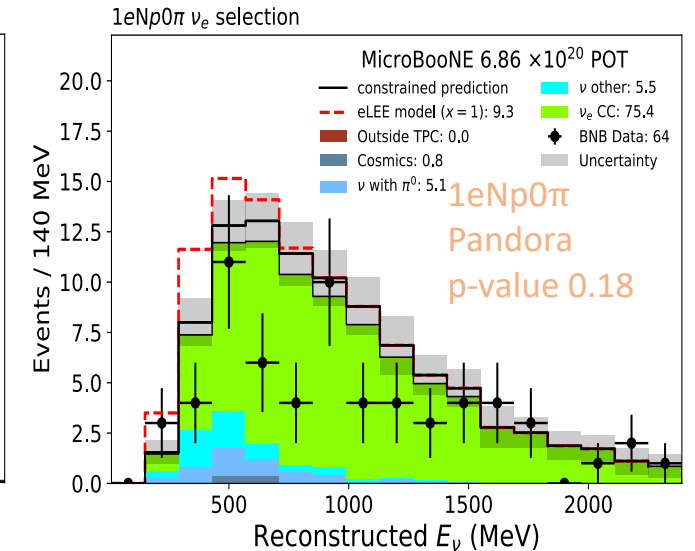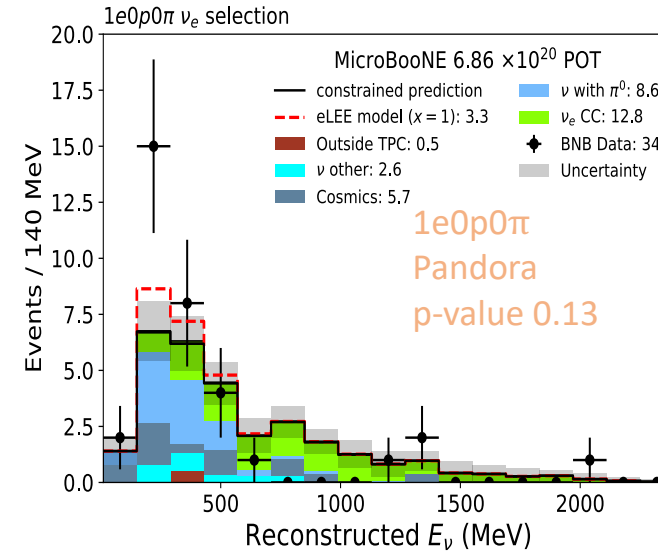1e0p0π candidate data event

1eNp0π candidate data event

1e1p candidate data event

1eX candidate data event

Disfavor an interpretation of MiniBooNE's observed electron-like excess signature at >97% CL (results are found to be consistent with the nominal ν_e rate expectations from BNB)
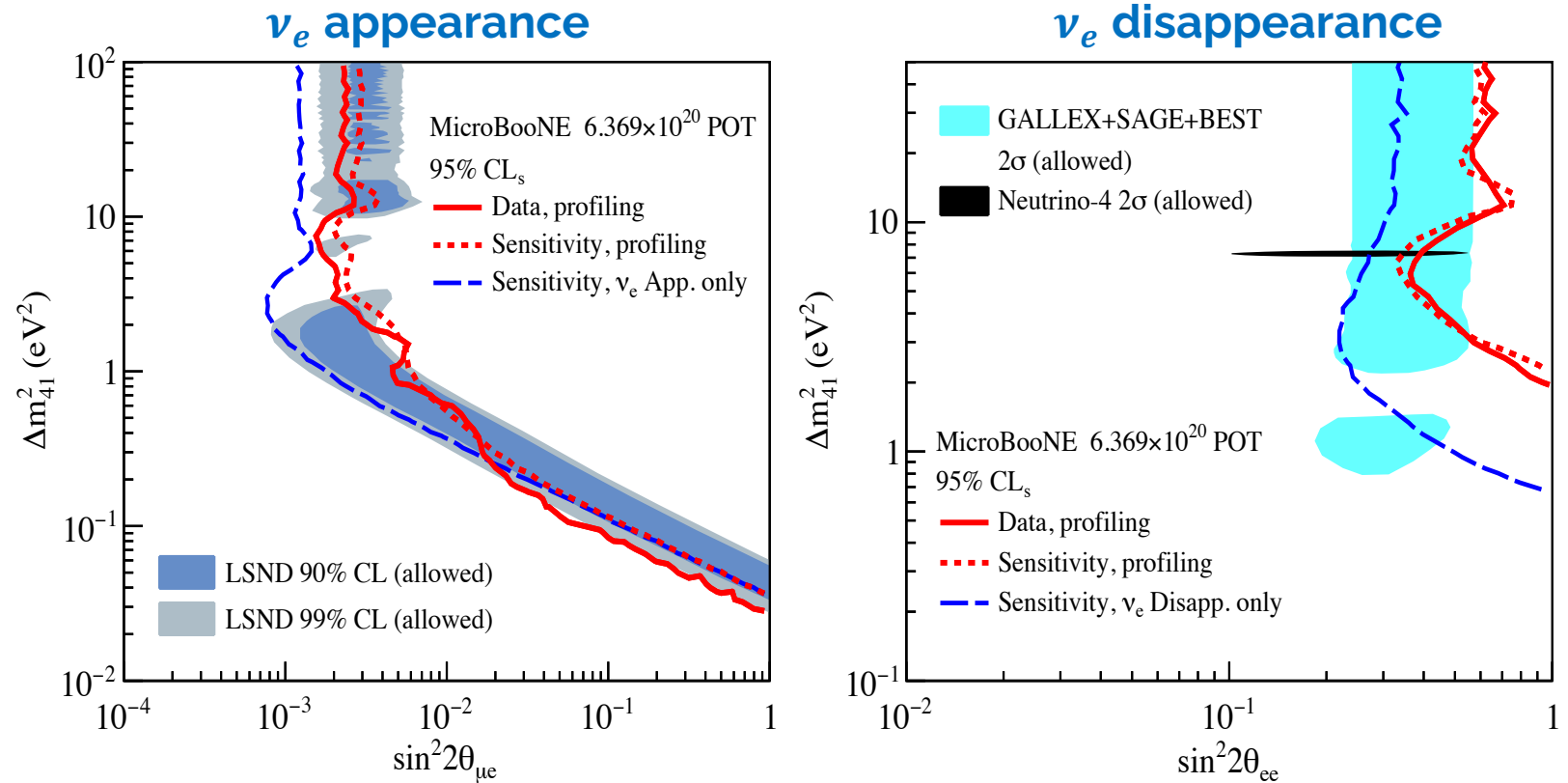

Phys. Rev. Lett. 128, 241801 (2022)

1e0p0π Pandora p-value 0.13

1eNp0π Pandora p-value 0.18

1e1p Deep Learning p-value 0.014

1eX Wire-cell p-value 0.85

ν_e appearance

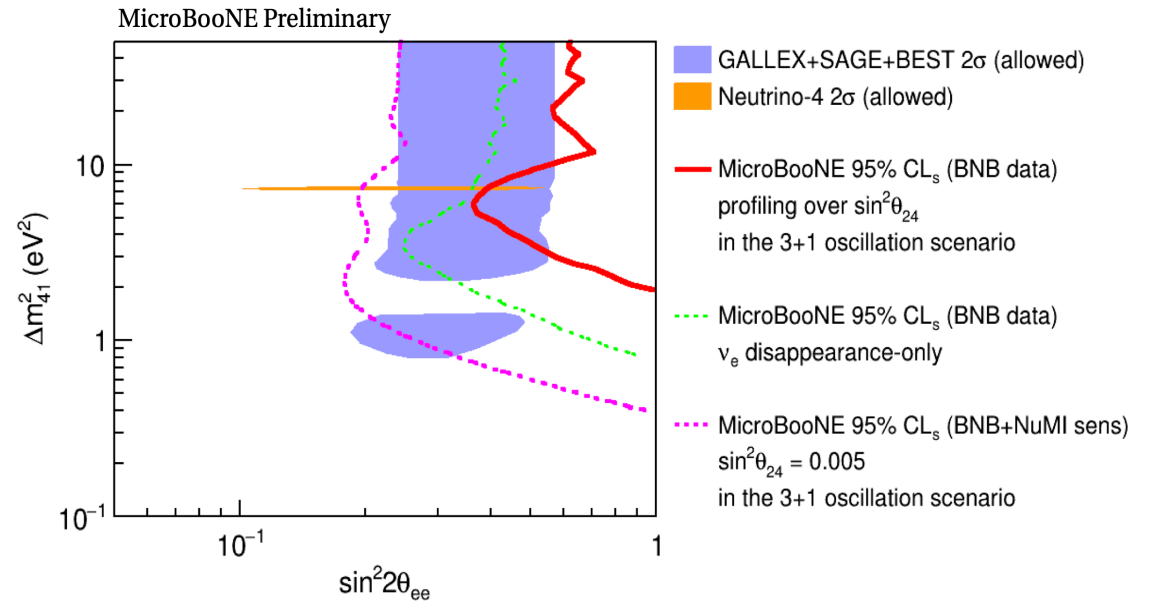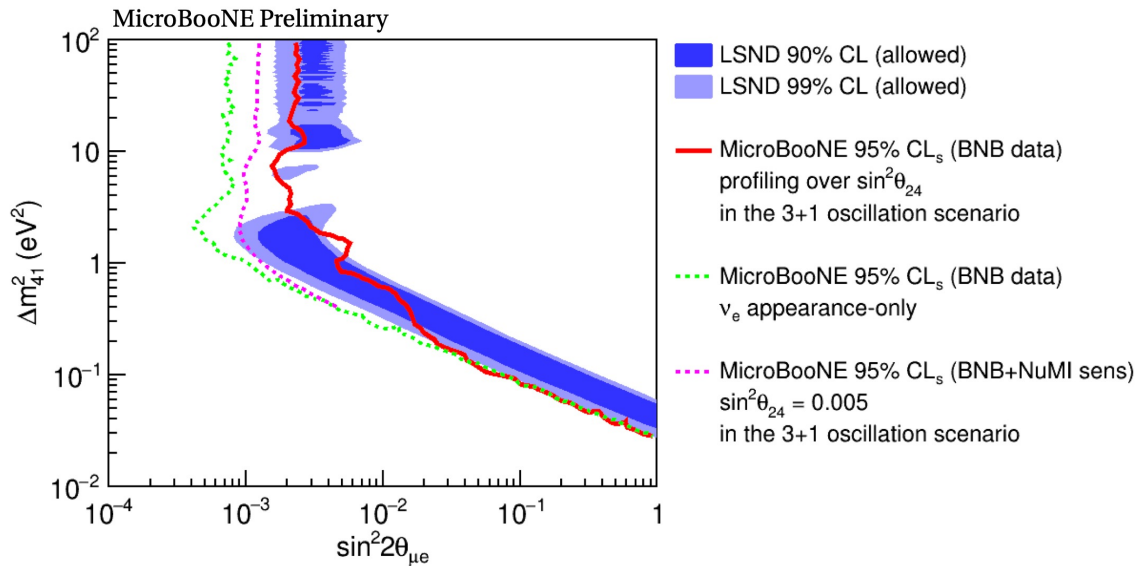**ν_e disappearance**

- **Full 3+1 search using BNB Run 1-3 data**

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

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - (-1)^{\delta_{\alpha\beta}} \sin^2(2\theta_{\alpha\beta}) \sin^2\left(\frac{1.27\Delta m_{41}^2 L}{E}\right)$$

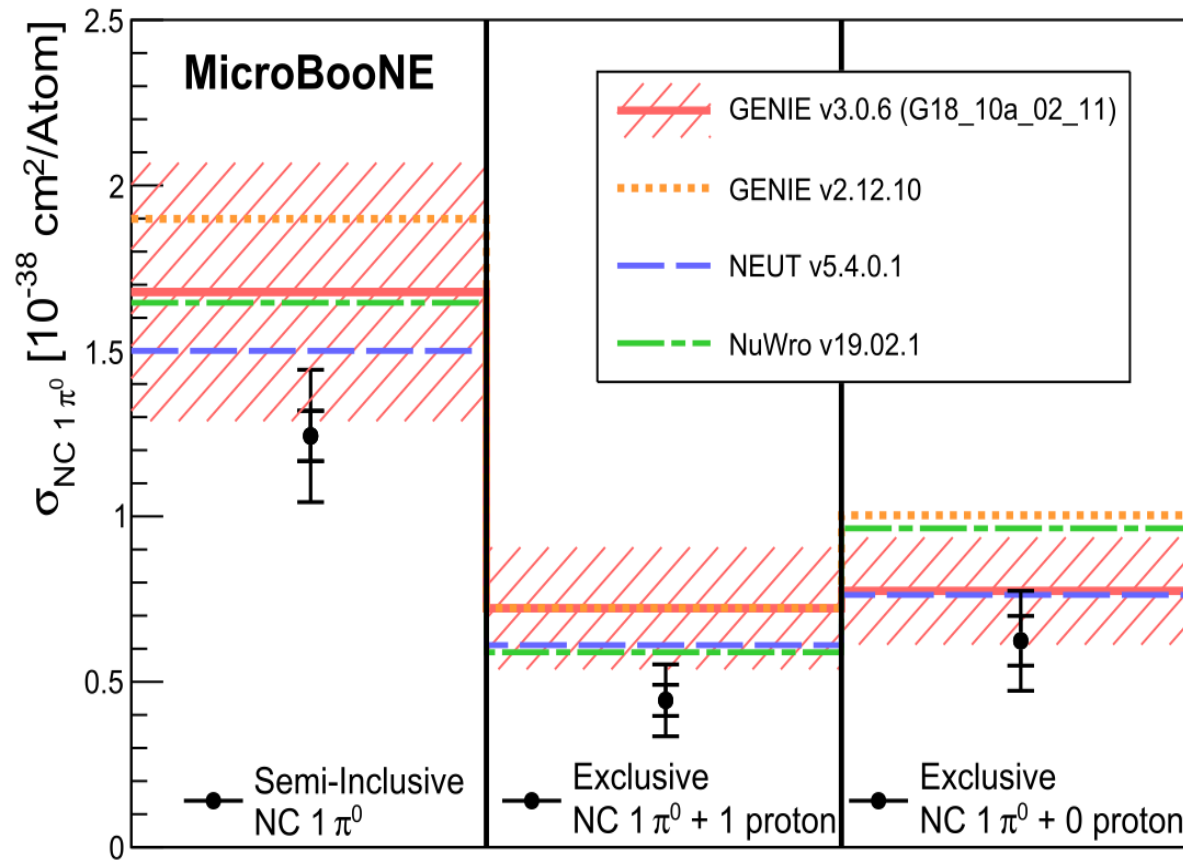**Full 3+1 search using BNB & NuMI data**

ν_e **appearance**

MICROBOONE-NOTE-1116-PUB

MicroBooNE – Exploration of MiniBooNE LEE

First series of results (1/2 the MicroBooNE data set)

Models \ Reco topology	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma 0p$	$1\gamma 1p$	1γX
eV Sterile ν Osc	✔	✔	✔	✔					
Mixed Osc + Sterile ν	✔	✔	✔	✔			✔		
Sterile ν Decay	✔	✔	✔	✔			✔	✔	✔
Dark Sector & Z' *	✔				✔	✔	✔	✔	✔
More complex higgs *					✔	✔	✔	✔	✔
Axion-like particle *					✔		✔		
Res matter effects	✔	✔	✔	✔					
SM γ production							✔	✔	✔

*Requires heavy sterile/other new particles also

PRD 107, 012004 (2023)

NC $1\pi^0$ production on argon

- Highest-statistics to date
- Powerful constraint for backgrounds to single-photon searches