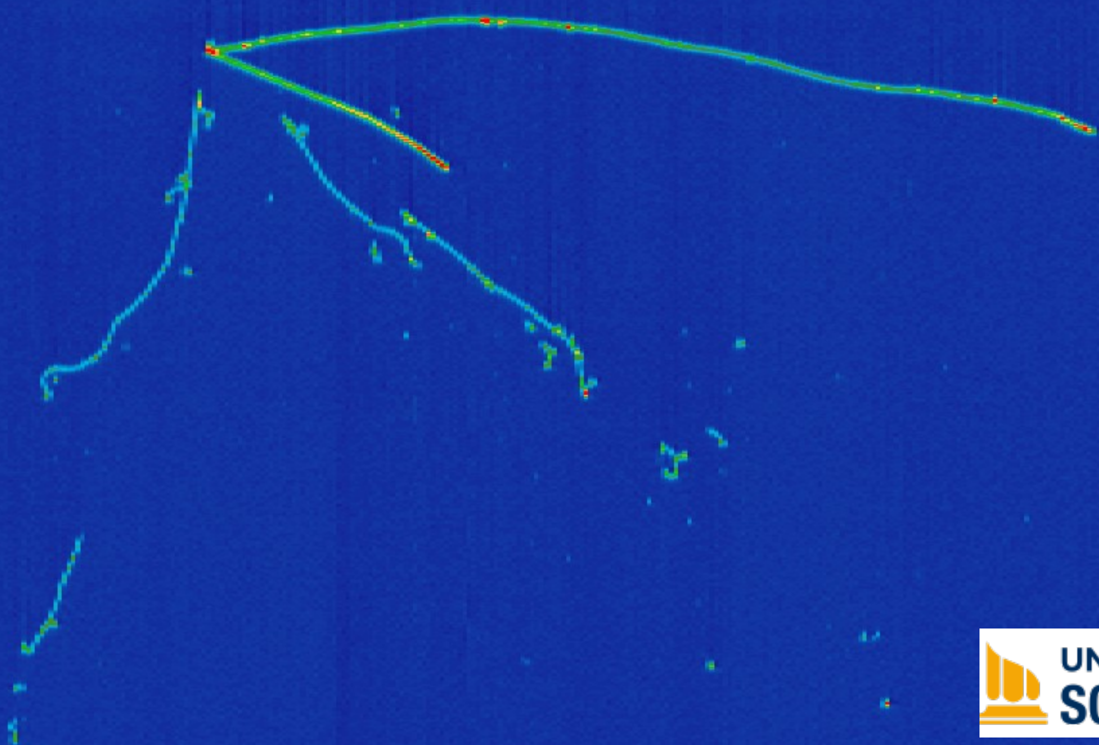
Recent Results from MicroBooNE and Status of the Short-Baseline Neutrino Program

Brandon Eberly, University of Southern Maine
on behalf of the **MicroBooNE Collaboration**

Conference on Science at the Sanford Underground Research Facility, May 16, 2024



MicroBooNE Physics Program

MicroBooNE Collaboration:

- ~190 collaborators (~50% students and postdocs)
- 61 papers, about half physics, half R&D

Investigate the MiniBooNE Low-Energy Excess (LEE) and search for BSM physics

- Same neutrino beamline and approximately the same location as MiniBooNE

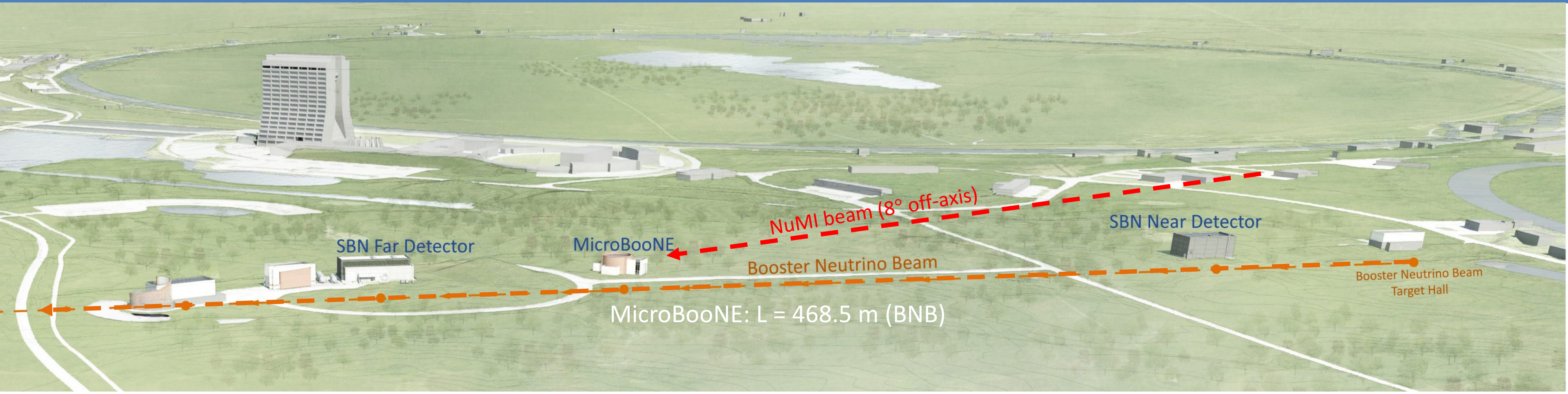
Study neutrino-argon interactions

- ~500k ν-Ar interactions observed (largest to date)
- Inclusive and exclusive cross sections

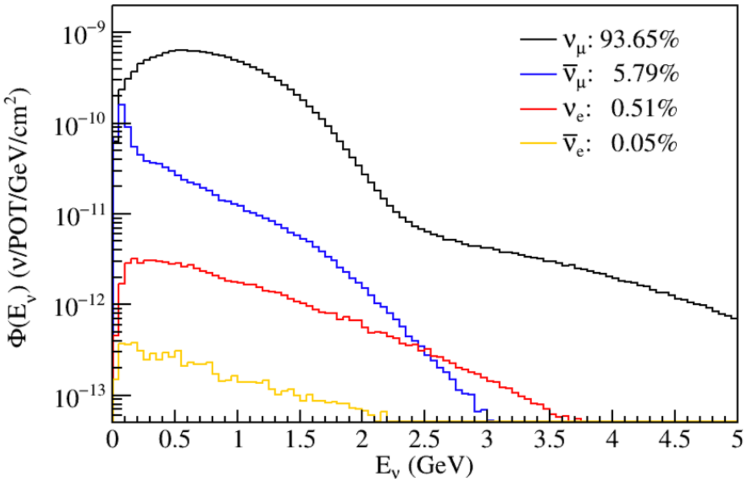
Liquid-argon time-projection chamber (LArTPC) hardware and software R&D

- Cold electronics, noise filtering, signal processing, and event reconstruction

Neutrino Beamlines

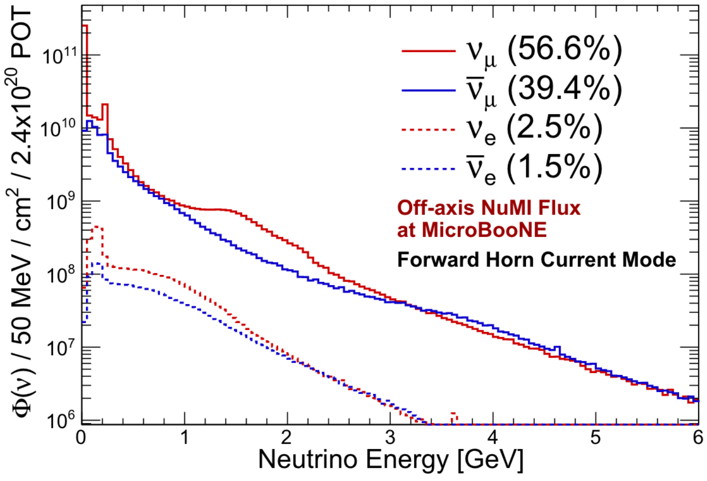


On-axis BNB



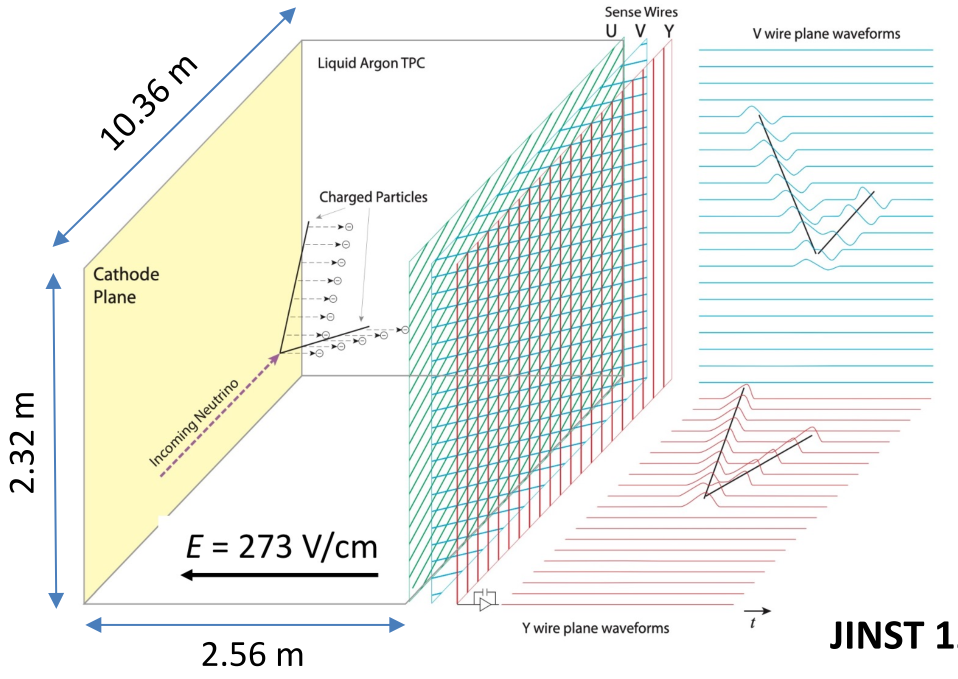
PRD 105, 112005 (2022)

Off-axis NuMI



PRD 104, 052002 (2021)

MicroBooNE Detector

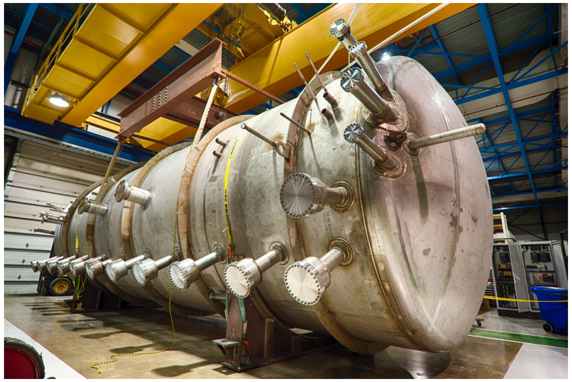


JINST 12 P02017 (2017)

~mm spatial resolution

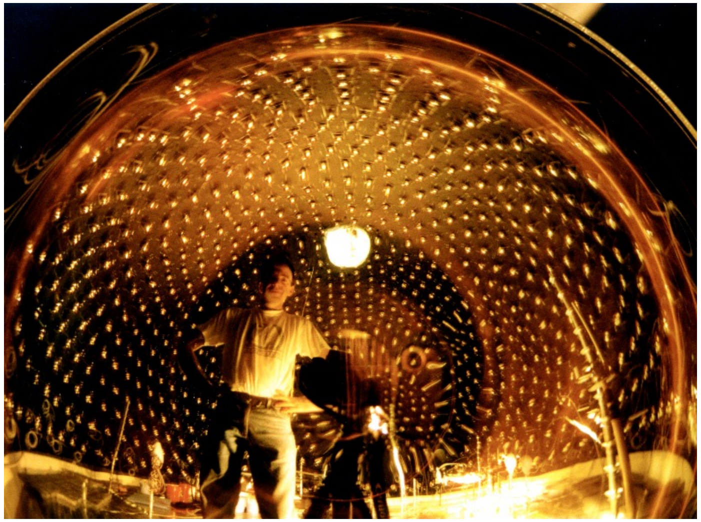
Sub-MEV energy threshold
- **PRD 109, 052007 (2024)**

~ns timing resolution
- **PRD 108, 052010 (2023)**



MiniBooNE Low Energy Excess

MiniBooNE detector: mineral oil (CH_2) Cherenkov detector designed to investigate the LSND anomaly



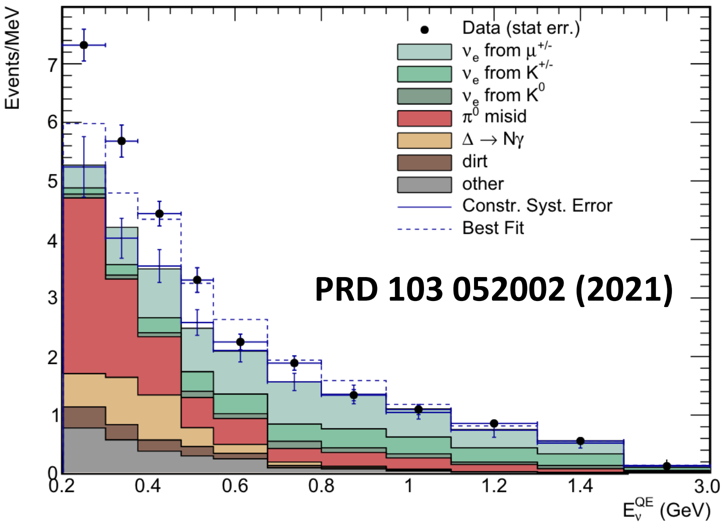
MiniBooNE sees a 4.8 sigma excess of electron-like events (EM showers) at low energy

- If from oscillation, result is inconsistent with the 3-neutrino paradigm

Large photon background in region of interest

- Difficulty distinguishing photon and electron showers

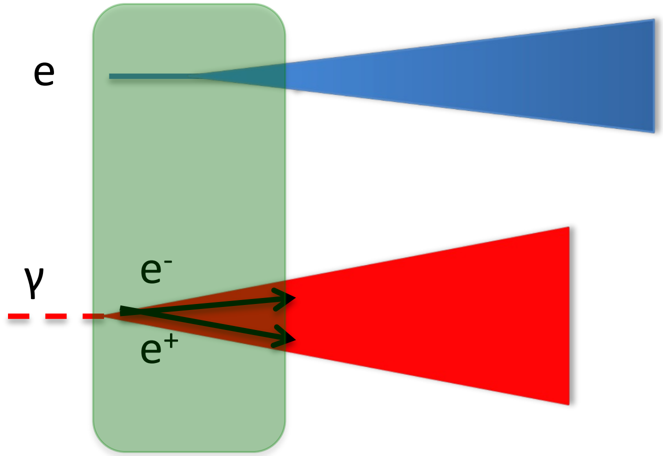
Unclear whether excess is truly ν_e or due to novel source of photon background



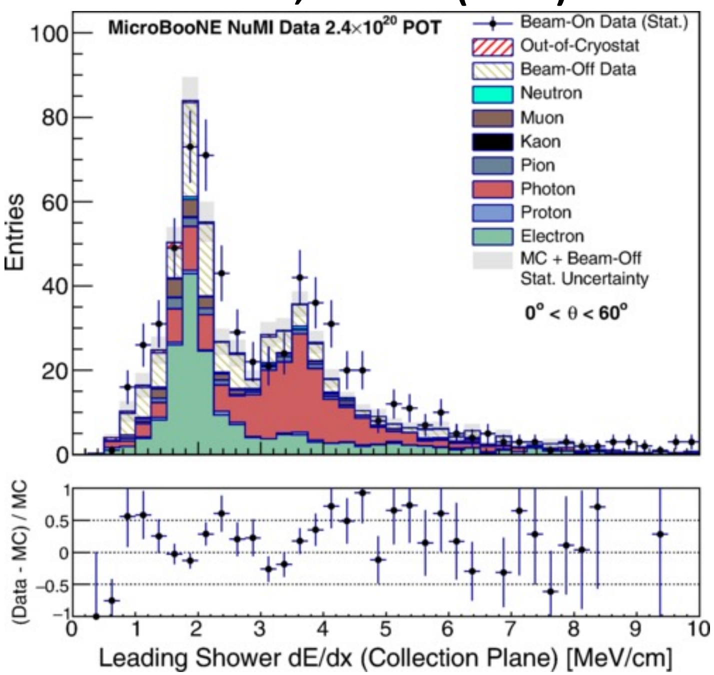
PRD 103 052002 (2021)

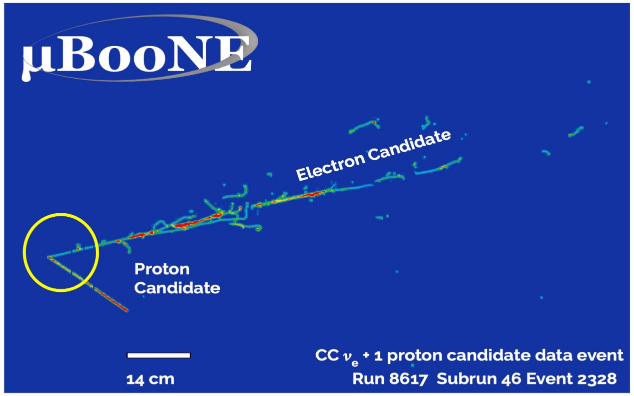
Electron-Photon Separation in MicroBooNE

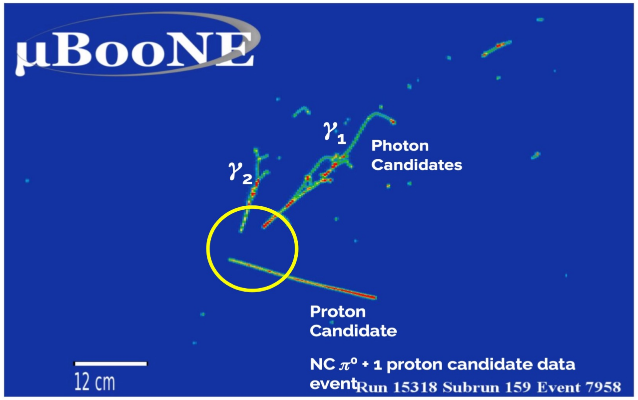
Leverage dE/dx difference between electrons and photons at the start of the EM shower



PRD 104, 052002 (2021)







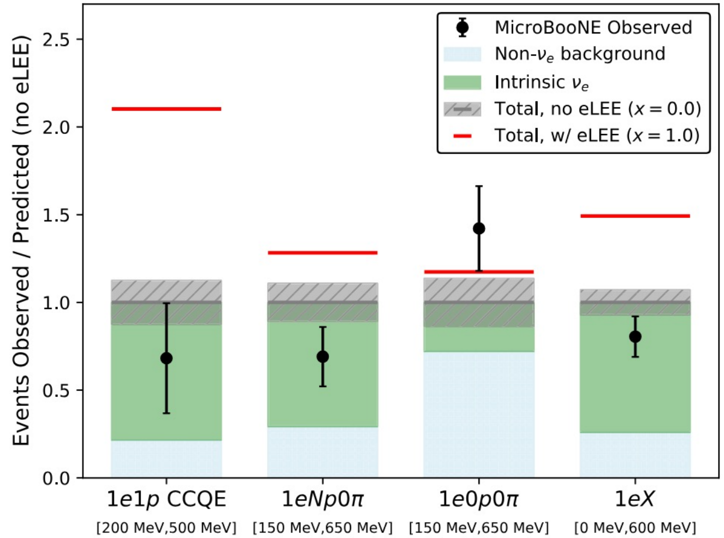
First MicroBooNE LEE Searches (~50% data)

Three independent ν_e searches (1e final state)

- Exclusive $1e1p$ final state with deep learning reconstruction: **PRD 105, 112003 (2022)**
- Semi-inclusive no-pion final state with particle-flow reconstruction: **PRD 105, 112004 (2022)**
- Inclusive $1eX$ final state with tomographic event reconstruction: **PRD 105, 112005 (2022)**

Results: no evidence of excess ν_e events observed, and we exclude this as sole explanation for MiniBooNE LEE at 97% CL

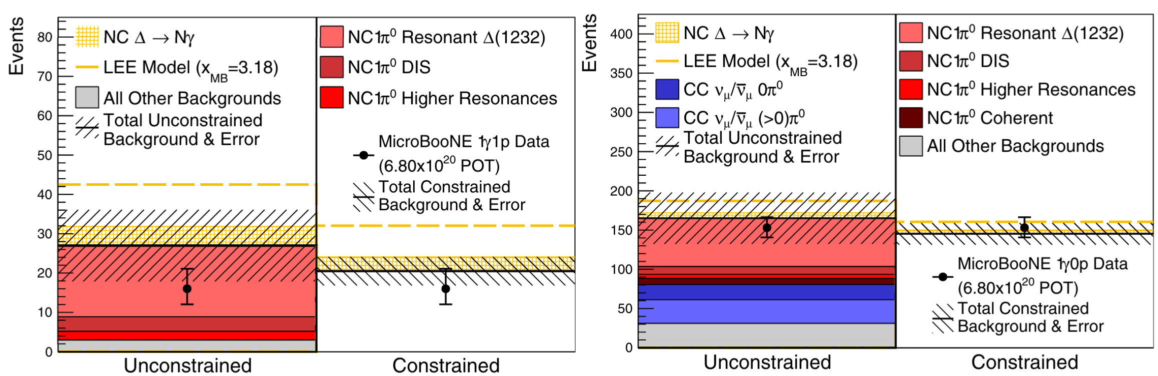
- **PRL 128, 241801 (2022)**



Search for neutral current Δ(1232) production with radiative decay

- **PRL 128, 111801 (2022)**

Results: no evidence of excess NC $\Delta \rightarrow N\gamma$ events observed, and we exclude this as sole explanation for MiniBooNE LEE at 95% CL



Background constraint: NCπ^0 samples

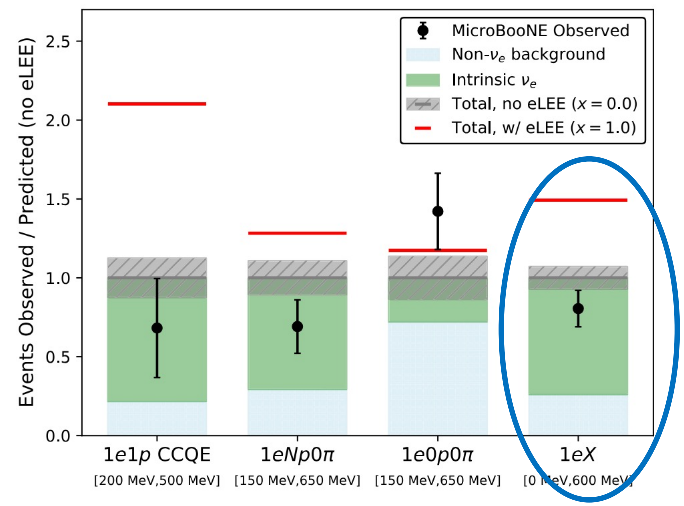
MicroBooNE Light Sterile Neutrino Search

A full 3+1 neutrino oscillation analysis using the data from the inclusive $1eX$ LEE search: **PRL 130, 011801 (2023)**

Considers ν_e appearance and disappearance and ν_μ disappearance relative to the nominal BNB flux

Three free fit parameters: Δm^2_{41}, $\sin^2\theta_{14}$, and $\sin^2\theta_{24}$

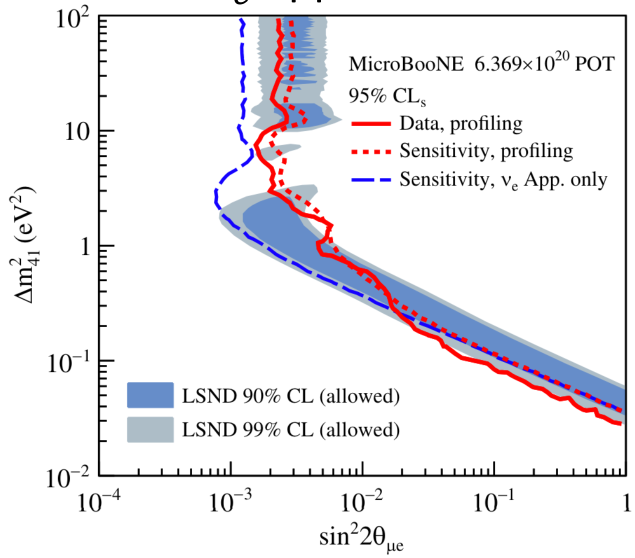
Results: data consistent with 3ν hypothesis within 1σ



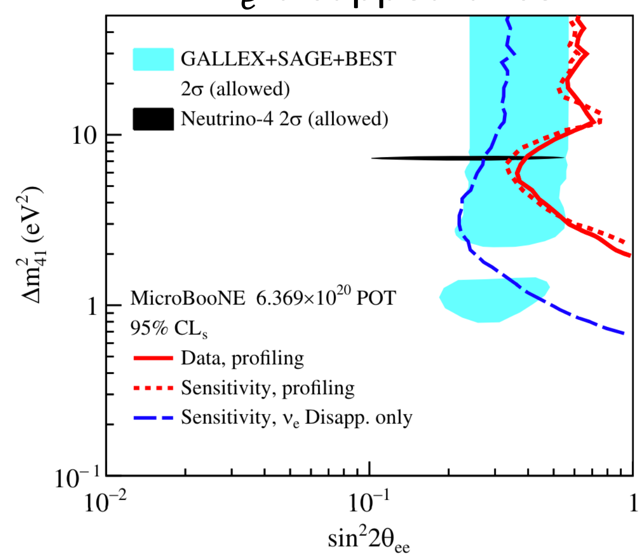
***ν_e* Appearance:**
Excludes significant portions of LSND allowed region

***ν_e* Disappearance:** Excludes some of the allowed regions from nuclear source experiments

ν_e appearance



ν_e disappearance



MicroBooNE: Heavy Neutral Leptons

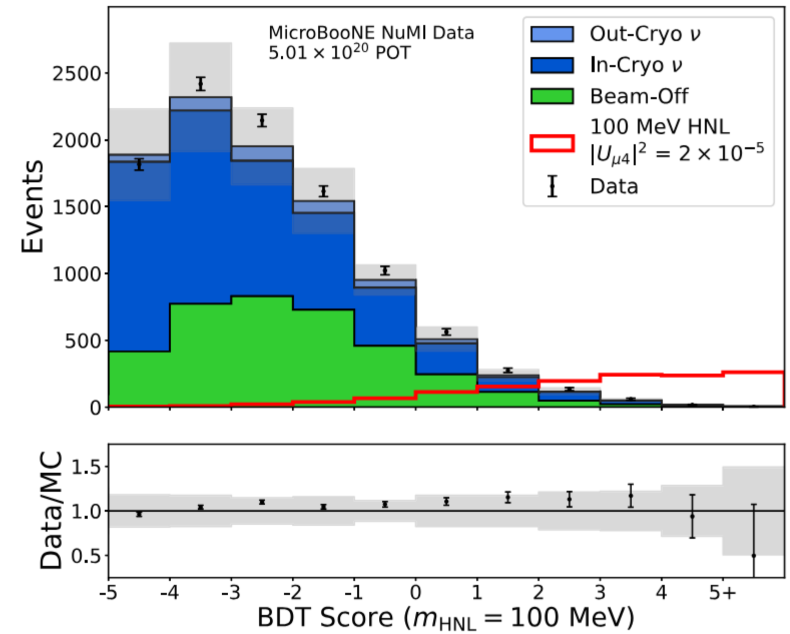
Heavy neutral leptons (HNLs) that mix weakly with the three neutrinos can explain the origin of neutrino mass, generation of baryon asymmetry through leptogenesis, and the nature of dark matter.

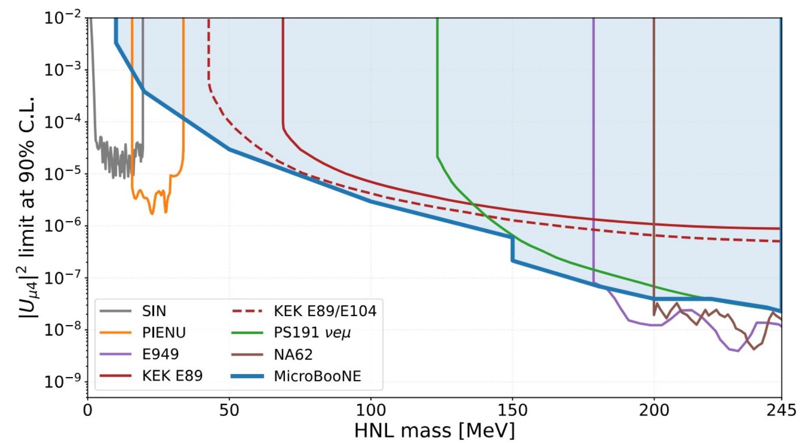
Previous MicroBooNE searches: $\mu^{\pm}\pi^{\mp}$ decay modes

- **PRD 101, 052001 (2020)** and **PRD 106, 092006 (2022)**

New search: $\nu e^{+}e^{-}$ and $\nu\pi^{0}$ (first ever!) with the NuMI beam and a boosted decision tree (BDT) analysis: **PRL 132, 041801 (2024)**

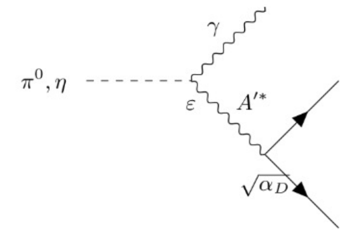
Results: HNL decays not observed. We have the most stringent constraints on $\left|U_{\mu 4}\right|^{2}$ in the mass range 34 – 175 MeV.





MicroBooNE: Dark Trident Processes

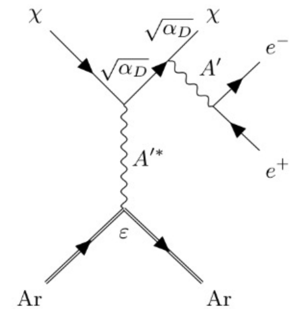
Dark trident processes: light dark matter could be produced in neutrino beamline targets via neutral meson decays mediated by a dark photon



production

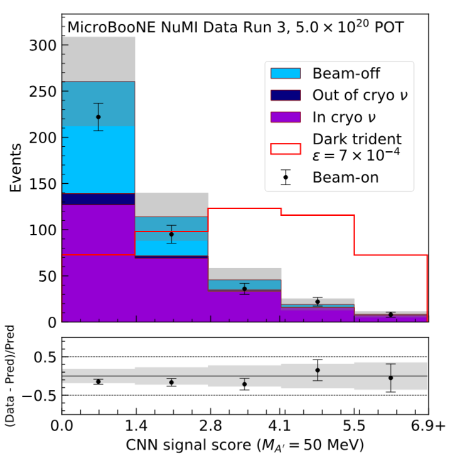
MicroBooNE uses a convolutional neural network analysis to search for the e^+e^- shower produced by a dark photon decay

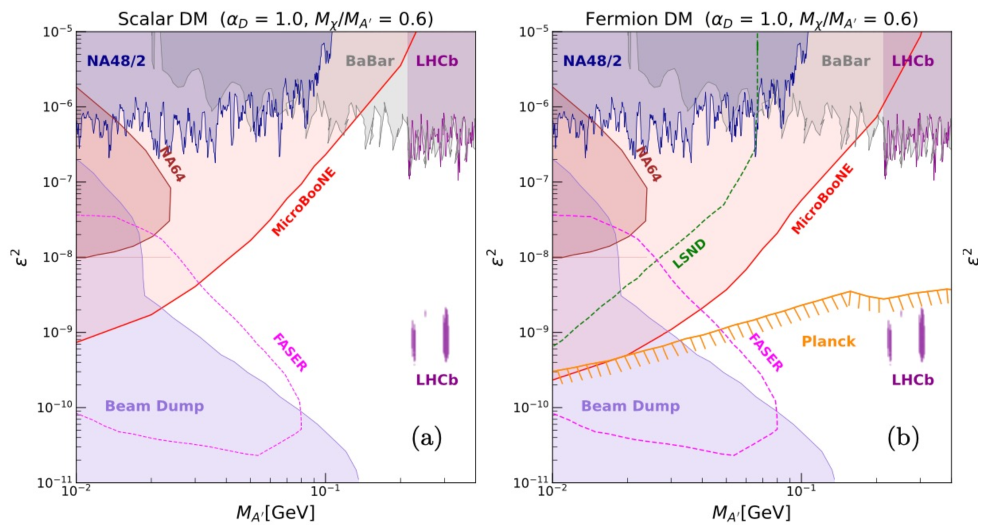
- **arxiv:2312.13945**



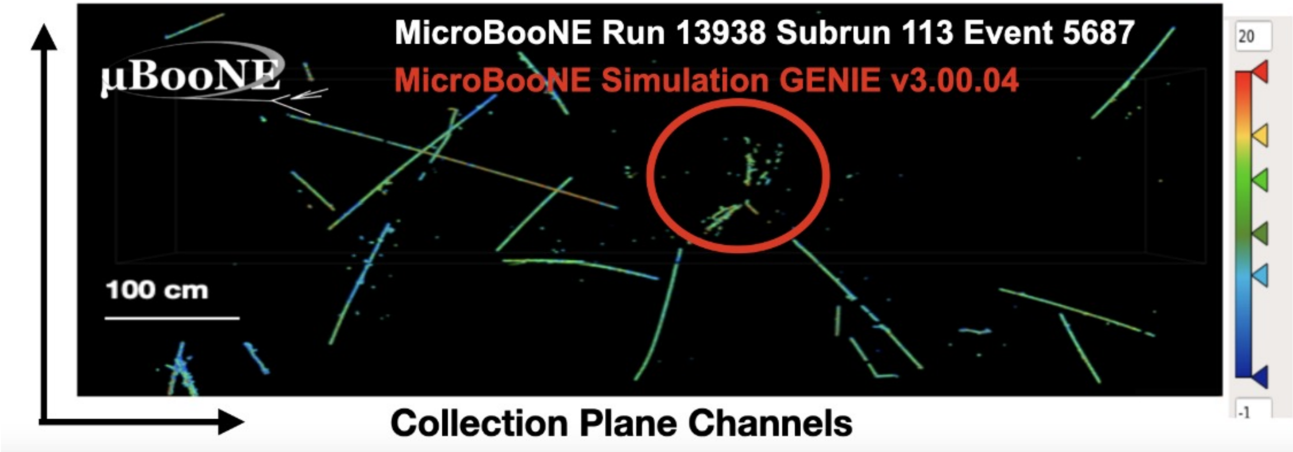
detection

Results: No evidence for dark-trident processes observed. Limits cover previously unconstrained parameter space in two benchmark models

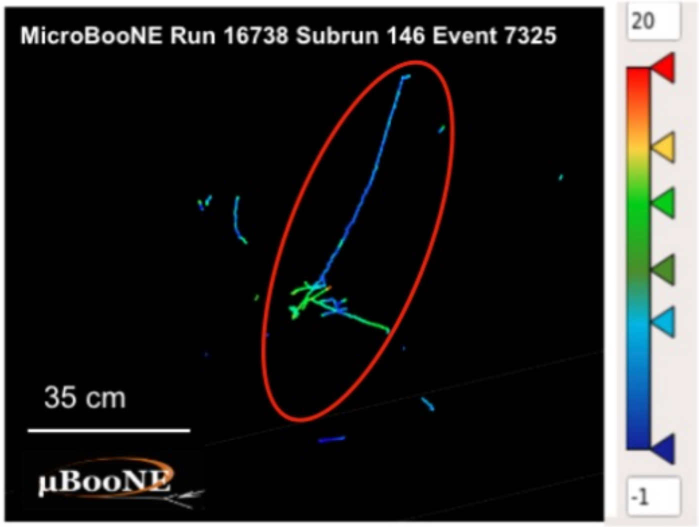




MicroBooNE: $n \rightarrow \bar{n}$ transitions



Discovery of $n \rightarrow \bar{n}$ transitions or stringent limits on the process would be an important contribution to our understanding of the baryon asymmetry of the universe



DUNE will likely be capable of providing competitive limits on the process

MicroBooNE presents the first search for $n \rightarrow \bar{n}$ in a LArTPC. Deep learning methods are used.

- **arxiv:2308.03924**

MicroBooNE: $n \to \bar{n}$ transitions

See Daisy's talk Wednesday afternoon in the proton decay session for all the details!

Discovery of $n \to \bar{n}$ transitions or
process would be an im
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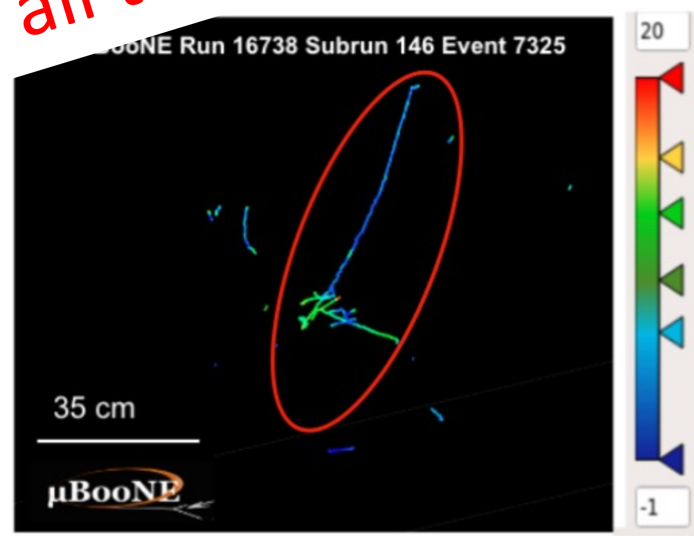
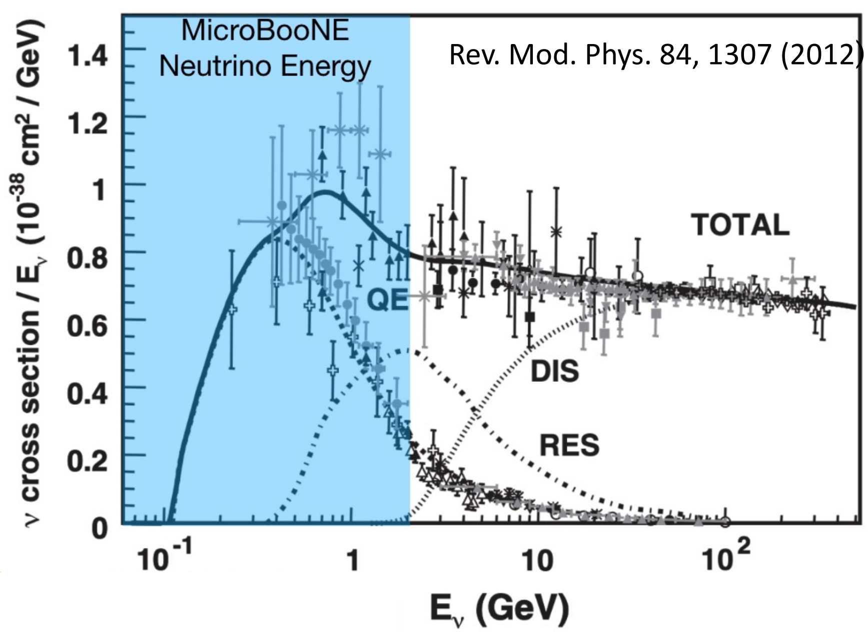


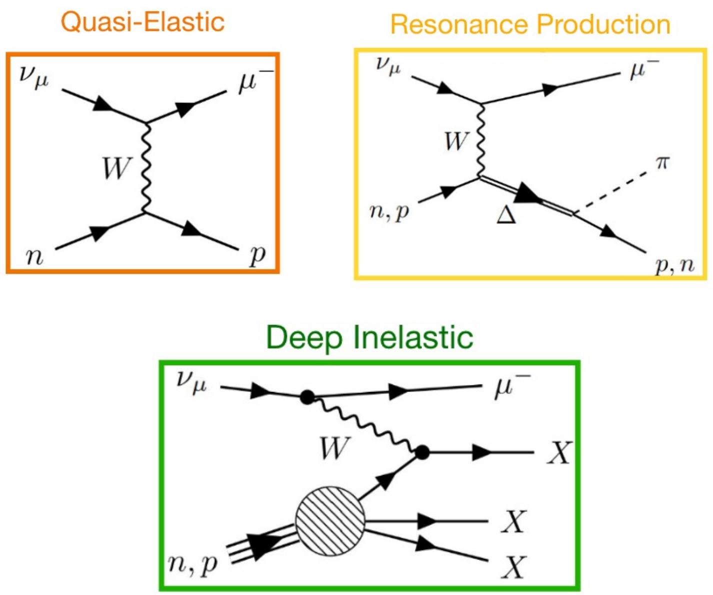
MicroBooNE: Neutrino Interaction Physics

Uncertainties in neutrino-nucleus interaction modeling are among the largest uncertainties in neutrino oscillation experiments.

MicroBooNE has an extensive neutrino-argon interactions physics program

- Largest neutrino-argon interaction dataset in the world
- Exploring inclusive and exclusive topologies in unprecedented detail
- Over 15 publications with another couple dozen active analyses





Kinematic Imbalance Variables

Novel variables that disentangle various nuclear effects

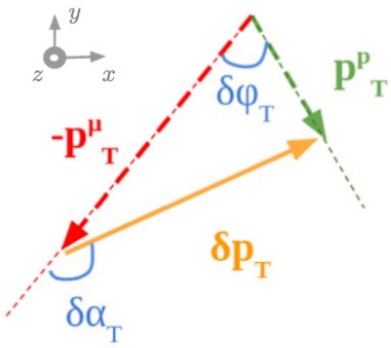
Initial efforts focused on variables in the plane transverse to the beam

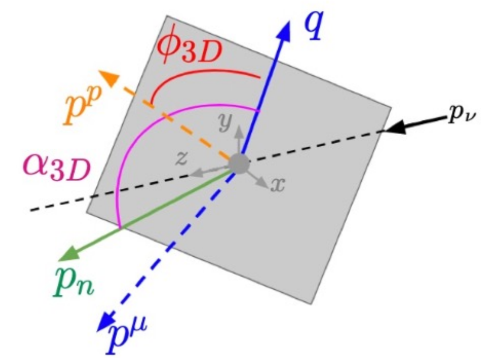
- **PRL 131, 101802 (2023)**

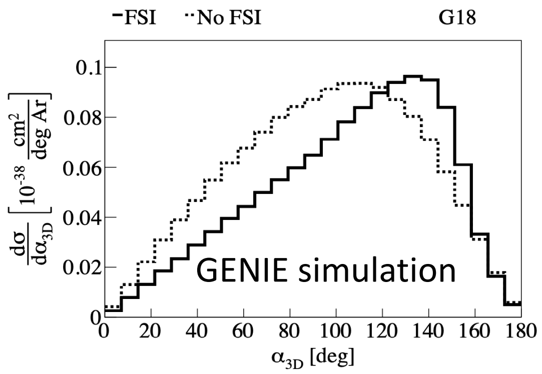
New analysis: **arxiv:2310.06082**

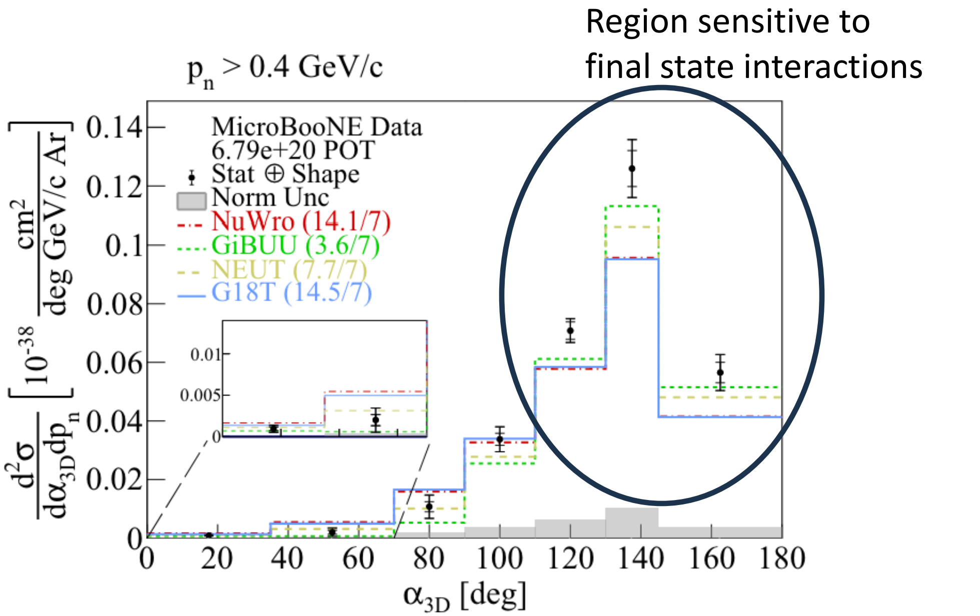
- extends to longitudinal variables

- **Signal:** ν_μ CC1p0π interactions (~50% BNB data)









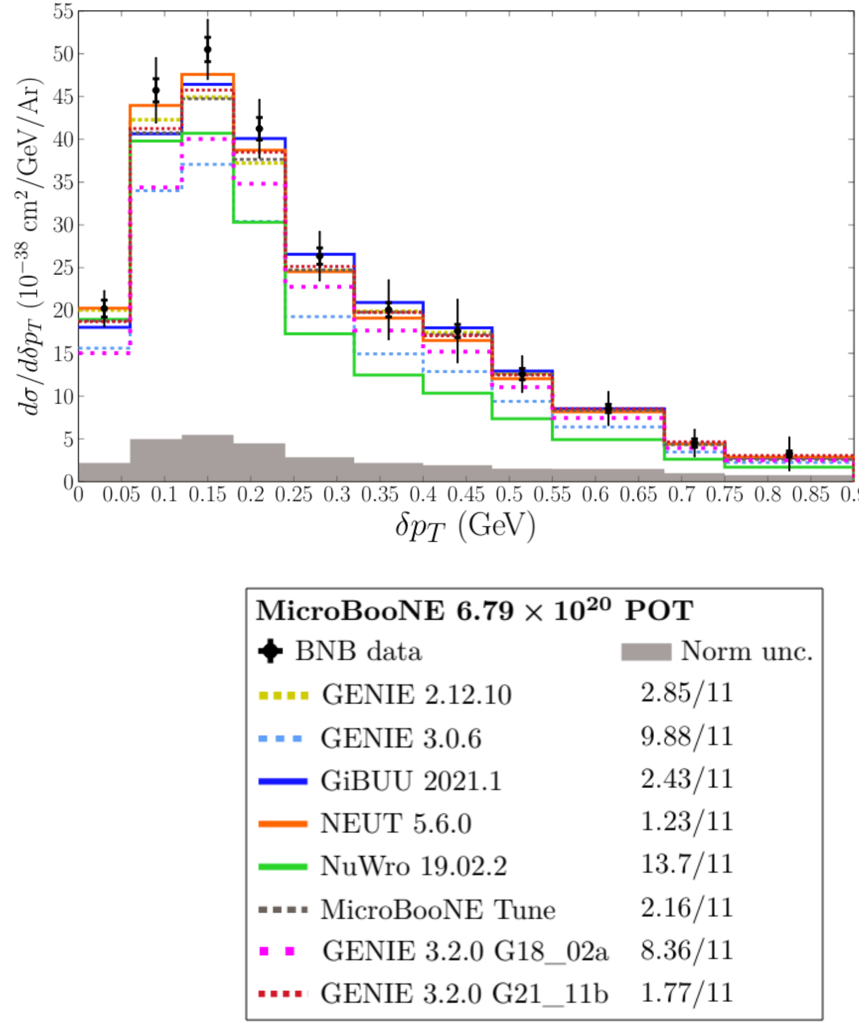
ν_μ CCNp0π: Correlations Across Observables

Signal: ν_μ CCNp0π interactions (~50% BNB data)

Report 14 distinct single- and double-differential cross sections, including muon, proton, and some transverse kinematic imbalance variables

Fully quantify and report correlations across the 359 bins comprising the 14 observables

arXiv:2403.19574

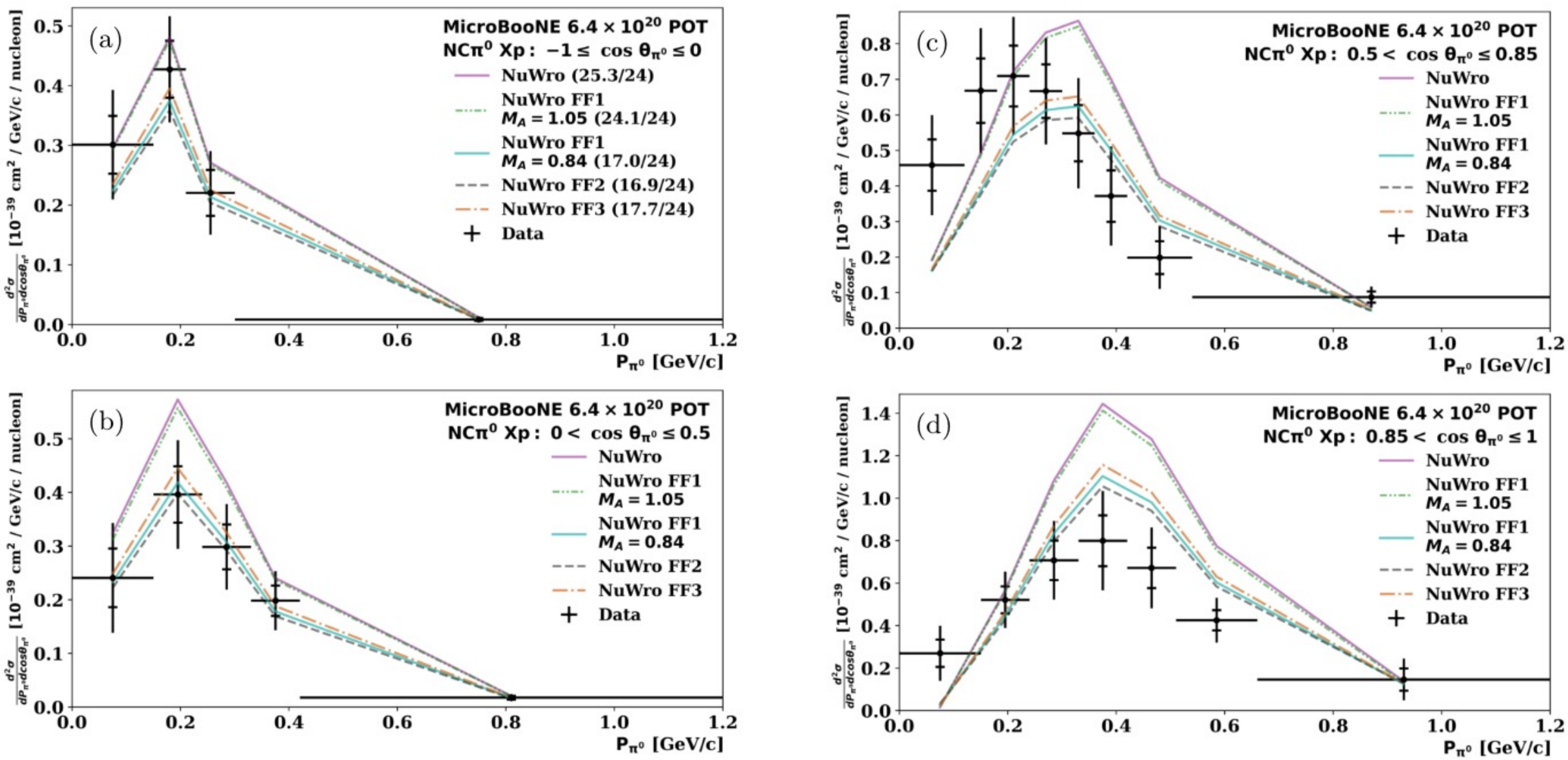


Model	χ^2 / 359 bins
GENIE 3.0.6	1859
NEUT 5.6.0	2582
MicroBooNE Tune	2673
GENIE 3.2.0 G21_11b	2947
GiBUU 2021.1	4836
NuWro 19.02.1	5315
GENIE 3.2.0 G18_02a	5724
GENIE 2.12.10	7799

ν_μ Neutral Current π^0 Production

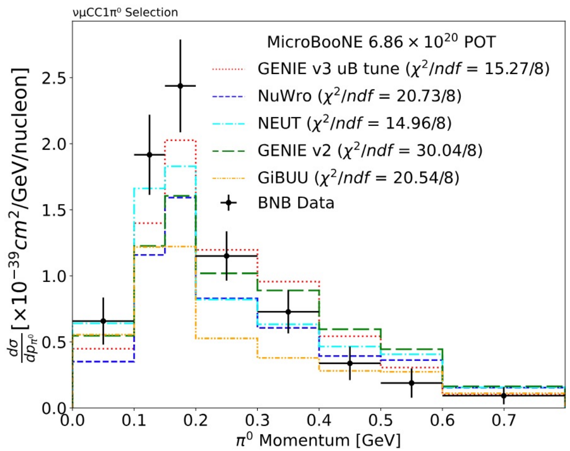
Neutral current π^0 production is a significant background for neutrino CP violation searches and BSM physics searches

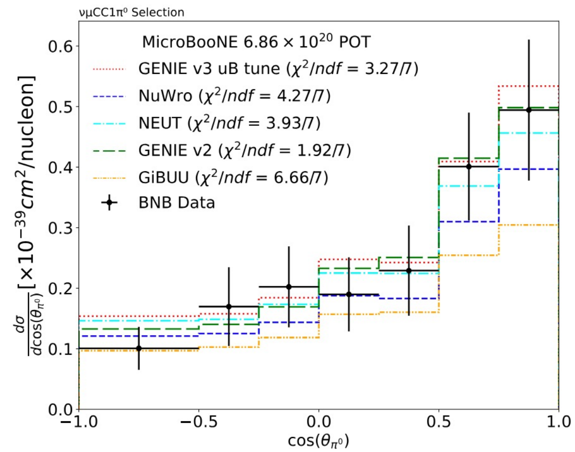
MicroBooNE reports the first double-differential cross section measurement of this process in neutrino-argon scattering: **arXiv:2404.10948**

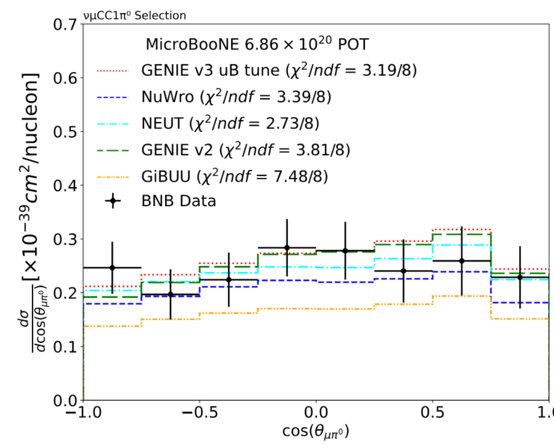


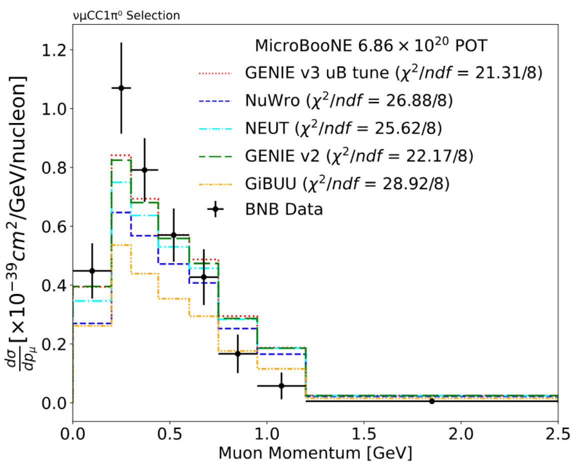
ν_μ Charge Current π^0 Production

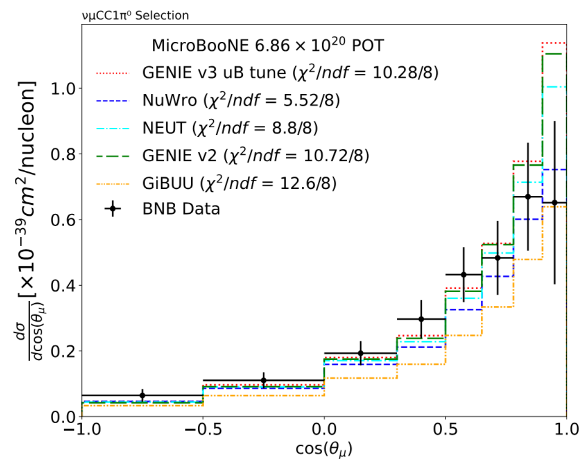
MicroBooNE also reports single-differential cross section measurements of charge current π^0 production in neutrino-argon scattering: **arXiv:2404.09949**











MicroBooNE Summary and Outlook

- Completed data taking in 2021
  - Longest running LArTPC and largest neutrino-argon dataset in the world

- No evidence of excessive ν_e or NC radiative Δ decay interactions; MiniBooNE LEE anomaly remains unexplained.

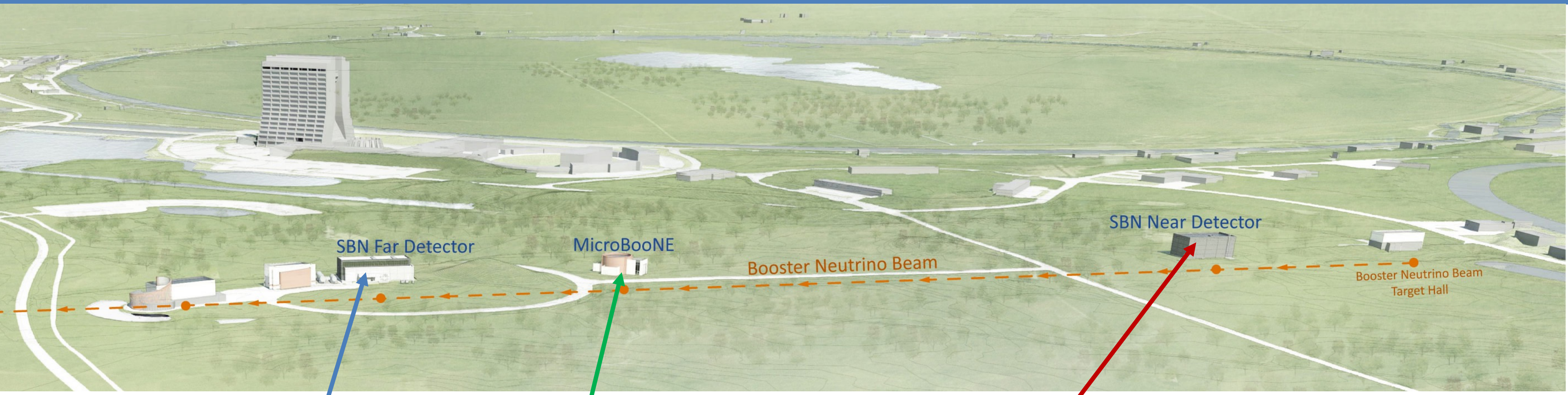
- No evidence of sterile neutrinos in a 3+1 model

- Several BSM physics searches have been presented, and more are in development

- Unprecedentedly detailed analysis of neutrino-argon interaction physics, with much more coming soon

- All of the above was with ~half the full data set; expect to see results with the full data set soon!

Short Baseline Neutrino Program



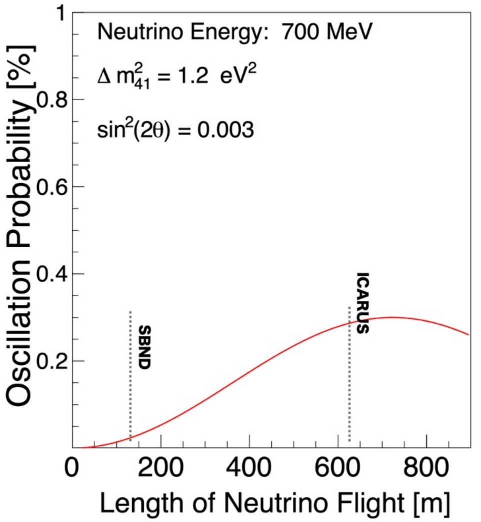
ICARUS Far Detector
600 m baseline
476 tons

MicroBooNE
468.5 m baseline
85 tons

SBND Near Detector
110 m baseline
112 tons

Primary Goal: Conclusively address oscillations with an eV-scale sterile neutrino

Will also have an extensive neutrino interaction cross section program and searches for BSM and rare physics



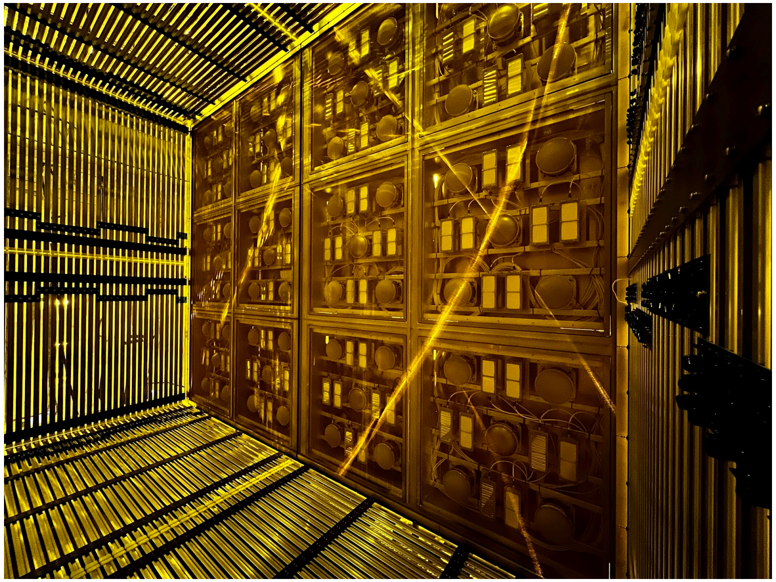
The ICARUS Detector

- Two modules, two TPCs per module with a central cathode
- Three readout wire planes per TPC, 3 mm wire pitch
- 360 PMTs for scintillation light detection
- Cosmic-ray tagger

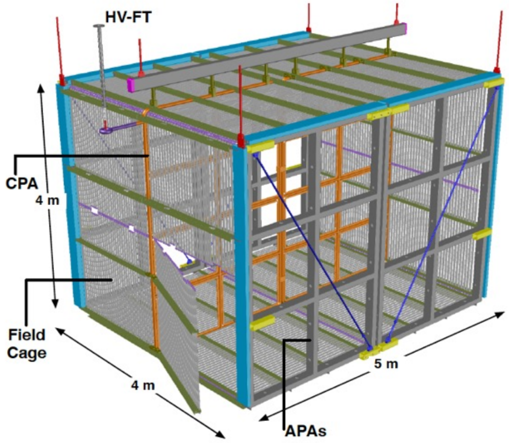
Timeline:
2015-2017: Overhaul at CERN
2018: Transport to and installation at FNAL
2020: Start of commissioning
December 2022: Start of physics data taking

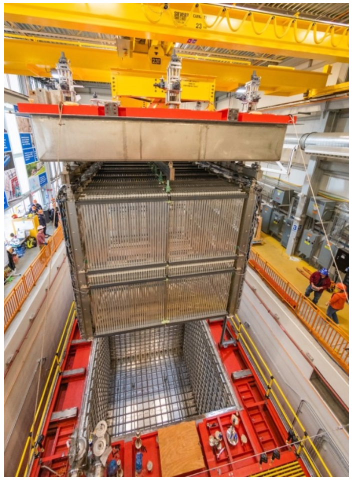
The SBND Detector

- One TPC with central cathode plane
- Each anode plane has three wire planes with different orientations. 11,260 wires total with 3 mm wire pitch
- Light detection: 120 8-inch PMTs, 192 X-ARAPUCAs, and TPB-coated reflective foils on the cathode plane
- Scintillator cosmic ray tagger



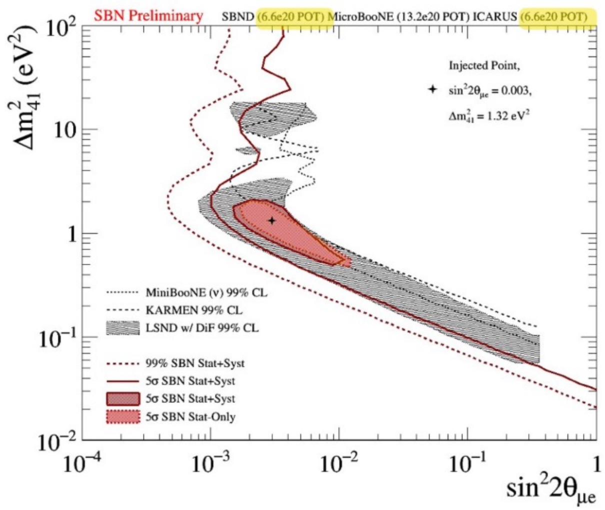
Status:
Installation finished December 2023
Argon fill started beginning of 2024
Commissioning began in February
First physics run later this year!



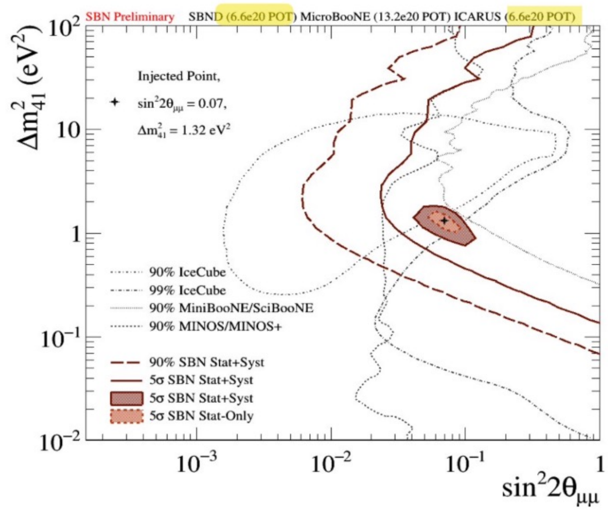


SBN and Sterile Neutrinos

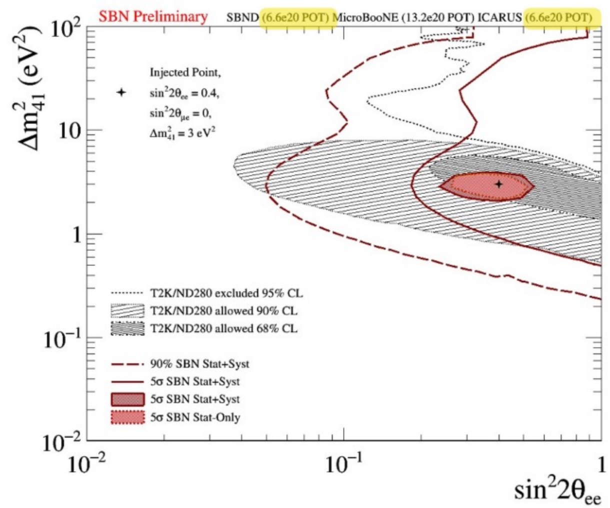
ν_e Appearance



ν_μ Disappearance



ν_e Disappearance



Credit to: J. Novak, *SBND and Short Baseline Neutrino Program*, Nu Phys 2023

World's-best limits over large portions of 3+1 parameter space

5σ discovery regions are significantly smaller than the allowed ~2-3σ regions from other experiments

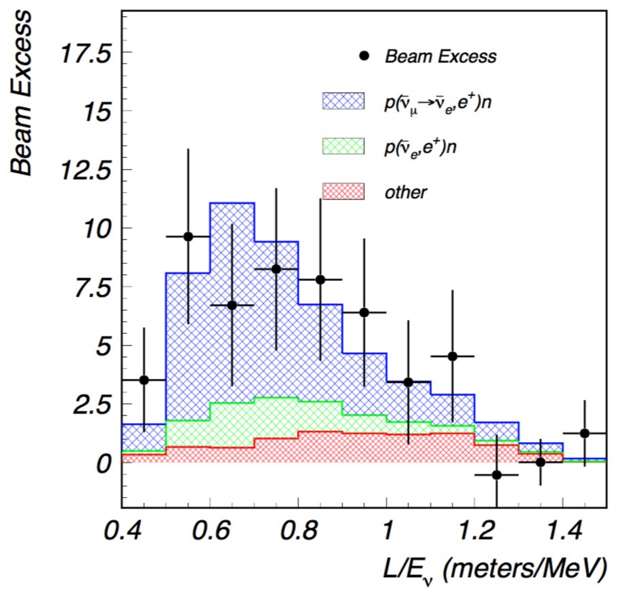
Thank you!

Backups

Oscillation Anomalies - LSND

LSND saw an excess of $\bar{\nu}_e$ events from decay-at-rest π^+

Phys.Rev.D64:112007,2001



π^+ → Decay at rest → $\mu^+ \nu_\mu$ → Muon Decay → $e+ \nu_e \bar{\nu}_\mu \nu_\mu$

Interpreting the excess to be neutrino oscillations:

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

L/E = 30 m / 50 MeV → $\Delta m^2 \sim 1\ eV^2$:

But $\Delta m_{21}^2 \sim 10^{-5}\ eV^2$, and $\Delta m_{31}^2 \sim 10^{-3}\ eV^2$

LSND result is not consistent with 3-ν mixing

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	$1\gamma 0p$	$1\gamma 1p$	$1\gamma X$
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

MicroBooNE Detector

Liquid Argon Time Projection Chamber (LArTPC) located in same beam and similar baseline as MiniBooNE

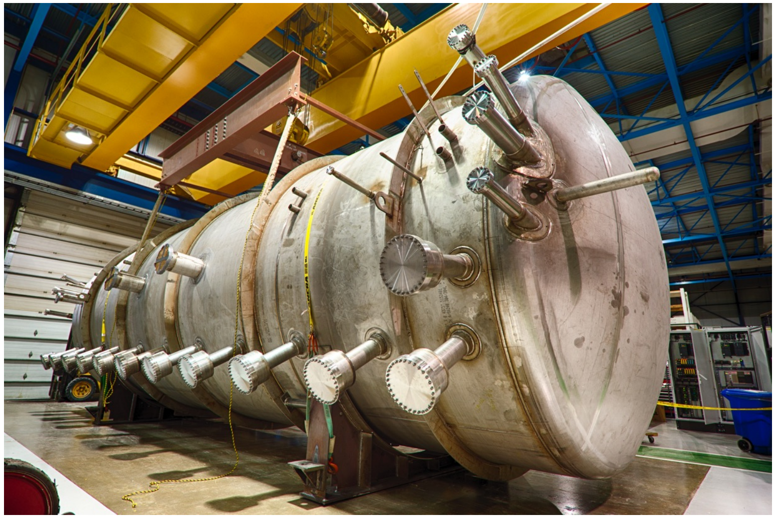
170 tons of liquid argon, 85 tons active

8192 readout wires
- 3456 collection wires (Y plane)
- 4736 induction wires (U+V planes)

32 8" cryogenic PMTs to tag neutrino interactions with high cosmic ray background

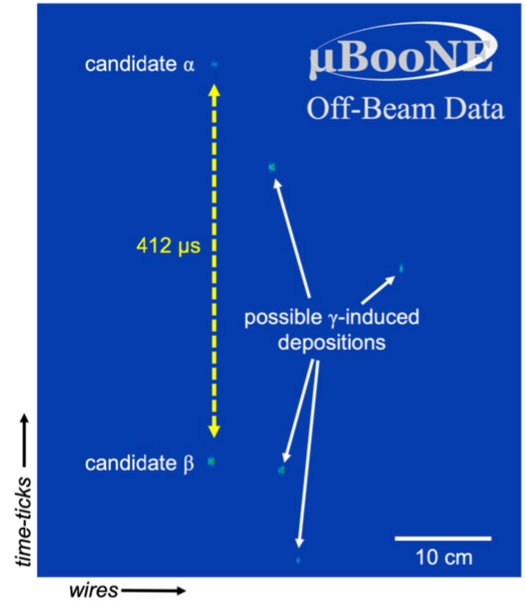
Cosmic ray tagger (CRT) installed around TPC

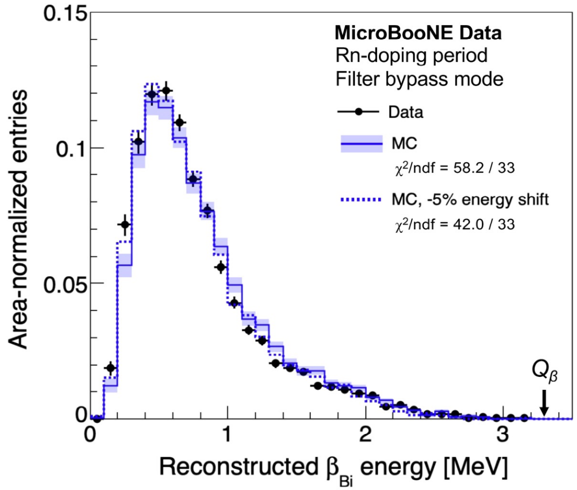
JINST 12 P02017 (2017)

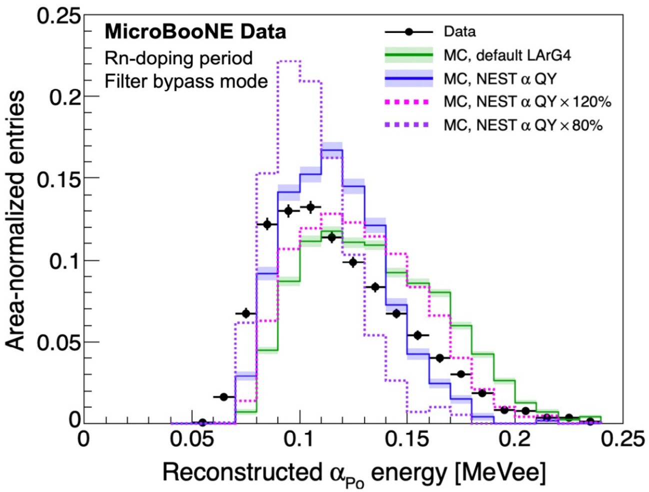


Sub-MeV Energy Capabilities

- Insert ^{226}Ra source and search for $^{214}Bi \rightarrow {}^{214}Po$
  - Separate filtered and filter-bypass samples
- Topology: ~Few MeV β and 7.7 MeV α displaced by an average 18 cm in drift coordinate
- The α is highly quenched by recombination, so we select clusters with an electron-equivalent energy of < 0.24 MeV
- **Results:** < 0.35 mBq/kg @ 95% C.L. (first such measurement in liquid-filtered LArTPC), which meets the DUNE stated target of < 1 mBq/kg.







Inclusive CC ν_μ “3D” Cross Section

First measurement of $d^2\sigma(E_\nu)/d\cos(\theta_\mu)dp_\mu$ for inclusive charged-current muon-neutrino scattering on argon

- **arxiv:2307.06413**

Used about 50% of the full BNB dataset

Extensive validation of missing energy model to support unfolding to true E_ν

E_ν dependence allows greater separation of QE and resonant components